國立政治大學資訊科學系

Department of Computer Science
National Chengchi University

碩士論文

Master's Thesis

IEEE 802.16 Mesh Mode 分散式排程之數學模型建立

Modeling the Distributed Scheduler of IEEE 802.16 Mesh Mode

研究生：陳彥賓

指導教授：蔡子傑

中華民國九十五年九月

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研究生：陳彥賓　Student：Yan-Bin Chen

指導教授：蔡子傑　Advisor：Tzu-Chieh Tsai

國立政治大學
資訊科學系
碩士論文

A Thesis
submitted to Department of Computer Science
National Chengchi University
in partial fulfillment of the Requirements
for the degree of
Master
in
Computer Science

中華民國九十五年九月

Sep 2006

記錄編號：G0093971017

國立政治大學

博碩士論文全文上網授權書

（提供授權人裝訂於紙本論文書名頁之次頁用）

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論文題目：IEEE 802.16 Mesh Mode分散式排程之數學模型建立

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Modeling the Distributed Scheduler of IEEE 802.16 Mesh Mode

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中華民國 九十五 年 九 月 六 日

Department of Computer Science
College of Science
National Chengchi University
Taipei, Taiwan, R.O.C.

As members of the Final Examination Committee, we certify that we have read the thesis prepared by **CHEN, YAN-BIN** entitled Modeling the Distributed Scheduler of IEEE 802.16 Mesh Mode. and recommend that it be accepted as fulfilling the thesis requirement for the Degree of Master of Science.

Thesis Advisor:

Chairman:

Date: 2006/09/6

IEEE 802.16 Mesh Mode 分散式排程之數學模型建立

摘要

IEEE 802.16 是一支援都會型無線網路的協定，IEEE 802.16 支援PMP模式(點對多點)和網狀模式兩種。在網狀模式中，所有節點的構成仿如ad-hoc 方式，並依據在控制性子框中的排程資訊來計算下次遞送時間。在資料傳送之前，會有一段設定連線的時間。這段時間，每一個節點都必須跟鄰節點競爭，以取得廣播它的排程資訊給鄰節點的機會。這樣的行為跟它過去的歷史無關。換句話說，它具有”時間同質性”而適合以隨機程序來模擬。在這篇論文中，我們將用排隊程序來建立排程行為的模型，然後以馬可夫鏈來估計它的平均延遲時間，也就是一節點持續地競爭直到贏為止的這段等待時間。

Modeling the Distributed Scheduler of IEEE 802.16 Mesh Mode

Abstract

The IEEE 802.16 standard is a protocol for wireless metropolitan networks. IEEE 802.16 MAC protocol supports both of PMP (point to multipoint) and Mesh mode. In the mesh mode, all nodes are organized in a fashion similar ad-hoc and calculate their next transmission time based on the scheduling information performed in the control subframe. Before data transmission for a certain node, there is a period of time to setup the connection. During this period, each node has to compete with each other for the opportunity to advertise scheduling messages to its neighbors. This behavior does not depend on past history. In other words, it is a “Time Homogeneous” and suitable for being modeled by stochastic process. In this thesis, we will model this scheduling behavior by queuing process, and apply the Markov Chain to estimate its average delay time which a node keep waiting until it win the competition.

Acknowledgements

First, I would like to express my deepest gratitude to my advisor, Dr. Tzu-Chieh Tsai, for his constant support and expert guidance. He showed me different logical thinking to approach a research problem and the need to be persistent to accomplish any goal. During these two years, he has been a friend and mentor to encourage me to face the challenges, and has confidence in me when I doubted myself. More important, I appreciate his guidance from my mathematic analysis in this study that enriches my knowledge and concepts. Without his encouragement and assistance, I could not have finished this thesis.

A special thanks goes to my committees: Dr. Hsiao-Kuang Wu, Dr. Chen-Fu Chou, and Dr. Yea-Li Sun for offering their insightful comments on this work. They asked me good questions to help me think through my problems. Besides, constructive suggestions were provided to make this study more complete.

I am also greatly indebted to my lab members, Chuan-Yin Wang and Chian-Chi Lin. We had many discussions together for my coding, numerical analysis and experimental statistics, even burned many nights in the lab. Zheng-Lin Li and Sol-Han Chang, thank you for sharing the experience and spirit in our research. The encouragement and supports of other friends in National Chengchi University are also gratefully acknowledged with special thanks to Lu-Te Chien, Chih-Hua Chang, Ying-Sheng Kuo, Yao-Hsien Wu,

Che-Kang Lu, and Cheng-Chang Tsai. I would like to express my special thanks to the friendship of Lee Hsu, thank you for your comments on the thesis writing.

Last, but not least, I would like to express my warmest gratitude and love to my father and mother, for everlasting patience, for educating me with constant unconditional support, for standing by me to pursue my future ideal. Yan-Ren and Ting thank for your many ideas of resolving the technical problems, for your listening to my complaints and frustrations, for giving me more self-confidence, and for believing in me. I have also benefited from discussions with you on various subject matters.

Above all of these, I would like to dedicate this thesis to my father and mother. I thank God for all this; I must confess that I am not the one who finishes this thesis. It is Him who works in me.

致謝

首先，請讓我對我的指導教授表達最深的感激，蔡子傑博士，他始終不斷地支持及非常專業地指導我。他告訴我要以不同角度的邏輯思考來解決研究過程遇到的問題，並希望我耐性地完成自己的目標。在這兩年中，他已成吾之良師益友，鼓勵我要面對挑戰，即使在我迷失自我時亦對我充滿信心。更重要地，在研究過程中，我感謝他在我數學分析方面的指導，豐富我許多知識與觀念。若沒有教授的鼓勵和協助，我無法完成這論文。

特別感謝我的口試委員: 吳曉光博士，周承復博士，孫雅麗博士，深具洞察力地對這研究提供他們的見解。他們問我很多非常好的問題，促進我對這些問題更深入地思考。此外亦提供非常建設性的建議讓這研究更為完整。

我也深深受惠實驗室同學王川耘及林建祈的許多幫忙。儘管無日無夜地待在實驗室熬夜，我們仍是一起討論程式的撰寫，數值的分析及實驗統計。李政霖和張碩漢，謝謝你們在研究時分享了你們的經驗和想法。也謝謝政大其他朋友的鼓勵和協助，特別是簡盧德，張志華，郭穎生，吳耀先，呂哲康和蔡承璋。我更要對許為義表達我的感謝，謝謝他在我論文撰寫方面提供寶貴的意見。

最後但並非最不重要，我要對我父親及母親表示最溫暖的愛和感激之情，他們無怨無悔的耐心，無條件地讓我接受良好的教育，依傍在側支持我追求自己的未來。彥任和婷婷，謝謝你們在技術問題上提供的好點子，傾聽我抱怨和挫折，給我自信，永遠地信任我。在跟你們的每次討論中，我真的受惠良多。

最重要的，我要將這論文獻給自己的父親、母親。我也要感謝上天；我必須坦承我絕非完成這論文的人，而是有上天協助我。

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CHAPTER 1

Introduction

The IEEE 802.16 standard [1, 2] “Air Interface for Fixed Broadband Wireless Access Systems”, also known as WiMAX, targets at providing last-mile wireless broadband access in metropolitan area networks. IEEE 802.16 offers an alternative to cabled access networks, such as fiber optic links, DSL links. Furthermore, IEEE 802.16 is a wireless network, which has the high capacity to cover more broad geographic areas without the costly infrastructure development. The technology may prove less expensive to deploy and may lead to more ubiquitous broadband access [3]. The clients also can connect to the IEEE 802.16 by adopting various existing wireless solutions, such as IEEE 802.11 (WiFi). IEEE 802.16 provides a cheaper and more ubiquitous solution to connect home or business to Internet. Much attention was paid to the IEEE 802.16 issues in recent years and a lot of industries formed a WiMAX Forum in order to certify compatibility and interoperability of various 802.16 products.

A Markov Chain to model this distributed scheduling of mesh mode as well as a mathematical model are proposed in this thesis to evaluate the average delay time.

1.1. Background

The initial version of 802.16 was published in 2001. It supported the multiple frequency allocations at 10--66GHz for Line-of-Sight (LOS), initially. Single Carrier was designed in PHY during this period. Two years later, 802.16a was published in January 2003. The frequency allocations at 2--11GHz for non Line-of-Sight (NLOS) were interested, and three types of PHY, that OFDM, OFDMA and Single Carrier were included in this version. There was an 802.16d [1] published in 2004, as a revision of original 802.16, 802.16a and 802.16c, which was a version belong to the fixed broadband wireless access. In 2005, 802.16e was published to be an amendment to 802.16d on enhancement to support mobility [2].

General PHY knowledge introduced here makes us realize the IEEE 802.16 more concretely. Both TDD (time division duplex) and burst FDD (frequency division duplex) variants are defined as its access schemes. Adaptive modulations, such as BPSK, QPSK, 16-QAM and 64-QAM are applied. This scheme is very different from 802.11 that the fixed modulation is used. By the way, channel bandwidths of 20 or 25 MHz (typical U.S. allocation) or 28 MHz (typical European allocation) are specified. The data transmission rate is up to 130 Mbps/s. The typical transmission range is up to 30 miles (approximate to 50km). 802.16e promises to support mobility up to speeds of 70–80 mile/h (105 - 120 km/h)and an asymmetrical link structure that will enable the subscriber station to have a handheld form factor for PDAs, phones, or laptops [4].

Up to the global view of MAC (Media Access Control) layer, there are two modes defined in the IEEE 802.16, which are the PMP (point-to-multipoint) mode and the Mesh mode. PMP mode is like the traditional star topology, or like the infrastructure mode in the

802.11. Mesh mode is like the ad-hoc mode in the 802.11. The traffic from BS (Base Station) to SS (Subscriber Station) is called downlink subframe; opposite direction, from SS to BS is called uplink subframe. Contrary to the basic PMP mode, there are no clearly separate downlink and uplink subframes in the mesh mode. Only TDD is supported in the mesh mode base on the standard’s definition. The BS and SS consists in the 802.16 network. The BS serves as the central gateway between 802.16 network and backhaul internet or another 802.16 networks. The SS plays the role of client in the 802.16 network.

The IEEE 802.16 defined the mesh frame structure as a convenience to organize the mesh network. The frame is divided into two subframes. One is the data subframe; the other is control subframe. The scheduling information and how many time slots in the data subframe it will request are specified in the control subframe. Understanding the scheduling of the control subframe is very useful to adjust the performance. That’s why we focus on estimating scheduling of the control subframe in this thesis.

The 802.16 mesh mode topology is depicted as Figure 1.1. There are many SSs in this topology which terminals, such as PDAs, notebooks or cellular phones, can be connected to via 802.11 or other protocols. The mesh mode is organized throughout these SSs and BSs. The link coverage is expanded under mesh network. Certain SSs are responsible to connect to the BSs. By these BSs, they connect to the backhaul or internet.

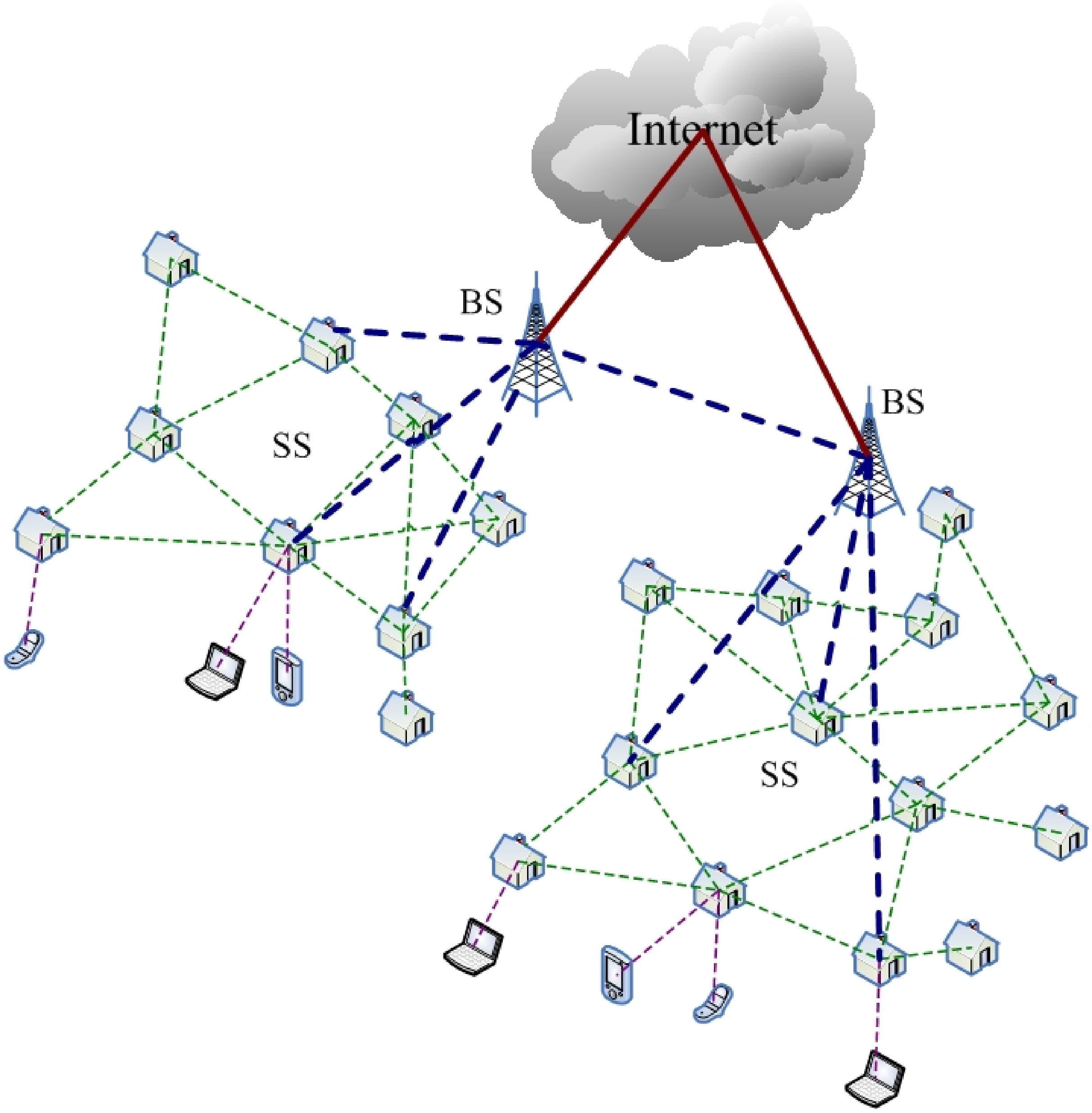


Figure 1.1: IEEE 802.16 Mesh Mode Topology

1.2. Motivation

More works on the IEEE 802.16 have primarily focused on the PMP mode. The BS is the key point in the PMP mode, because all of the flows from the SSs or to the SSs need pass through the BS. In that case, most of traffic controls depend on the BS. Naturally, it is responsible for the heavy loading throughout the PMP mode topology. It may bring about the risks with the paralysis of the network, if BS doesn't work smoothly. Nevertheless, each node in the mesh mode can act as the controller and partakes of the loading and the risks with the paralysis of the network.

