Dynamic RWA Scheme using Fuzzy Logic Control（FLC RWA）on IP with GMPLS over DWDM Networks

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Abstract

The tremendous capacity of WDM networks with IP should be optimized to carry traffic for Internet applications. Moreover, a new technique called Generalized MPLS （GMPLS） is developed for combining all network technologies including ATM, SONET/SDH, TDM, and DWDM. The standard of GMPLS is established by IETF. In the framework of GMPLS, a virtual path must be set up before packets are delivered. The routing and wavelength assignment （RWA） algorithm efficiently manages optical network resources and the RWA problem is separated from the optical topology. This paper proposes a dynamic FLC RWA scheme using fuzzy logic control on IP with GMPLS over DWDM networks to achieve the best quality of network transmission. The proposed algorithm dynamically allocates network resources and reserves partial bandwidth based on the current network status, which

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includes the request bandwidth, average utilization for each wavelength and its coefficient of variance（C.V.）of data traffic, to determine whether the connection can be set up. Five fuzzy sets for request bandwidth, average rate and C.V. of data traffic are used to divide the variable space: very large（LP）, large（SP）, normal（ZE）, small（SN）, and very small（LN）. Setting the fuzzy limit is a key part in the proposed algorithm. The simulation of scenarios in this paper has two steps. In the first step, the appropriate Fuzzy Limits are evaluated based on simulation results pertaining to six network statuses. The second step is to compare the FLC RWA algorithm with periodic measurement of traffic（PMT）in ATM networks in six network situations to show that the proposed FLC RWA algorithm can provide better network transmission.

Key Words: IP/DWDM、GMPLS、FLC RWA algorithm、Fuzzy Theory

GMPLS 於 DWDM 光纖網路架構下 模糊邏輯控制 RWA（FLC RWA）演算法

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摘　要

GMPLS 是由 IETF 所制定的標準，在 GMPLS 的網路架構下，封包的傳送必須先建立起一條虛擬的路徑，利用 CR-LDP 或 RSVP-TE…等演算法，以達到 QoS 的功能。在許多的演算法中，使用保留部分的網路資源（Resource Reservation）以達到 Traffic Engineering 的機制，在網路使用效率較高的情況下，這樣的演算法的確是較佳的選擇，但是，我們無法保證網路中的每一連結都能達到較高的使用效率，一旦連結的空閒（idle）時間過長或是使用效率過低，網路資源將會過分的被浪費。而有些演算法則是根據對路徑條件的需求、網路的狀態及相關的資訊來判斷資料可傳輸與否。這樣的演算法對於路徑條件的描述更具彈性，並允許不同的 LSP（Label Switching Path）分享或是競爭網路中所擁有的資源，以減少資源的浪費，進而使用相對權重的觀念，建立起不同 LSP 間的相對優先權，以避免所建立的連結超過網路所能承受的負擔造成封包碰撞的情況。目前部分這類的演算法使用網路的平均流量來判斷是否可以加入新的連結，這的確是一個較簡單的方式，但是我們也無法保證網路資料的傳遞會依

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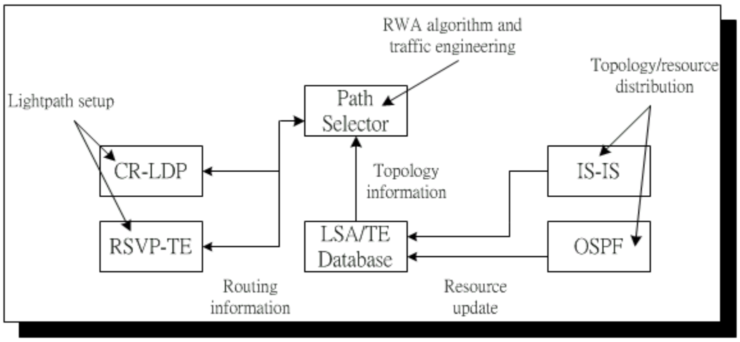
循著平均流量做很平順的傳送，如此的判斷將會顯得很不精確，甚至會出現大量資料遺失的情況。在本篇研究當中，對於連結的建立將避免使用資源保留的方式，對於波長是否由足夠的資源作爲新的連結傳送的路徑，我們既無法預測封包傳送的狀況，也無法使用確切的數值來表示傳送的情形，若是將網路的狀態予以模糊化，一方面將可以適時的保留部分頻寬，避免突然間有大量的封包傳送；一方面又增加了波長的使用效率，以避免網路資源的浪費。在演算法的設計中，將以 Request bandwidth、Average rate 及 C.V.（Coefficient of Variance）作爲模糊理論判斷之參數，另外，訂定 Fuzzy Limit 參數，利用此參數來判斷連結是否可以被建立，而 Fuzzy Limit 值如何訂定，將是本論文中評估的重點之一。此外，演算法所建立的路徑，盡量減少封包傳送時經過波長轉換器的次數，以避免封包延遲或丟棄，並增加封包傳送的效率。在論文中，將針對波長的使用效率、路徑的長度、波長轉換器使用的個數及點對點傳送所花費的網路資源，來評估所研究的演算法執行效能。在模擬的結果中，我們可以發現使用 FLC RWA 確實更能掌握網路的狀態以判斷建立連結的與否，並將可以避免浪費網路的資源以達到較好的傳輸品質。