The mesh mode is more complex, since there is no clear node as a centralized controller and every node competes for the channel in a distributed manner. Many interesting issues, such as selection of links, synchronization, routing, power saving …etc., are become more complex under mesh topology. All of these issues need a good performance in scheduling. So the scheduler and competing behavior become more important in the mesh mode. On the other hand, it is difficult to predict the system throughput and delay performance in the mesh mode without understanding the scheduler and competing behavior in control channel thoroughly.

We hope propose a easy and more quickly method to evaluate the delay time of scheduling control subframe.

1.3. Organization

The rest of this thesis is organized as follows. Chapter 2 introduces related work about the behavior and performance of the IEEE 802.16 mesh mode. The first reference Modelling and Performance Analysis of the Distributed Scheduler in IEEE 802.16 Mesh Mode is explained here. Chapter 3 proposes and explains our analysis of IEEE 802.16 distributed scheduling algorithm. We propose a Markov Chain to model this distributed scheduling and a mathematic method to evaluate the delay time in chapter 4. We verify the accuracy of the model by comparing delay time with the result in the simulation in chapter 5. And chapter 6 concludes this thesis and remarks on future work.

CHAPTER 2

Related Work

The IEEE 802.16 technology is the standard for broadband wireless metropolitan area networks (WMAN). Access and bandwidth allocation algorithms of this technology must accommodate hundreds of terminals per channel, with terminals that may be shared by multiple end users. The PHY layer supports single carrier, OFDM and OFDMA works in frequencies between 2-11 GHz and 10-66 GHz. MAC layer supports two kinds of modes, namely PMP mode and mesh mode. Mesh networks are able to reduce costs as these networks are easy installable and can be extended fast, simple by adding new mesh nodes.

2.1. Behavior Studies about 802.16 Mesh mode

In 2002, Dave Beyer, Nico van Waes and Carl EKlund have detailed introduction as a tutorial document to make us have an 802.16 MAC layer mesh extensions overview [5]. Not only the MAC frame structures are introduced, but also mesh distributed election-based scheduling concept is depicted, as Figure 2.1.

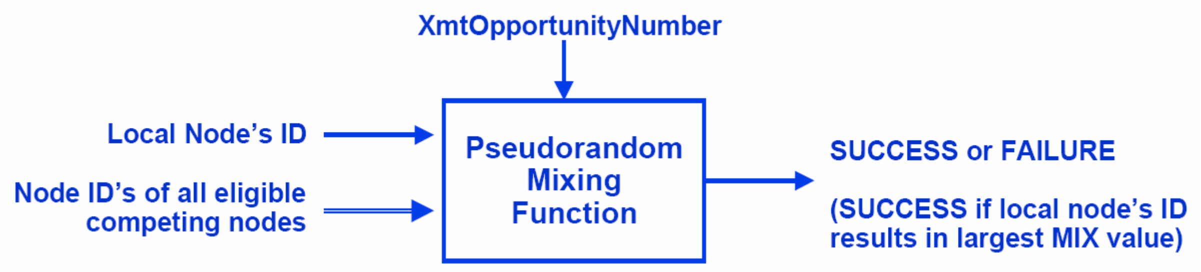


Figure 2.1: Mesh distributed election-based scheduling concept depicted by [5]

Nico Bayer, Dmitry Sivchenko, Bangnan Xu, Veselin Rakocevic and Joachim Habermann describe the election based transmission timing mechanism defined in the IEEE 802.16 standard [6]. This paper presents the influence of this mechanism on the overall network performance. It shows that in dense networks the interval between subsequent distributed scheduling messages (MSH-DSCH) is very large and thus causes significant delay on data packets. This interval is a special holdoff time defined in the IEEE 802.16 mesh mode, namely Transmission Holdoff Time. They propose a concept that reduces the constant 4 to 0 in following formula to lessen the transmission delay and enhance the performance.

$$H = 2^{\exp+4}$$

Scheduling IE, Request IE, Availability IE and Grants IE are messages to determine the available channel resource. The MSH-DSCH is the key component in the whole scheduling process and includes these messages. Within the MSH-DSCH transmission, available minislots are requested by the sender to ask its data transmission resource. Fuqiang LIU, Zhihui ZENG, Jian TAO, Qing LI, and Zhangxi LIN propose an algorithm to look up certain continuous available minislots at the same position of the continuous frames [7]. This paper proposes a slot allocation algorithm based on prioritization for IEEE 802.16 in the Mesh mode to achieve QoS with a low delay and low packet drop rate for high prioritized data flows.

2.2. Performance Studies about 802.16 Mesh mode

Some of papers are researched the performance between MAC and PHY, because 802.16 provides various PHY modulations [8]. They evaluate maximum theoretical throughput per OFDM symbol.

To the best of our knowledge, there are fewer papers, emphasized the MAC layer issue, devoted to model distributed scheduling of IEEE 802.16 mesh mode, except [9]. Min Cao, Wenchao Ma, Qian Zhang, Xiaodong Wang and Wenwu Zhu propose a geometric distribution to model the distributed scheduling of IEEE 802.16 mesh mode. They consider the modeling and analysis of the control sub-channel, which is characterized by the distributed election algorithm. [9] uses the following conclusion to evaluate the delay time.

$$E[S] = (N-1)\frac{V + E[S]}{H + E[S]} + 1 = (N-1)\frac{2^x + E[S]}{2^{x+4} + E[S]} + 1$$

CHAPTER 3

Analyze IEEE 802.16 Distributed Scheduling Algorithm

Before we model the distributed scheduler in IEEE 802.16 Mesh Mode, we have to know its behavior. The main difference between the PMP and Mesh modes is that in the PMP mode, traffic only occurs between BS and SSs, while in the Mesh mode traffic can be routed through other SSs and can occur directly between SSs. Centralized scheduling and Distributed scheduling are the two scheduling types defined in the IEEE 802.16 standard. Depending on the transmission protocol algorithm used, the traffic scenario can be done on the basis of using distributed scheduling, or on the basis of centralized scheduling, or on a combination of both. In this thesis, we focus on the distributed scheduling in the mesh mode.

3.1. Global Scenario

As we mentioned in the previous introduction, the IEEE 802.16 mesh mode is more complex because, without any central control, every station competes for the channel in a distributed manner. There are no clearly separate downlink and uplink subframes in the mesh mode. The mesh mode frames are divided into two subframes, one is control subframe, and the other is data subframe. IEEE 802.16 mesh mode uses the control subframe to exchange the schedule information, which is saved in the MSH-DSCH will be introduced at next section. Each node computes its schedule information based on parameters from itself and its neighbors to decide the node's next transmission time. If a collision occurs with a node's neighbors after computing its next transmission time, the node has to run the competing algorithm, named MeshElection, to select which node wins. The winner occupies this time as its next transmission time; the loser has to back off.

3.2. MSH-DSCH in MAC Frame Structure

The IEEE 802.16 defined the mesh frame structure as a convenience to organize the mesh network. The frame is divided into two subframes. One is the data subframe, the other is control subframe. Every control subframe consists of sixteen transmission opportunities, which may be imaged as a "time slot", and every transmission opportunity equals seven OFDM symbols time. (Figure 3.1)

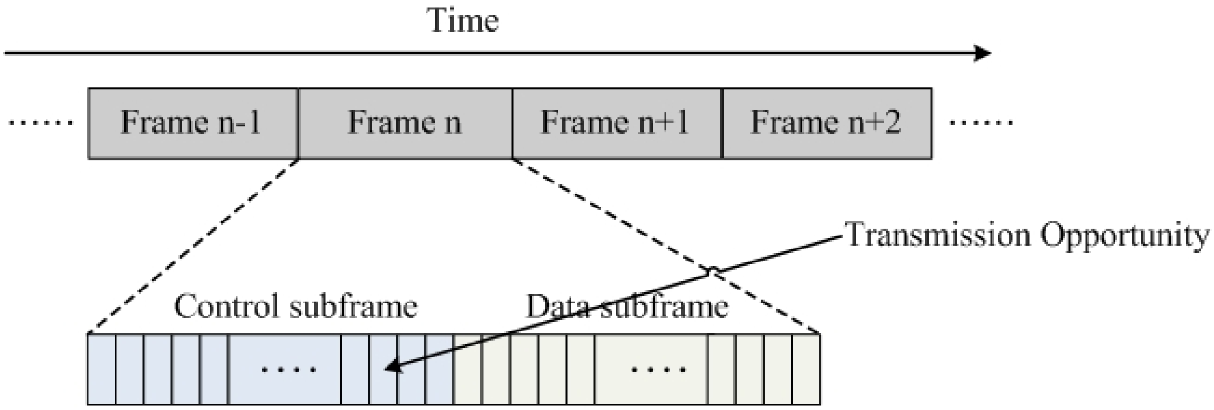


Figure 3.1 Data Subframe and Control Subframe

There are two control subframe types in a control subframe. One is network control that creates and maintains the cohesion between different systems. It also provides a new node to gain synchronization and initial network entry into a mesh network. The other is to coordinate scheduling of data transfers in system, namely, schedule control. The scheduling information is encapsulated here. Frames with the network control subframe occur periodically and all the other frames contain schedule control subframes tag along the network control subframe.

Two messages “MSH-NENT” and “MSH-NCFG” are used in the network control subframe. MSH-NENT means a mesh network entry, which is a message for a new node to gain synchronization and initial network entry into a mesh network; furthermore, MSH-NCFG means a mesh network configuration, provides a basic level of communication between nodes in different nearby networks. On the side, in the schedule control subframe, “MSH-CSCH” and “MSH-DSCH” means the mesh network centralized scheduling and the mesh network distributed scheduling, separately. MSH-DSCH is the key point that this thesis concentrates on.

As mentioned in this section’s first paragraph, we have introduced that every control subframe consists of sixteen transmission opportunities. Nevertheless, they are just the opportunities to own these time slots, but the really time slot occupied is indicated by “MSH-CTRL-LEN”. MSH-CTRL-LEN is a field saved in the MSH-NCFG message to express the control subframe length. MSH-DSCH-NUM is also saved in the MSH-NCFG message to express the number of MSH-DSCH opportunities in the schedule control subframe. Of course, what's left after MSH-DSCH-NUM is subtracted from MSH-CTRL-LEN becomes the number of MSH-CSCH opportunities. All of the parameters we introduced thus far are depicted in Figure 3.2.

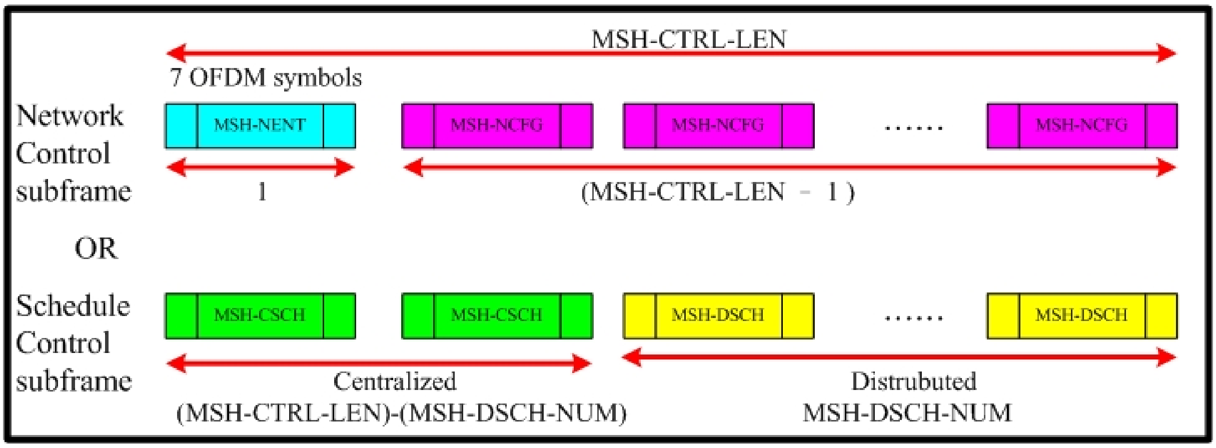


Figure 3.2: Network Control subframe and Schedule Control subframe

There is a parameter "Scheduling Frames" in the MSH-NCFG which specifies how many frames have a schedule control subframe between two frames with network control subframes in multiples of four frames. For example, there are 4 schedule control subframes, if Scheduling Frames equals 1; there are 8 schedule control subframes, if Scheduling Frames equals 2, …etc. (Figure 3.3)

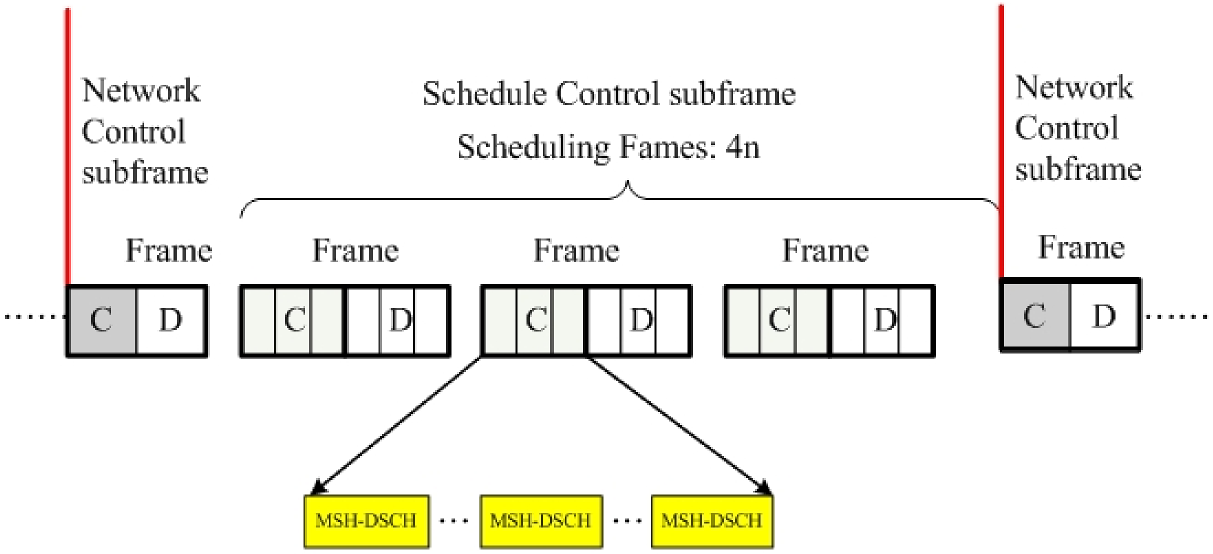
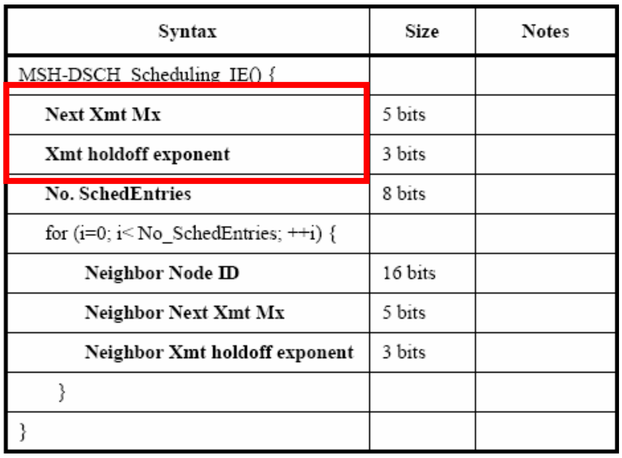


Figure 3.3: MSH-DSCH in the Schedule control subframe

3.3. Next Transmission Time and Transmission Holdoff Time

In this section, we will introduce parts of the terminologies and abbreviations in the IEEE 802.16 specification.

The schedule information for each node is described by two parameters **Next Xmt Time** and **Xmt holdoff Time**. In the IEEE 802.16 specification, **Next Xmt Time** is not employed directly. It uses **Next Xmt Mx** to calculate the **Next Xmt Time**. It doesn't use **Xmt holdoff Time**, neither. It uses **Xmt holdoff exponent** to calculate the **Xmt holdoff Time**. As the Figure 3.4 shows, **Next Xmt Mx** and **Xmt holdoff exponent** are two parameters in the MSH-DSCH message to perform the schedule information. So that whenever a node transmits MSH-DSCH message, every node has the schedule information of its neighbors.



Syntax	Size	Notes
MSH-DSCH_Scheduling_IE() {		
Next Xmt Mx	5 bits	
Xmt holdoff exponent	3 bits	
No. SchedEntries	8 bits	
for (i=0; i< No_SchedEntries; ++i) {		
Neighbor Node ID	16 bits	
Neighbor Next Xmt Mx	5 bits	
Neighbor Xmt holdoff exponent	3 bits	
}		
}		

Figure 3.4: Next Xmt Mx and Xmt holdoff exponent in the MSH-DSCH

(source: IEEE 802.16-2004)

3.3.1. Next Xmt Time

A node has to decide the next transmission time to know when to transmit the next MSH-DSCH message. There is a special terminology employed in the IEEE 802.16 specification to describe this transmission duration named "**Eligible Interval**". This next transmission time is denoted as **Next Xmt Time** and calculated from **Next Xmt Mx**. Assume "*Next*" is denoted as **Next Xmt Time** of an observed node; "*Mx*" and "*x*" means its corresponding **Next Xmt Mx** and **Xmt holdoff exponent** separately. Duration of **Next Xmt Time** could be shown as the following formula (1)defined in the standard.

$$2^{x} \cdot \mathrm{Mx} < \mathrm{Next} \leq 2^{x} \cdot (\mathrm{Mx} + 1) \tag{1}$$

By the observation of this formula, we know 2^{x} is the length of "*Next*". "*x*" is clearly an exponential value to express the length of "*Next*".

3.3.2. Xmt Holdoff Time

Xmt Holdoff Time is also a special terminology applied in the IEEE 802.16 specification to indicate that this node is not eligible to transmit messages. Assume "*Holdoff*" is denoted as **Xmt Holdoff Time** of an observed node; "*x*" means its corresponding **Xmt holdoff exponent**. Then, **Xmt Holdoff Time** could be shown as the following formula (2) defined in the standard.

$$\text{Holdoff} = 2^{x+4} \tag{2}$$

As explained in the previous section, we know 2^x is the length of "Next". From this formula, we know the holdoff time is in multiples of sixteen "Next".

3.3.3. Next Xmt Time and Xmt Holdoff Time on time axis

The following figure shows these variations on time axis. (Figure 3.5) **Earliest Subsequent Xmt Time** is a terminology in the standard to denote the earliest possible transmission time, without been determined. The parameters defined in the standard and will be discussed in this thesis are shown as Table 3.1.

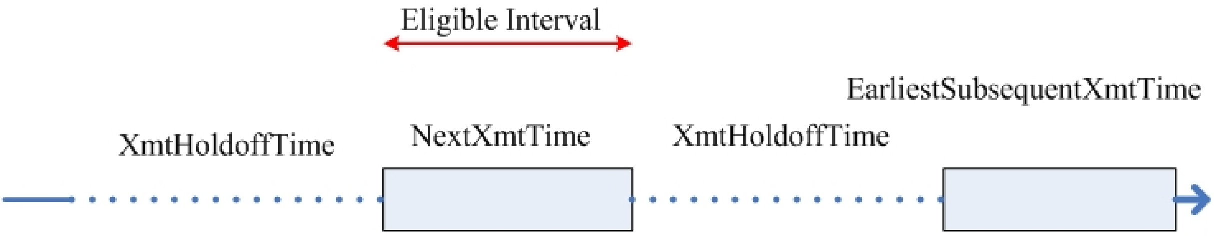


Figure 3.5: Next Xmt Time and Xmt Holdoff Time

Table 3.1: Abbreviation defined in the 802.16 Standard

Abbreviation in the 802.16 Standard	Description
Xmt Time	Transmission time
Current Xmt Time	Current transmission time
Next Xmt Time	Next transmission time
Xmt Holdoff Time	Transmission holdoff time
Next Xmt Mx	Next transmission maximum, used for Next Xmt Time
Xmt Holdoff Exponent	Transmission hold off exponent, used for the Xmt Holdoff Time
Earliest Subsequent Xmt Time	Earliest subsequent transmission time

3.4. Competing Behavior and Scheduling Algorithm

Distributed scheduling ensures that the transmissions are collision-free. There is an election algorithm named MeshElection defined in the IEEE 802.16 standard to achieve collision-free.

The competing behavior and scheduling algorithm occur in each of nodes which are activating all over the neighborhood in mesh network. For instance, we observe certain node's competing behavior and its scheduling algorithm. We assume this node as an observed node; its neighboring nodes are denoted as neighbors. In the period of the competing behavior happened on this observed node, the scheduling algorithm is been computed. First, observed node orders its neighbor table by the Next Xmt Time. Then for each entry of the neighbor table, adds the each neighbor's Next Xmt Time to its Xmt Holdoff Time to arrive at the neighbor's Earliest Subsequent Xmt Time, as in (3). Subsequently, sets Temp Xmt Time equal to this observed node's advertised Xmt Holdoff Time added to the current Xmt Time, as in (4). So far, the observed node understands its possible Next Xmt Time; even now it is just a Temp Xmt Time. The observed node also has its neighbors' information includes Next Xmt Time, Xmt Holdoff Time and Earliest Subsequent Xmt Time, simultaneously.

$$\text{Earliest Subsequent Xtm Time} = \text{Next Xmt Time} + \text{Xtm Holdoff Time} \tag{3}$$

$$\text{Temp Xtm Time} = \text{Current Xmt Time} + \text{Xtm Holdoff Time} \tag{4}$$

Depends on the information obtained previously, the observed node has the sufficient information to judge whether the possible collisions will occur or not. That is, there is a probability that this observed node's Next Xmt Time results in collision with neighbors' Next Xmt Time. The competing nodes are the subset of the neighbors with a Next Xmt Time eligibility interval that includes Temp Xmt Time or which an Earliest Subsequent Xmt Time equal to or smaller than Temp Xmt Time. These collision situations are depicted as Figure 3.6 to express the collisions will be occurred between an observed node's Next Xmt Time and its neighbors'. The neighbor i is save. The neighbor j has its Next Xmt Time at the same time with the observed node. Neighbor k owns its Next Xmt Time early but its Earliest Subsequent Xmt Time overlaps the observed node's Next Xmt Time. In brief, observed node has two collisions with neighbor j and neighbor k.

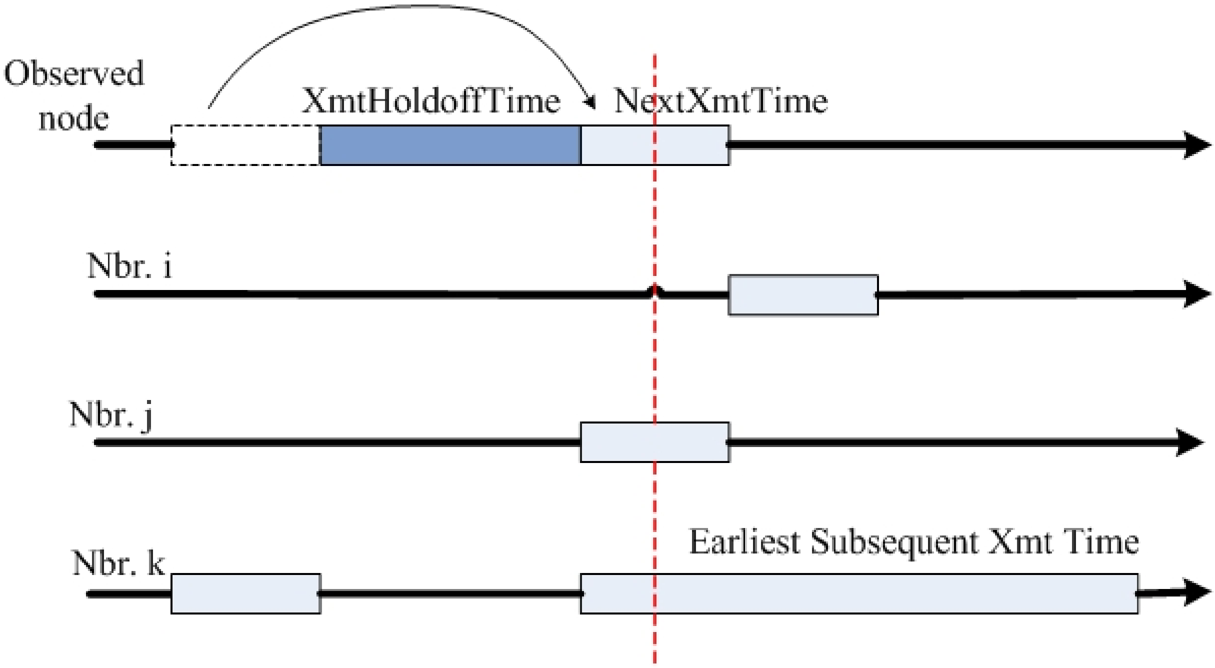


Figure 3.6: One node results in collision with neighbors

If the collision will happen on observed node's Next Xmt Time as mentioned previously, the algorithm MeshElection will be executed during this computing period of distributed schedule. MeshElection is a C code function implemented in the standard. The Boolean value will be come out after MeshElection. "TRUE" means that this observed node wins the competing; on the contrary, "FALSE" means not. Corresponding procedures of them are:

- TRUE: Set Temp Xmt Time to Next Xmt Time, and ends off this algorithm.
- FALSE: Temp Xmt Time need to back.