關鍵詞：網際網路協定/高密度波長分割多工、通用多協定標籤交換、FLC RWA 演算法、模糊理論

I、Introduction

Dense wavelength-division multiplexing（DWDM）networks have been deployed in modern communication networks to meet the rapidly increasing demands of Internet applications. DWDM has become a network-level technology as the optical components, such as *optical add/drop multiplexers*（OADMs）and *optical cross-connects*（OXCs）,have matured. Accordingly, the efficient internetworking of higher-layer protocols, most notably simple IP over DWDM networks, has become increasingly important. Several research institutes are studying related issues, one of them is the *generalized multi-protocol label switching*（GMPLS）framework defined by IETF（Kompella et al., 2001a; Kompella et al., 2001b; Kompella et al., 2002; Bellato et al., 2001）. Information is delivered in the form of optical packets, which are routed based on the information in the optical label using GMPLS-related techniques. In GMPLS, packet routing does not need complicated algorithms to interpret the information in the IP header, so the handling time of optical packets is greatly reduced. Figure 1 shows the lightpath routing of GMPLS. *Open Shortest Path First*（OSPF） and *Intermediate System to Intermediate System*（IS-IS） allow nodes to exchange information about network topology and resource distribution. The *routing and wavelength assignment* （RWA）algorithm in *Path Selector* is used to select a lightpath based on specified resources and/or policy. The optical path computation algorithm uses the topology and resource information stored and maintained in the *Link State Advertisement/Traffic Engineering* （LSA/TE）database. Then, packet transmission builds a virtual path using *Constraint-Based Routing Label Distribution Protocol* （CR-LDP）and/or *Resource Reservation Protocol with TE*（RSVP-TE） to achieve the required QoS.

Figure 1. Flow chart of lightpath routing in GMPLS



Routing and wavelength assignment （RWA） involves efficiently managing optical network resources and the RWA problem is separated from the optical topology（Zhang et al., 2001; Assi et al., 2001）. Solving the RWA problem generally has two steps - route selection and wavelength assignment. Three basic approaches to solve the route selection problem for different types of connection requests（static, incremental, and dynamic）are presented in the literature - fixed routing, fixed-alternate routing and adaptive routing. Several heuristics for solving the wavelength assignment problem have been studied - Random Wavelength Assignment, First-Fit, Least-Used, Most-Used, Min-Product, MAX-SUM, Least-Loaded, Relative Capacity Loss, Distributed Relative Capacity Loss, and others.

In all optical networks without wavelength conversion, the *wavelength continuity* constraint applies and a lightpath must be established using a common wavelength on all links along the route. This approach is not scalable as the number of wavelengths becomes too large and the probability of wavelength blocking increases due to volume and dynamical connection requests on the Internet. The RWA algorithm normally divides the WDM network architecture into various layers based on wavelength to establish independent routing to solve the wavelength continuum problem. If some section of the wavelength on a layer cannot build the connection, then it is removed and the shortest path from the remaining wavelengths is calculated. This method can effectively solve the wavelength continuum problem, but when the lightpath is set, the probability of wavelength blocking often increases. The wavelength continuity constraint can be relaxed using wavelength converters, such as OXCs in DWDM networks, and the connections can be established without finding out unoccupied wavelength, especially for dynamic traffic. The objective is to optimize the system performance, such as the blocking probability, number of wavelength conversions and delays. As expectedly, RWA problems are usually highly computational （as summarized in （Zhang et al., 2001; Assi et al., 2001）） and have been shown to be NP-hard （Jaffe, 1984; Wang & Crowcroft, 1996）.

This paper proposes a dynamic RWA （FLC RWA） scheme using fuzzy logic control on IP with GMPLS over DWDM networks to achieve the best quality of network transmission （Yu, 2002）. The proposed algorithm dynamically allocates the network resources and reserves partial bandwidth based on the current network status, which includes the request bandwidth, average utilization for each wavelength and the coefficient of variance（C.V.）of data traffic. If the average utilization for each wavelength is too high, then establishing new connections will fail due to collisions; otherwise, new connections can be built smoothly to increase the wavelength utilization. C.V. represents the bursty events of packets, which cannot be guaranteed to be transmitted as fast as expected. The bandwidth reserved by the system must be controlled to prevent data from packets loss. If a threshold value is used to reserve bandwidth, then guaranteeing that system resources will not be wasted is difficult. Five fuzzy sets for request bandwidth, average rate and C.V. of data traffic are used to divide the variable space, which are very large （LP）, large （SP）, normal（ZE）, small （SN）, and very small （LN）. Setting the fuzzy limit is crucial to the proposed algorithm. The simulation of scenarios in this paper includes two steps. In the first step, the appropriate Fuzzy Limits are evaluated based on simulation results for the six network statuses. The second step is to compare the system performance of the FLC RWA algorithm with the PMT （Zhao et al., 2001） used in ATM networks for six different network situations to show that the proposed FLC RWA algorithm can support better network transmission.