The Figure 3.7 and Figure 3.8 show the flowchart we introduced. In order to have the better presentation in the flowchart, abbreviations are used and described as Table 3.2.

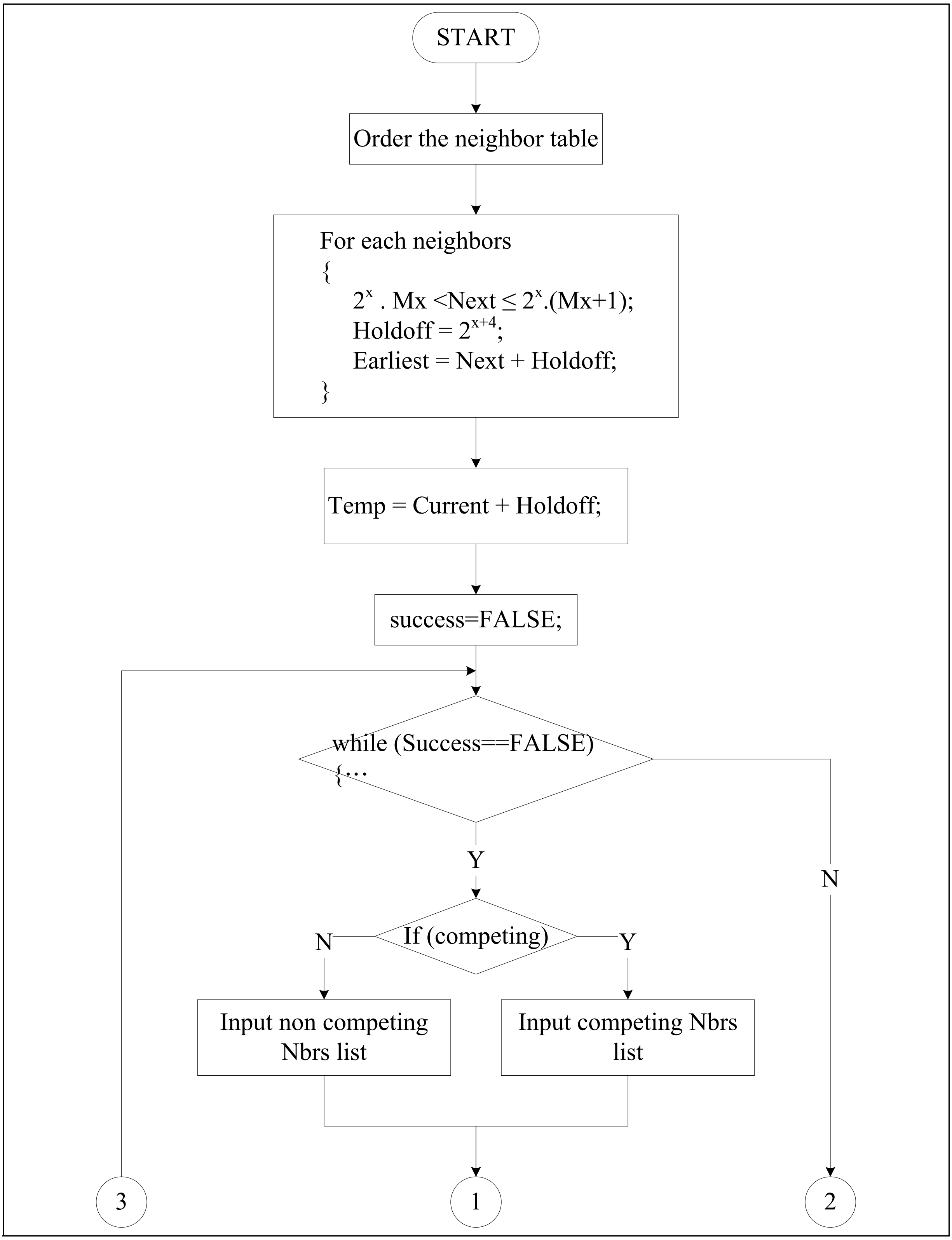


Figure 3.7: The flowchart of competing algorithm-1

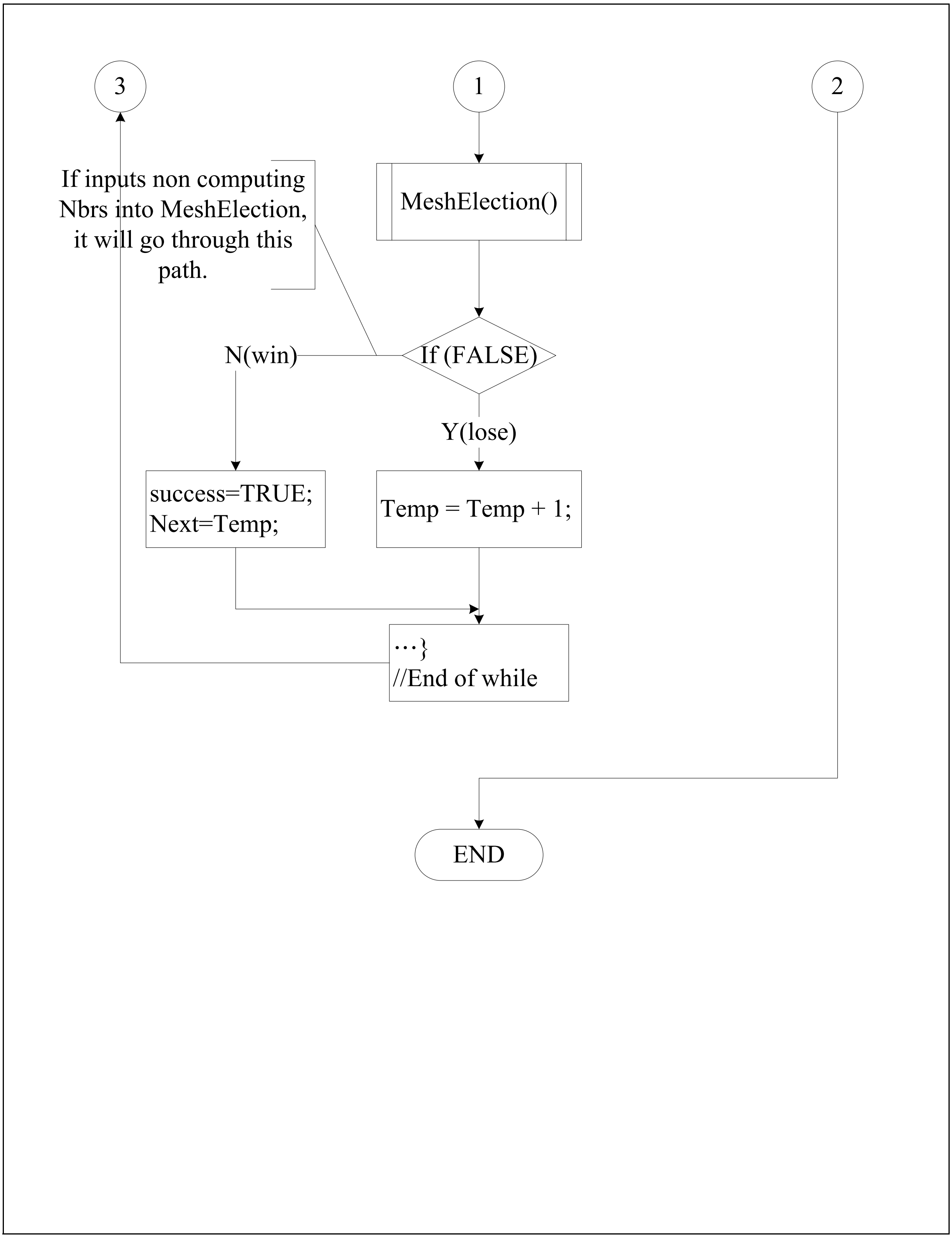


Figure 3.8 :The flowchart of competing algorithm-2

Table 3.2: The abbreviations in the flowchart

Abbreviations in the Figure 3.7 and Figure 3.8	Descriptions
Mx	Next Xmt Mx
Next	Next Xmt Time
Holdoff	Xmt Holdoff Time
Earliest	Earliest Subsequent Xmt Time
Temp	Temp Xmt Time
Current	Current Xmt Time

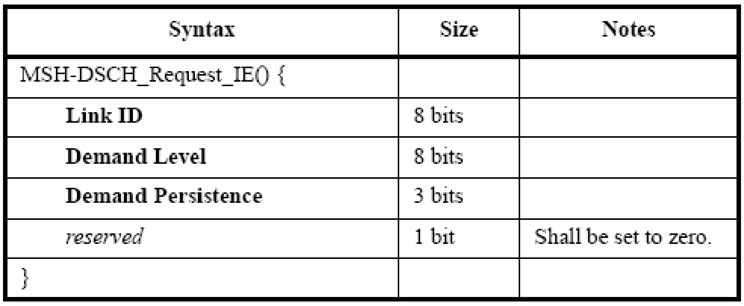
3.5. Three-Way Handshaking

So far, the competing behaviors of control subframe in the distributed scheduling of IEEE 802.16 mesh mode are introduced. Thansmiting the MSH-DSCH message to the neighbors shall stable then subsequent data transmission may work better. Before data transmission, both of the coordinated and uncoordinated scheduling employs a three-way handshake to setup the connections with neighbors. This mechanism is used to convey the channel resources for the preparation of consequent data transmission. As follows, the three-way handshaking IEs (information elements) "**Request IE**", "**Availability IE**" and "**Grants IE**" are encapsulated in the MSH-DSCH, too. Hence it implies that the performance of MSH-DSCH packet traffic influences the three-way handshaking. This is why we concentrate upon the MSH-DSCH performance evaluation in this thesis.

- ”**Request-IE**” shall convey resource requests on per link basis. There is a Demand Persistence field in the request IE to submit the number of frames wherein the demand exists. (Figure 3.9)

- “**Availability-IE**” shall be used to indicated free minislot ranges that neighbors could issue Grants in.

- “**Grants-IE**” shall convey information about a granted minislot range selected from the range reported as available. Grants shall be used both to grant and confirm a grant, like the “acknowledge” in general communication protocol.



Syntax	Size	Notes
MSH-DSCH_Request_IE() {		
Link ID	8 bits	
Demand Level	8 bits	
Demand Persistence	3 bits	
reserved	1 bit	Shall be set to zero.
}		

Demand Persistence:

0 = cancel reservation
1 = single frame
2 = 2 frames
3 = 4 frames
4 = 8 frames
5 = 32 frames
6 = 128 frames
7 = Good until cancelled or reduced

Figure 3.9: Request IE Message

(source: IEEE 802.16-2004)

Followings are what the procedures of three-way handshaking are defined in the IEEE 802.16 standard.

- ”MSH-DSCH-request” is made along with ”MSH-DSCH-availabilities”, which indicate potential slots for replies and actual schedule.

- ”MSH-DSCH-grant” is sent in response indicating a subset of the suggested availabilities that fits, if possible, the request. The neighbors of this node not involved in this schedule shall assume the transmission takes place as granted.

- ”MSH-DSCH-grant” is sent by the original requester containing a copy of the grant from the other party, to confirm the schedule to the other party. The neighbor of this node not involved in this schedule shall assume the transmission takes place as granted.

By the way, the handshaking is depicted to be clearer in the Figure 3.10

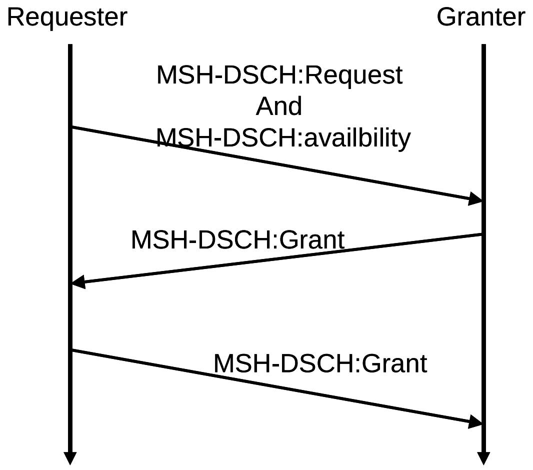


Figure 3.10: Three-way handshaking

CHAPTER 4

Mathematic Model

So far, the competing behaviors of control subframe in the distributed scheduling of IEEE 802.16 mesh mode are presented. Next, we are going to propose a mathematical analysis to model the MSH-DSCH transmission behavior of IEEE 802.16 mesh mode. The delay time of MSH-DSCH transmission will be evaluated by our proposed mathematical model.

4.1. Markov Chain

We observed the behavior of distributed scheduling in the mesh mode in previous chapter. We found this behavior does not depend on all of past history. In other words, it is a “Time Homogeneous” and suitable for being modeled by stochastic process. The delay time in the period of MSH-DSCH transaction is what we are interested in this thesis, which the Markov Chain is easy using to observe it. Depends on Leonard Kleinrock’s description in his book “QUEUEING SYSTEMS VOLUME I: THEORY”, Markov processes may be used to describe the motion of a particle in some space. We consider discrete-time Markov chains, which permit the particle to occupy discrete positions and permit transitions between these positions to take place only at discrete times.[11]

Assume X_n is denoted as a state in our consequent Markov Chain model that a node stays at a certain time to transmit MSH-DSCH. Time unit is an opportunity. A set of random variable $\{X_n\}$ forms a Markov chain if the probability that the next state is X_{n+1} depends only upon the current state X_n and not upon any previous stations. Base on our analysis in previous chapter, the next state merely depends on the current competing result, neither on the last nor on all of past history. Thus we have a random sequence in which the dependency extends backwards one unit in time. If this node's Temp Xmt Time overlaps with its neighbors, it implies the competing is occurred with them. If it wins or there is no competition, it will set this Temp Xmt Time as its Next Xmt Time. If it loses, it will back one opportunity to run this behavior again until it wins. In order to simplify the notification, we assume integer 1,2,3 … represent each of certain state X_n , the physical concept of our proposed Markov Chain are depicted as Figure 4.1.

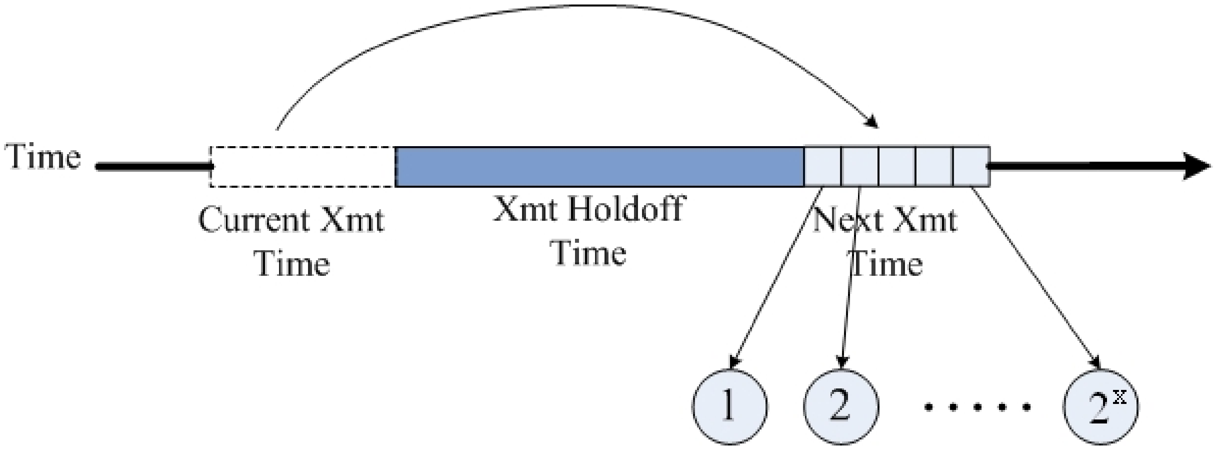


Figure 4.1: Each state corresponds to the Next Xmt Time-1

With this concept of Figure 4.1, we can model this behavior with a vertical chain as Figure 4.2. The states and transition definitions are defined as Table 4.1. From state 1 to state 2^x implies the time duration of one Next Xmt Time. Suppose we have N nodes totally, the probability which a node wins N-1 nodes can be expressed by formula (5).

Oppositely, the probability of a node loses them can be expressed by formula (6).

$$\text{Win} = \text{Prob}_{\text{N-1}} \tag{5}$$

$$\text{Lose} = 1 - \text{Prob}_{\text{N-1}} \tag{6}$$

Table 4.1: The Notation definitions in the Markov Chain

Notation	Description
Integers in the state	The state probability that the transmission time backs to certain opportunity
Prob	The transition probability to indicate the probability that the node wins.
X	Exponent of Xmt Holdoff Time
N	The number of nodes

For example, if our observed node loses, it transfers from state 1 to state 2, the transition probability is $1 - \text{Prob}_{\text{N-1}}$. If it wins, it stays at state 1, the transition probability is $\text{Prob}_{\text{N-1}}$.

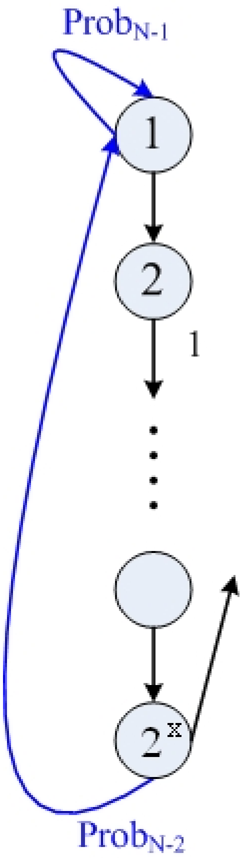


Figure 4.2: One vertical chain

In order to model it easily, we assume that as long as the node lose this competition, it does not back one opportunity. It has to back a length of Next Xmt Time. That's why the transition probabilities during the inter-states are always 1 in Figure 4.2. Thus, the state transfers to the second vertical chain are shown as Figure 4.4. If this node loses again, it will back a length of Next Xmt Time again to the third vertical chain …etc.

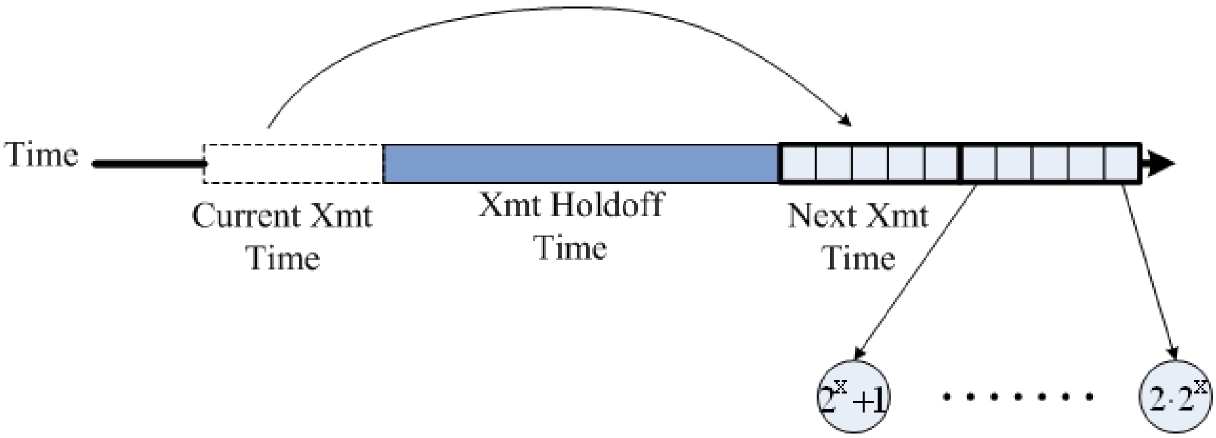


Figure 4.3: Each state corresponds to the Next Xmt Time-2

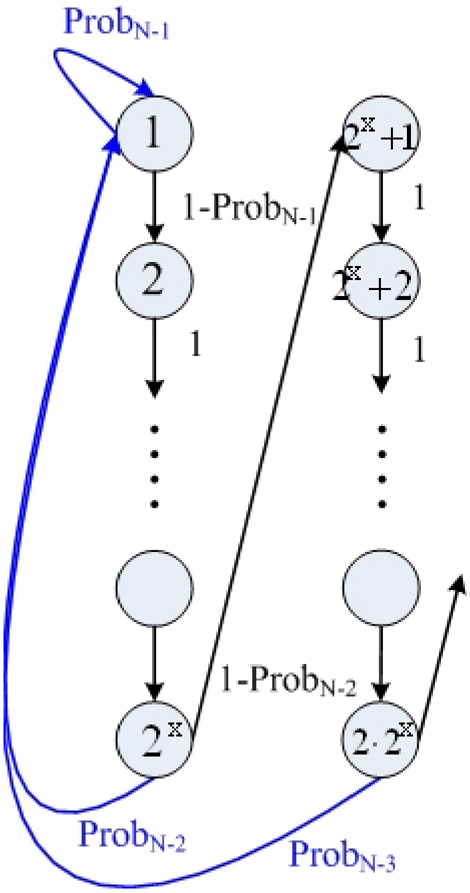


Figure 4.4 : Two vertical chains

At last, a Markov chain is organized as Figure 4.5.

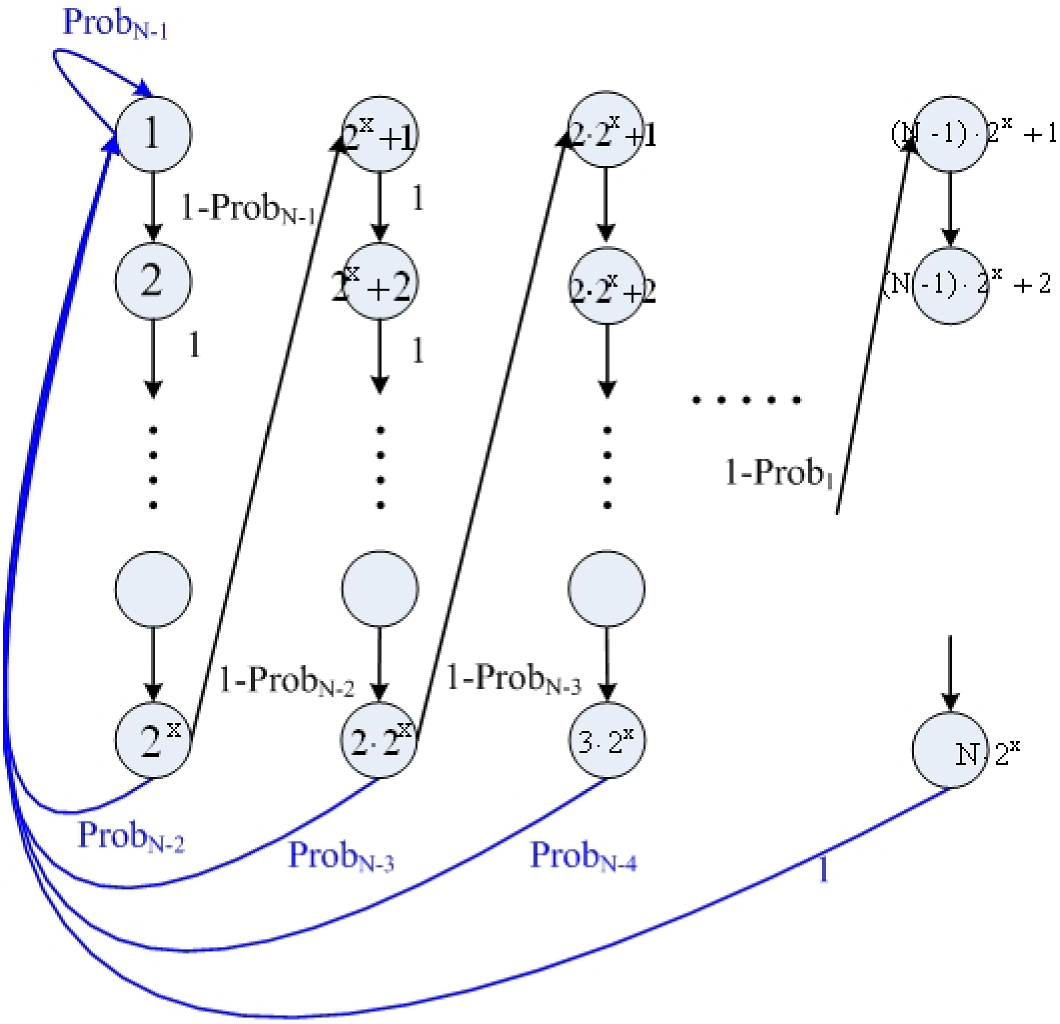


Figure 4.5: The Markov Chain

4.2. Mathematical Evaluation

The Markov Chain we proposed presents the variations of state transitions. We hope to induce an equation to evaluate the average delay time. The dependency of delay time relates to a probability of win. Before evaluating the delay time, we have to induce this probability formula initially. Then the expected value, the average delay time we target, is the product of probability and time.

4.2.1. Probability Theory and Assumptions

To begin with, we assume the number of nodes is N. Each observation of a node competes with neighbors is independent and represents one of two outcomes "competing" or "non-competing". So by using (7), we can get the competing probability $P_{competing}$. This is the binomial distribution we know. The P_c in the (7) is a probability that one node competes with one another node. More details can be retrieved from chapter 3.4 and Figure 3.6. $P_{competing}$ is different from P_c in our assumptions. P_c is the condition happened between one node and one node in a very short time. Nevertheless, $P_{competing}$ is the condition while at least one of the following events is happened: between one node and one node, or between one node and two nodes, or between one node and more another nodes. So formula (7) means one of the following situations is occurred: observed node competes with one neighbor, or observed node competes with two neighbors, or observed node competes with three neighbors …etc.

Table 4.2: Notations of equations

Notation	Description
Prob	Probability of $(\text{competing} \cap \text{win})$
$P_{competing}$	Probability of competing, at least one of more events happens
P_c	Probability of competing between one node to one of another node.

N	Number of nodes

$$
\begin{aligned}
&P_{\mathrm{competing}} \\
&= C_0^{N-1} \cdot P_c^{\,0} \cdot (1-P_c)^{N-1} + C_1^{N-1} \cdot P_c^{\,1} \cdot (1-P_c)^{N-1-1} + C_2^{N-1} \cdot P_c^{\,2} \cdot (1-P_c)^{N-1-2} + \ldots
\end{aligned} \quad (7)
$$

Moreover, the win probability should be an inverse proportion of the number of competing nodes. So we get (8) from (7).

$$
\begin{aligned}
&\mathrm{Prob}_{N-1} = P_{\mathrm{competing} \cap \mathrm{win}} \\
&= \frac{1}{1} C_0^{N-1} \cdot P_c^{\,0} \cdot (1-P_c)^{N-1} + \frac{1}{2} C_1^{N-1} \cdot P_c^{\,1} \cdot (1-P_c)^{N-1-1} + \frac{1}{3} C_2^{N-1} \cdot P_c^{\,2} \cdot (1-P_c)^{N-1-2} + \ldots \\
&= \sum_{k=0}^{N-1} \frac{1}{k+1} \cdot C_k^{N-1} \cdot P_c^{\,k} \cdot (1-P_c)^{N-1-k}
\end{aligned} \quad (8)
$$

In opposition, the losing probability can be derived as (9).

$$
1 - \mathrm{Prob}_{N-1} = 1 - \left(\sum_{k=0}^{N-1} \frac{1}{k+1} \cdot C_k^{N-1} \cdot P_c^{\,k} \cdot (1-P_c)^{N-1-k} \right) \quad (9)
$$

4.2.2. Delay Time

By the observation of Markov Chain (Figure 4.5), if the node wins at state 1, the transition probability of win can be expressed by using (10). If the node wins at the state 2^x that is the end of first vertical chain, the probability of win can be expressed by using (11). If the node wins at the state $2 \cdot 2^x$ that is the end of second vertical chain, the probability of win can be expressed by using (12)…etc.

$$\mathrm{Prob}_{\mathrm{N-1}} \tag{10}$$

$$(1 - \mathrm{Prob}_{\mathrm{N-1}}) \cdot \mathrm{Prob}_{\mathrm{N-2}} \tag{11}$$

$$(1 - \mathrm{Prob}_{\mathrm{N-1}}) \cdot (1 - \mathrm{Prob}_{\mathrm{N-2}}) \cdot \mathrm{Prob}_{\mathrm{N-3}} \tag{12}$$

This probability distribution gives the trial number of the first success, so it is a geometric distribution. Substitute (8) and (9) into (10), (11) and (12), we can derive the probability (13), (14) and (15).

$$\mathrm{Prob}_{N\text{-}1} = \left(\sum_{k=0}^{N\text{-}1} \frac{1}{k+1} \cdot C_k^{N\text{-}1} \cdot {P_c}^{k} \cdot (1 - P_c)^{N\text{-}1\text{-}k}\right) \tag{13}$$

$$(1 - \mathrm{Prob}_{N\text{-}1}) \cdot \mathrm{Prob}_{N\text{-}2} = \left(1 - \left(\sum_{k=0}^{N\text{-}1} \frac{1}{k+1} \cdot C_k^{N\text{-}1} \cdot {P_c}^{k} \cdot (1 - P_c)^{N\text{-}1\text{-}k}\right)\right) \cdot \left(\sum_{k=0}^{N\text{-}2} \frac{1}{k+1} \cdot C_k^{N\text{-}2} \cdot {P_c}^{k} \cdot (1 - P_c)^{N\text{-}2\text{-}k}\right) \tag{14}$$

$$\begin{aligned}&(1 - \mathrm{Prob}_{N\text{-}1}) \cdot (1 - \mathrm{Prob}_{N\text{-}2}) \cdot \mathrm{Prob}_{N\text{-}3}\\ &= \left(1 - \left(\sum_{k=0}^{N\text{-}1} \frac{1}{k+1} \cdot C_k^{N\text{-}1} \cdot {P_c}^{k} \cdot (1 - P_c)^{N\text{-}1\text{-}k}\right)\right) \cdot \left(1 - \left(\sum_{k=0}^{N\text{-}2} \frac{1}{k+1} \cdot C_k^{N\text{-}2} \cdot {P_c}^{k} \cdot (1 - P_c)^{N\text{-}2\text{-}k}\right)\right)\\ &\cdot \left(\sum_{k=0}^{N\text{-}3} \frac{1}{k+1} \cdot C_k^{N\text{-}3} \cdot {P_c}^{k} \cdot (1 - P_c)^{N\text{-}3\text{-}k}\right)\end{aligned} \tag{15}$$

So far, each probability on the corresponding vertical chain has been derived. The expected value can be calculated by the summation of these probabilities and multiplied by time, Then formula (16) can be obtained. The unit of time in this formula is opportunity.

$$
\begin{aligned}
&E(\text{opportunity}) \\
&= (\underset{\text{Win}}{\underline{\sum_{k=0}^{N-1} \frac{1}{k+1} \cdot C_k^{N-1} \cdot P_c^{\ k} \cdot (1-P_c)^{N-1-k}}}\ ) \cdot 2^x \\
&+ \\
&(1-(\sum_{k=0}^{N-1} \frac{1}{k+1} \cdot C_k^{N-1} \cdot P_c^{\ k} \cdot (1-P_c)^{N-1-k}\ )) \cdot (\underset{\text{Win}}{\underline{\sum_{k=0}^{N-2} \frac{1}{k+1} \cdot C_k^{N-2} \cdot P_c^{\ k} \cdot (1-P_c)^{N-2-k}}}\ ) \cdot (2 \cdot 2^x) \\
&+ \\
&(1-(\sum_{k=0}^{N-1} \frac{1}{k+1} \cdot C_k^{N-1} \cdot P_c^{\ k} \cdot (1-P_c)^{N-1-k}\ )) \cdot (1-(\sum_{k=0}^{N-2} \frac{1}{k+1} \cdot C_k^{N-2} \cdot P_c^{\ k} \cdot (1-P_c)^{N-2-k}\ )) \\
&\cdot (\underset{\text{Win}}{\underline{\sum_{k=0}^{N-3} \frac{1}{k+1} \cdot C_k^{N-3} \cdot P_c^{\ k} \cdot (1-P_c)^{N-3-k}}}\ ) \cdot (3 \cdot 2^x) \\
&+ \\
&....
\end{aligned}
\tag{16}
$$

Finally, we generalize our equation, as (17). In conclusion, the input parameters are N and x. It means the delay time is affected by the number of nodes and holdoff exponent.

$$
\begin{aligned}
&E[\text{opportunity}] \\
&= \sum_{j=2}^{N} \prod_{i=1}^{j-1} (1-(\sum_{k=0}^{N-(i-1)} \frac{1}{k+1} C_k^{N-(i-1)} P_c^{\ k} (1-P_c)^{N-(i-1)-k})).(\sum_{k=0}^{N-i} \frac{1}{k+1} C_k^{N-i} P_c^{\ k} (1-P_c)^{N-i-k})(2^x \cdot j)
\end{aligned}
\tag{17}
$$

4.2.3. The Success Probability of MSH-DSCH Transmission

Except for delay time, we hope to know what the mean value of wining probability is that a node transmits MSH-DSCH. We know Markov Chain is more suitable to get the average probability of each state. If $\pi^{(k)}$ is the probability of certain state at certain time k in our proposed Markov Chain, $\pi^{(k-1)}$ is its probability of certain state at the time before k. P is the transition probability from the state of probability $\pi^{(k-1)}$ to the state of probability $\pi^{(k)}$ (Figure 4.6). Formula (18) and (19) are applied to evaluate the wining probability that a node transmit MSH-DSCH. These two formulas imply a recursive function and converge at ξ denoted as a convergence value. $\underline{\pi} = \{\pi_1, \pi_2, \pi_3 \ldots\}$ is a vector and each element $\pi_1, \pi_2, \pi_3, \ldots$ within the vector is denoted as the probabilities of corresponding state 1, 2, 3….in Figure 4.5. $\underline{\underline{P}}$ is a two dimension matrix which the size equals to $2^x \cdot (N-1) \times 2^x \cdot (N-1)$. For example x=2, N=5, the matrix $\underline{\underline{P}}$ will be shown as equation (20).

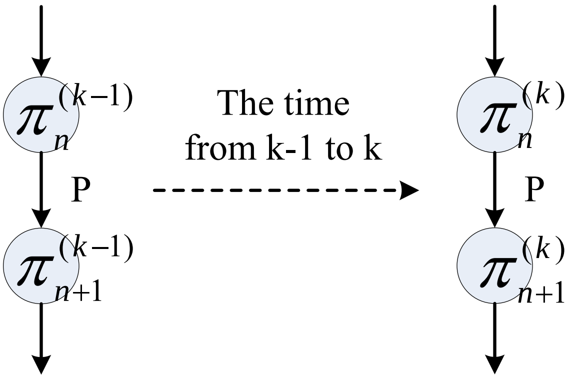
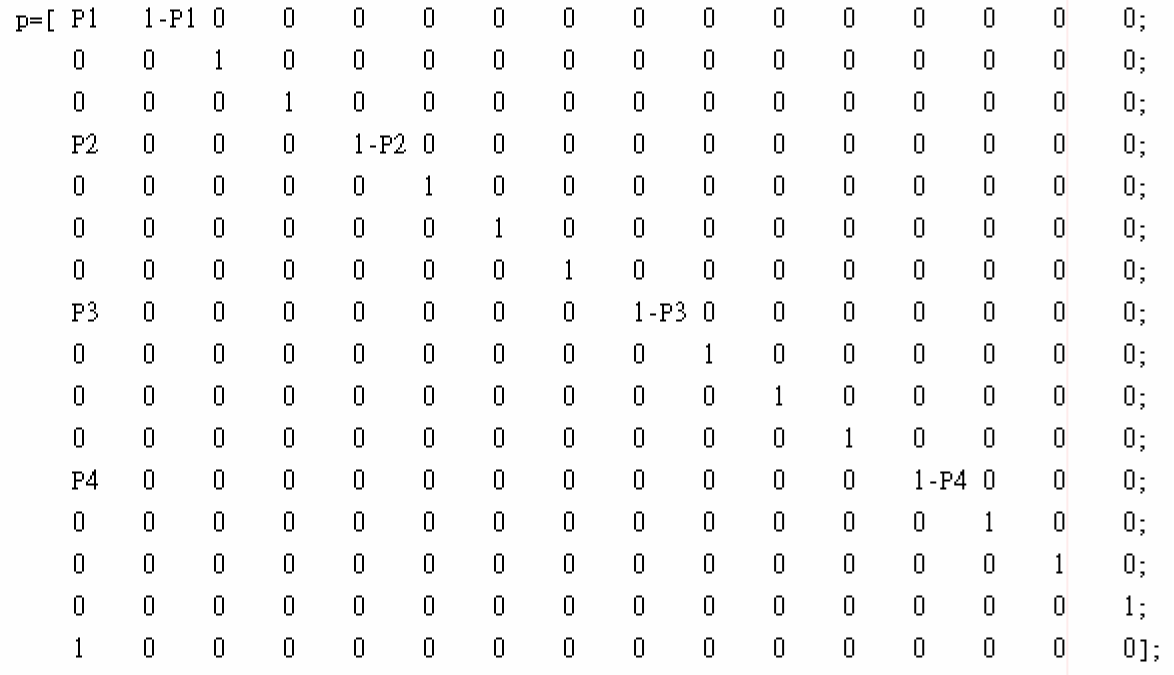


Figure 4.6: The transition probability of certain state

$$\underline{\pi}^{(k)} = \underline{\pi}^{(k-1)} \underline{\underline{P}} \tag{18}$$

$$\left|\underline{\pi}^{(k)} - \underline{\pi}^{(k-1)}\right| < \xi \tag{19}$$



```
p=[ P1   1-P1 0    0    0    0    0    0    0    0    0    0    0    0    0    0;
    0    0    1    0    0    0    0    0    0    0    0    0    0    0    0    0;
    0    0    0    1    0    0    0    0    0    0    0    0    0    0    0    0;
    P2   0    0    0    1-P2 0    0    0    0    0    0    0    0    0    0    0;
    0    0    0    0    0    1    0    0    0    0    0    0    0    0    0    0;
    0    0    0    0    0    0    1    0    0    0    0    0    0    0    0    0;
    0    0    0    0    0    0    0    1    0    0    0    0    0    0    0    0;
    P3   0    0    0    0    0    0    0    1-P3 0    0    0    0    0    0    0;
    0    0    0    0    0    0    0    0    0    1    0    0    0    0    0    0;
    0    0    0    0    0    0    0    0    0    0    1    0    0    0    0    0;
    0    0    0    0    0    0    0    0    0    0    0    1    0    0    0    0;
    P4   0    0    0    0    0    0    0    0    0    0    0    1-P4 0    0    0;
    0    0    0    0    0    0    0    0    0    0    0    0    0    1    0    0;
    0    0    0    0    0    0    0    0    0    0    0    0    0    0    1    0;
    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    1;
    1    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0];
```

(20)

In order to simplify the expressions, P1 and 1-P1 within the matrix $\underline{\underline{P}}$ stand for the formula (5) and (6). With this same rule, we simplify other expressions as P2, 1-P2, P3, 1-P3… Then P(success) can be calculated by (21).

$$\text{P(success)} = \sum \text{Prob}_{\text{Win}} \cdot \pi_{\text{win}} \tag{21}$$

CHAPTER 5

Simulation Results

In this chapter, we validate our model. The transmission behavior simulation base on the Figure 3.7and Figure 3.8 was implemented by the C code. The mathematic evaluation base on our proposed schemes throughout the CHAPTER 4 was computed by the MATLAB 7.0. There are two major items that we will evaluate, which are the delay time and the success probability of MSH-DSCH transmission.

5.1. Delay Time

The formula (17) is our proposed scheme to evaluate the delay time of one certain node transmitting its scheduling information MSH-DSCH. The MATLAB 7.0 is applied to calculate this complex operation in our numeric validations. Following parameters are applied:

Exponent = 2

Node ID: random number between 1~4095

Probability: Pc= 0.5

And the result is shown as Figure 5.1. The “sim” denotes a curve by simulation; “math” denotes a curve by mathematics. With this figure, it shows our mathematical model approaches the simulation result. By the way, the error rate is analyzed by the statistic method, as Figure 5.2, presents the difference in distance between the method by behavior simulation and by our proposed mathematic formula. The error is under 10% while the nodes of number between 2 to 20. Except for the exponent x=2, we are also interested in x=3 and x=4. These simulation results are shown from Figure 5.3 to Figure 5.6. The errors are under 10% throughout the above simulations. The stable accuracy is performed all over these simulation results; even the different exponents are applied.

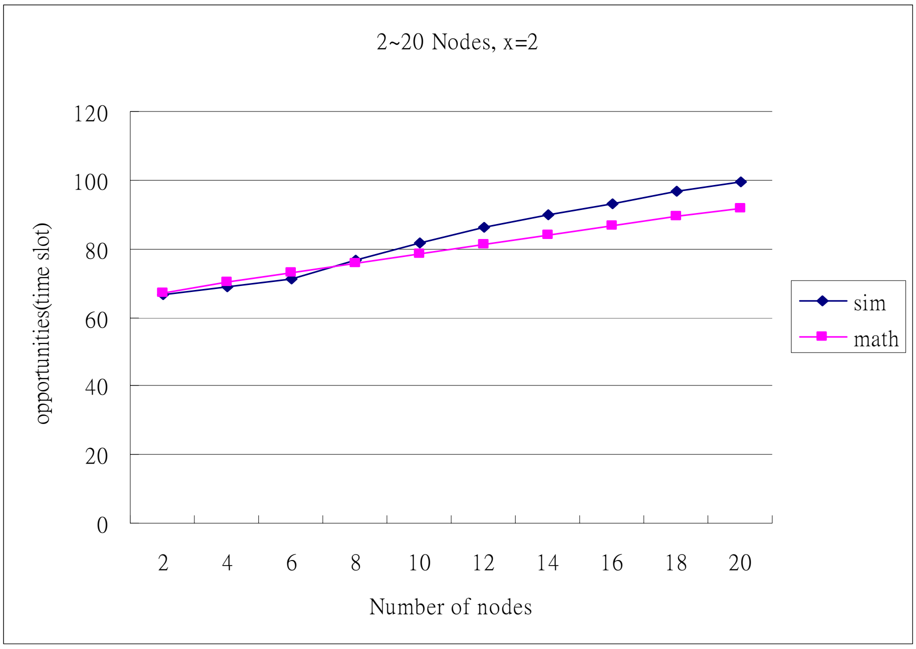


Figure 5.1: The delay time of opportunities between simulation and mathematic model-1

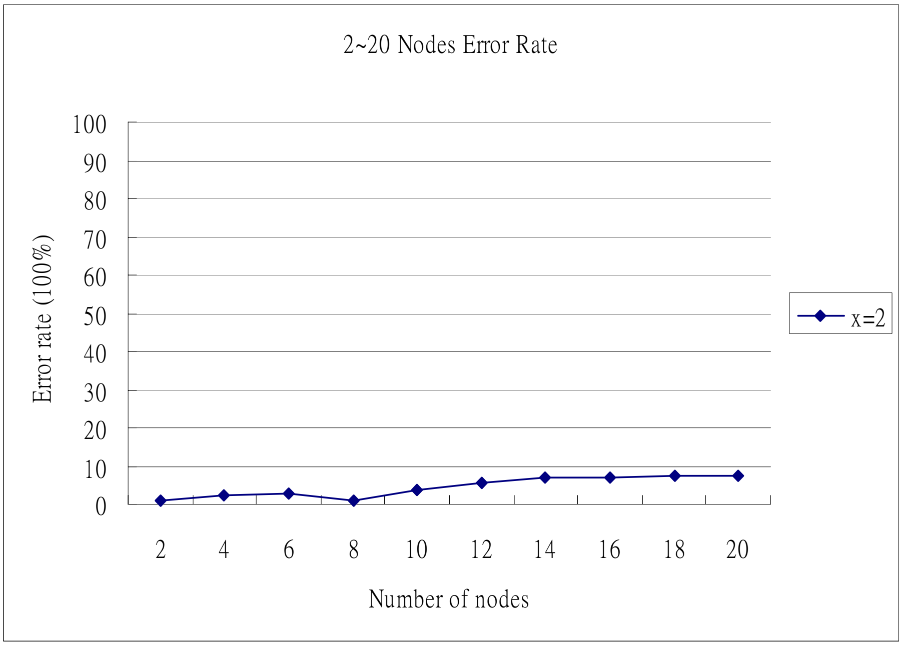


Figure 5.2: The error rate between simulation and mathematic model-1

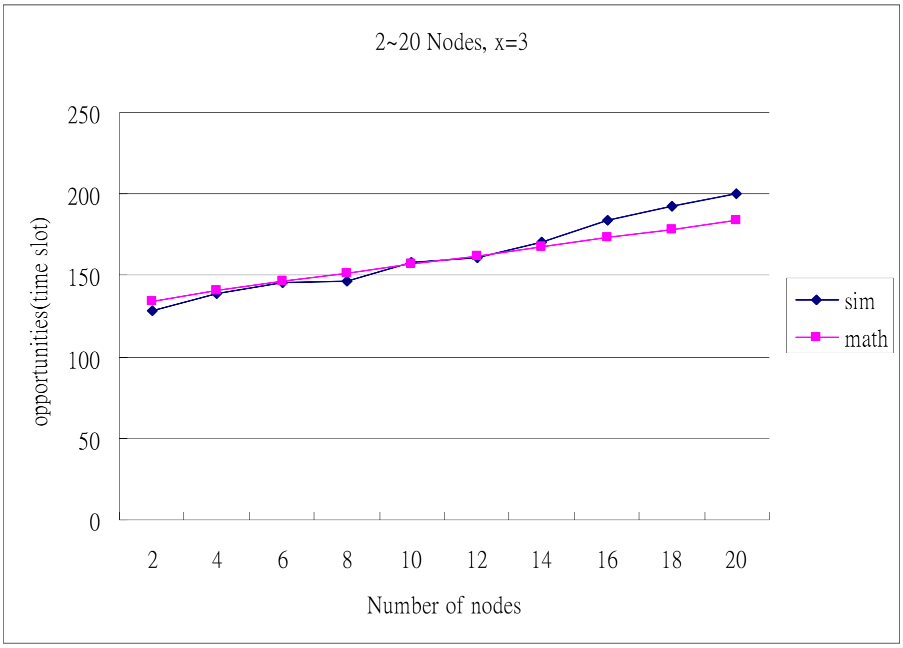


Figure 5.3: The delay time of opportunities between simulation and mathematic model-2

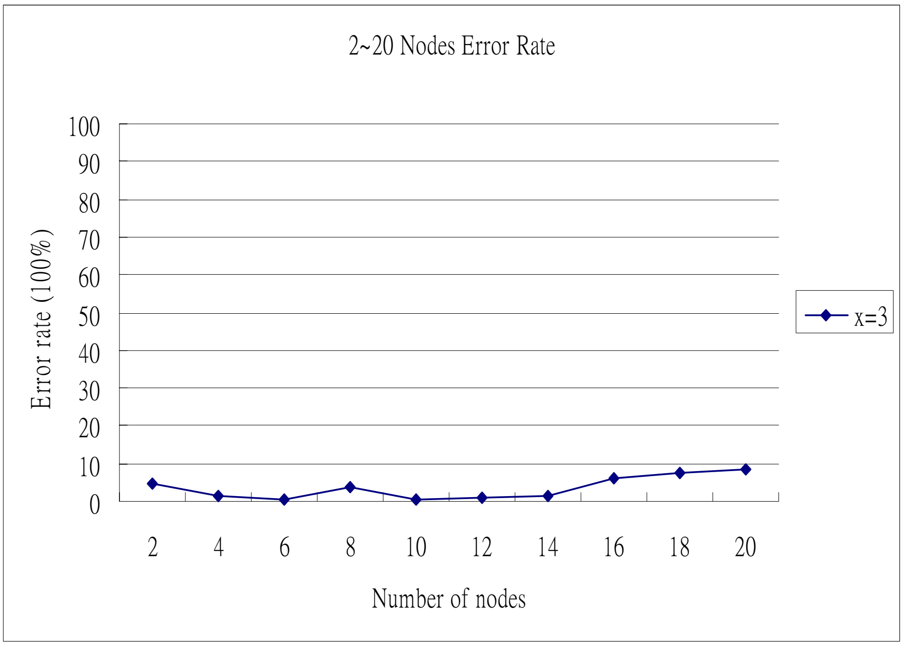


Figure 5.4: The delay time of opportunities between simulation and mathematic model-2

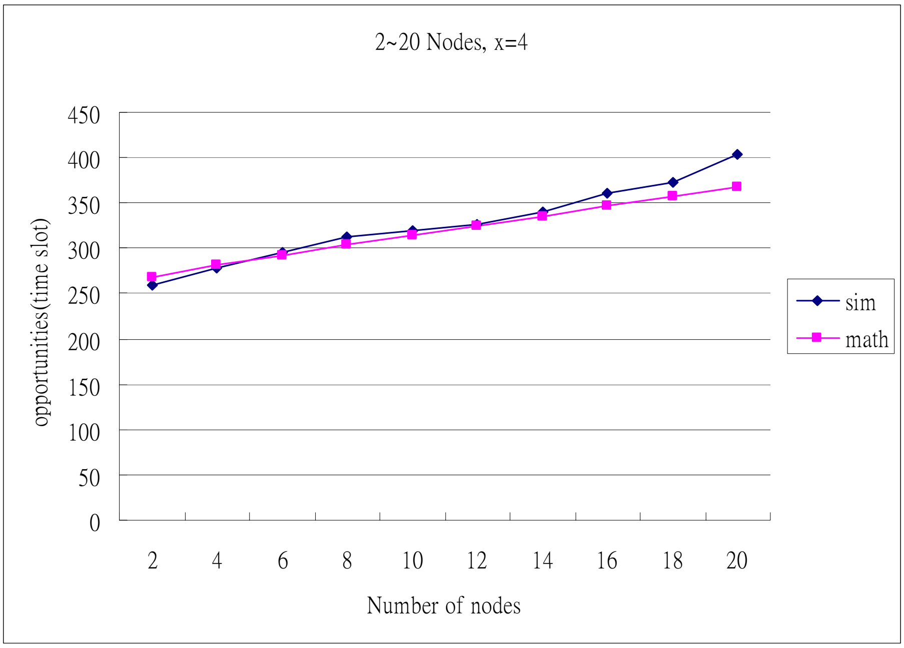


Figure 5.5: The delay time of opportunities between simulation and mathematic model-3

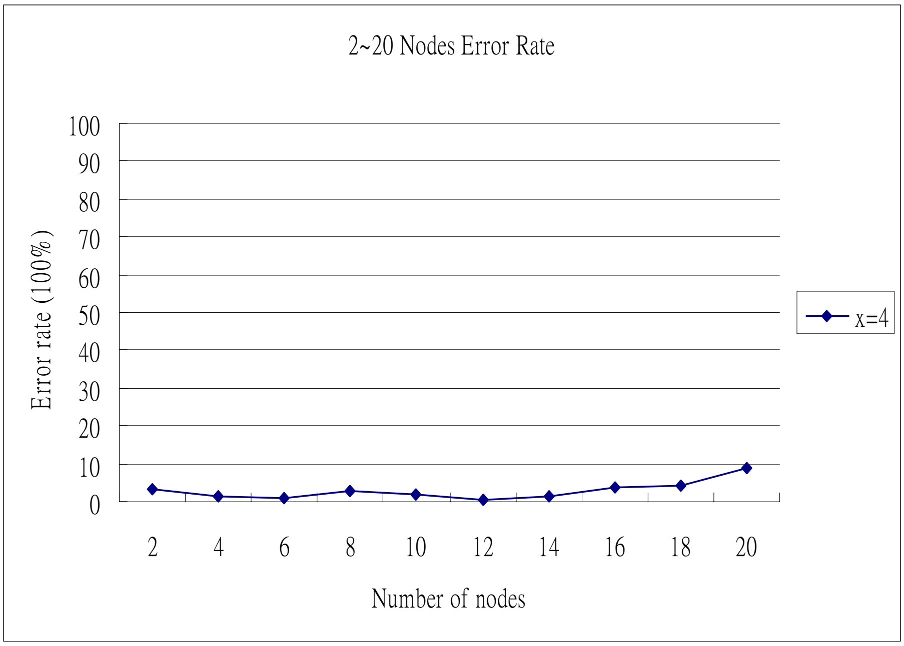


Figure 5.6: The delay time of opportunities between simulation and mathematic model-3

Besides, as shown in the Table 5.1 and Figure 5.7, there is an error rate comparison between the [9] and proposed evaluation. In order to compare with original analysis, Table 5.1 follows the original table format in the [9], that's why the exponent x is list here without regular order.

Table 5.1: Comparison between original and proposed evaluation

Numbers of Nodes	X	Original (100%)	Proposed (100%)
2	2	2.47	0.75
3	3	3.12	1.97
4	3	2.81	1.39
5	1	0.85	0.36
6	0	0.36	0.38
7	2	2.28	2.2
8	2	3.85	0.9
9	1	0.86	0.65
10	0	0.42	0.1

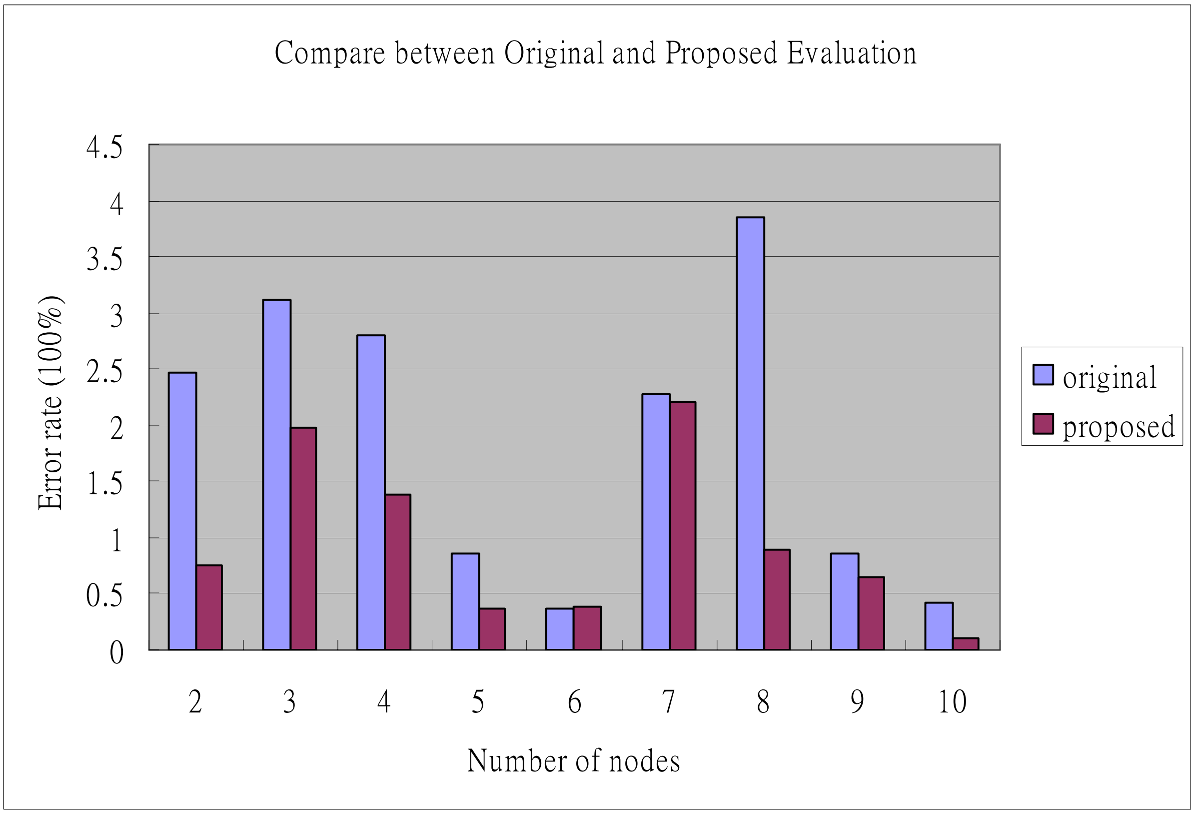


Figure 5.7: Comparison between original and proposed evaluation

The Figure 5.7 shows that the values predicted by our model have a smaller degree of error than the values generated by [9]'s model do.

5.2. The Success Probability of MSH-DSCH Transmission

The formula (18) is a recursive function, so the initial value should be assumed for the recursive calculation. The initial value of $\underline{\pi}$ is assumed as follows,

$$\underline{\pi}^{(0)} = (1, 0, 0, 0, \ldots)$$

If we are interested in the exponent x=2, the probability of success is evaluated as Figure

5.8. The inverse ratio depicted in this figure shows that as the number of nodes increases, the probability of success decreases.

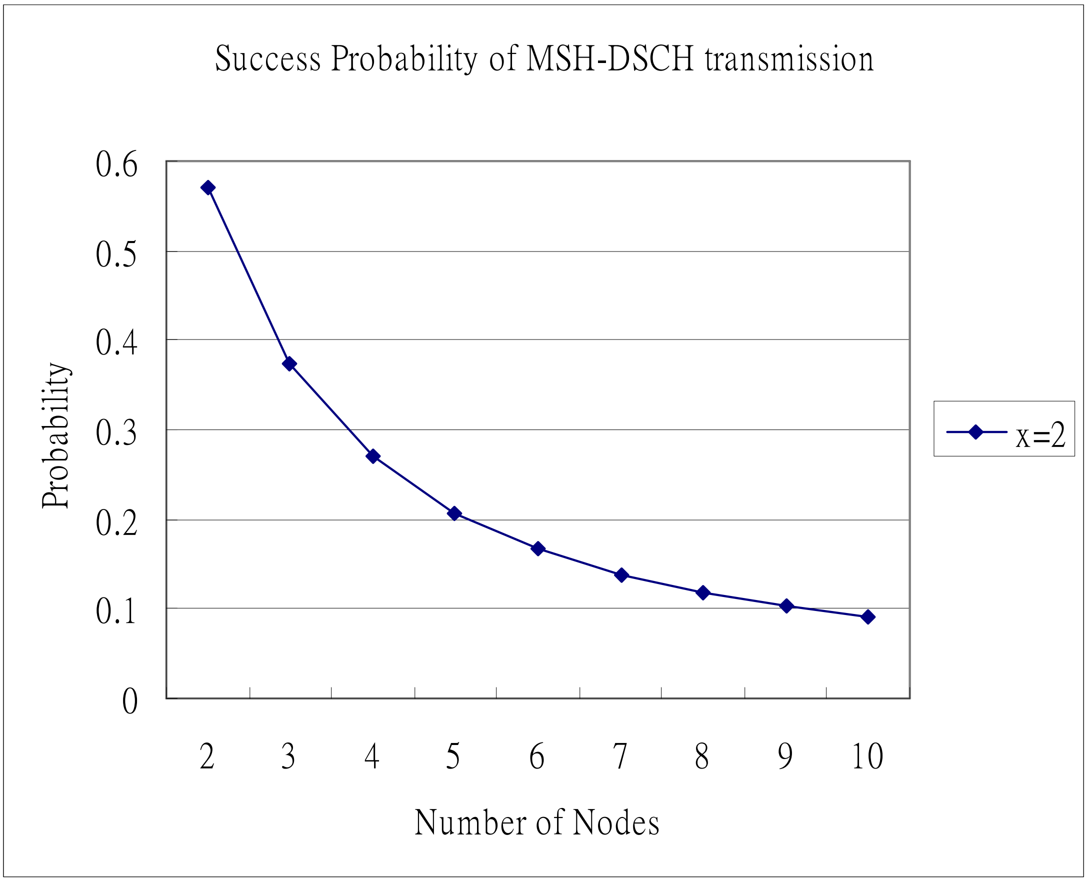


Figure 5.8: The mean of success probability that a node transmit MSH-DSCH

The Figure 5.9 shows the probabilities of success which three different exponents are compared. This figure shows that as the number of exponent increases, the probability decreases. So there is a concept that the small exponent can speed-up the MSH-DSCH transmission. This is useful in the future as a mechanism of QoS or call admission control. For example, a node which has the small exponent may have the more probabilities to transmit its scheduling information MSH-DSCH. The time for transmitting the MSH-DSCH may image as a call setup time at beginning of a link connection. Thus the higher probability for transmitting scheduling information MSH-DSCH implies the higher chance or priority it will be to initialize a connection.

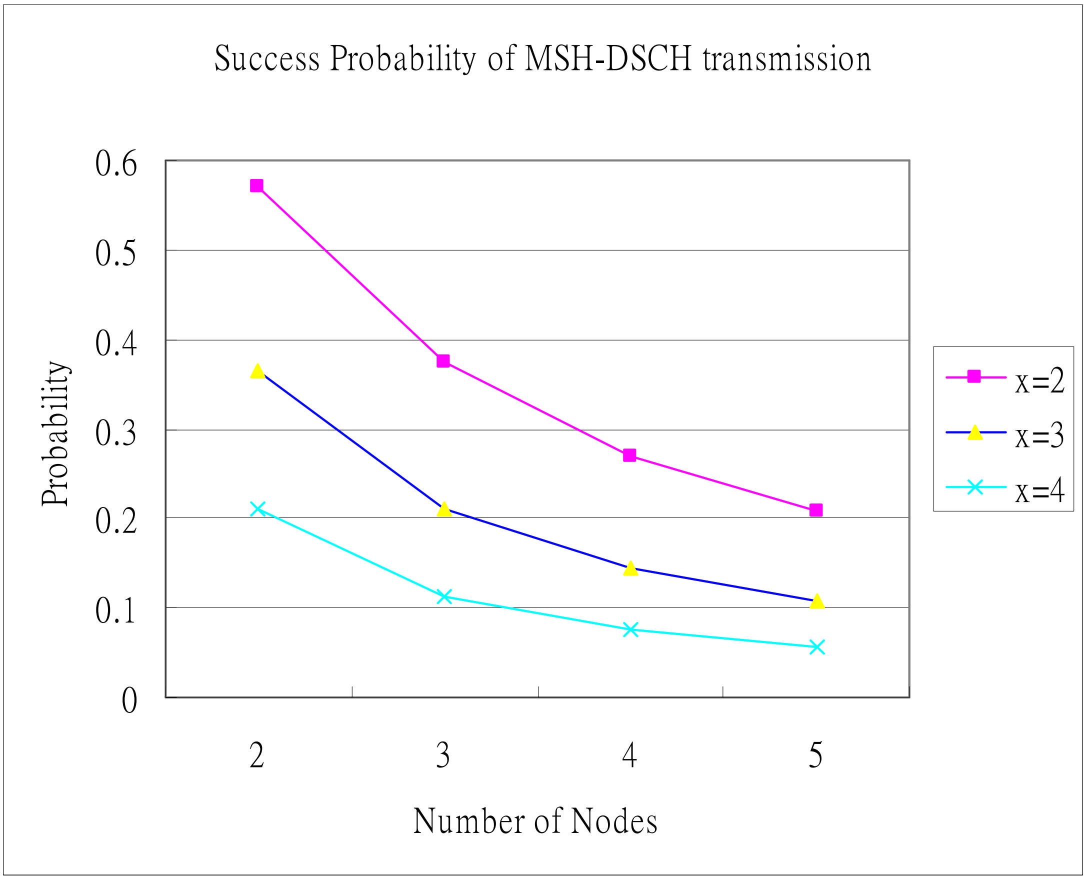


Figure 5.9: The mean of success probability when x is non-identical

CHAPTER 6

Conclusions and Future Works

In this thesis, we have proposed a Markov Chain model which can be used to simulate MSH-DSCH transmission behavior in 802.16 mesh mode. This model considers the competing probability and back behavior of transmitting MSH-DSCH. It also helps us to realize the competing behavior more clearly. In the future, there will be more possibilities to design the WiMax mesh mode based on this model.

Based on this model, we derived a formula to evaluate an average delay time of MSH-DSCH transmission. Furthermore, this delay time may impact the starting time of a link connection. Thus the higher probability for transmitting scheduling information MSH-DSCH implies the higher chance or priority it will be to initialize a connection. More important, the processing time of the following three-way handshaking is also influenced by MSH-DSCH transmission delay. By this model, we separate out the factors that affect the delay time. These factors are possibly useful for future researches.

Our scheme also evaluates the success probability of MSH-DSCH transmission. That is useful for QoS negotiation and adaptation. A conclusion is obtained that the success probability is inversely proportionate to the number of nodes. We may get a threshold to guarantee the connection is more stable by applying this probability in the future.

Finally, we have a simulation. It appears that results calculated from our mathematic model closely resemble the results from simulation. In other words, the theoretical model fits the experimental data well.

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