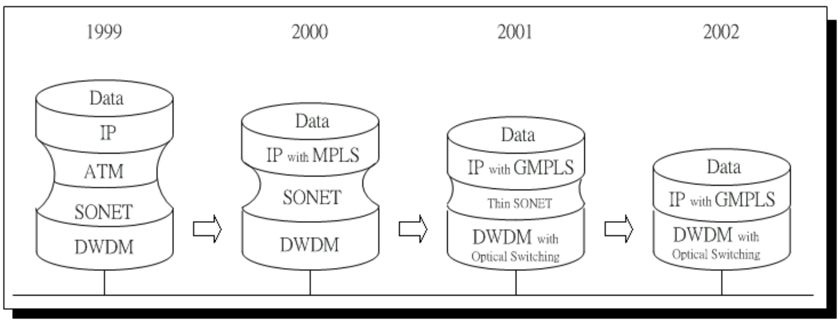
The rest of this paper is organized as follows. Section II introduces IP with GMPLS over DWDM. Section III describes network architectures and the proposed FLC RWA algorithm. Section IV describes the simulation environment and compares the system performance with that of PMT in six different network situations. Section V summarizes the conclusions.

II、Related Research

1、IP over WDM

The WDM network architecture with advanced components, such as an optical multiplexer and de-multiplexer, combines several wavelengths into a single optical fiber. Hence, the capacity and transmission speed are greatly increased, solving the bottleneck of the traditional transmission bandwidth. Furthermore, WDM also overcomes the problem of capacity deficiency and makes feasible the real-time multimedia application over the Internet. Since the Internet Protocol （IP） is the heart of so much revenue-generating activity in the world today and will become more and more entrenched in the future, that the tremendous capacity of WDM networks with IP will be optimized to carry traffic on the Internet seems inevitable （Melo et al., 2000）. Today’s data networks have four layers - IP for carrying applications and services, ATM for traffic engineering, SONET/SDH for transportation, and DWDM for physical communication. Multi-layer architectures normally suffer from the lowest common denominator effect: any layer can limit the scalability of the entire network and increase the cost of the network. Therefore, to save IP packet-processing time, the multiplayer architectures shown in Fig. 2 should be simplified to increase the transmission speed. Some peripheral devices, such as Optical Crossconnects （OXCs）, have developed rapidly to support vast amount of information in the DWDM network. OXCs can avoid O/E and E/O transfer and increase packet-processing speed from Gigabits to Terabits. Additionally, OXCs combine the features of MPLS Traffic Engineering （Viswanathan et al., 1998; Awduche & Rekhter, 2001） to enhance the capability of routing selection and routing management.

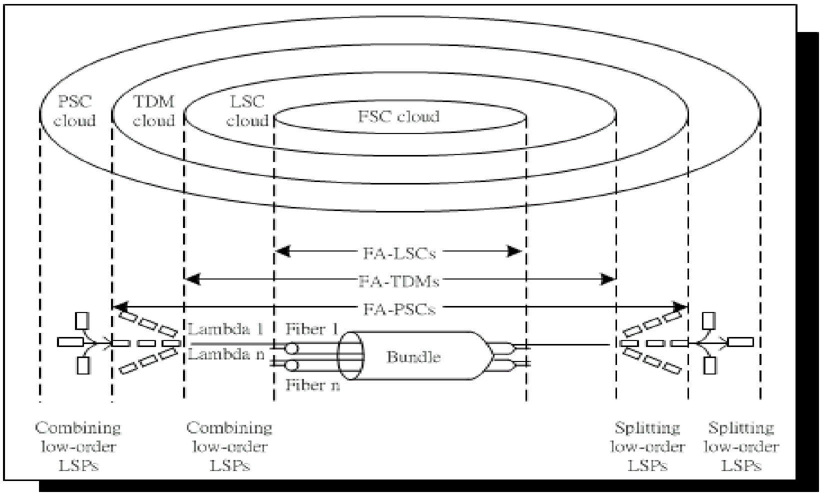
Figure 2. Evolution of photonic network architectures



2、IP with GMPLS over DWDM

MPLS technology solves traditional IP network problems to enable IP packets to be transmitted more rapidly in the network and support the QoS in the MPLS-TE. However, the MPLS technique is not available below the IP layer in the current network architecture. A new technique called Generalized MPLS （GMPLS）（Ashwood-Smith et al., 2002） is created to combine all network technologies including ATM, SONET/SDH, TDM, and DWDM. GMPLS efforts are applied to extending IP/MPLS technologies and protocols to control and manage lower non-packet based networks. The label information processed in the GMPLS includes not only that in packets or heads, but also VPI/VCI path information related to ATM network. Similarly, the label stands for wavelength information in the WDM network to form the Label Switching Path （LSP） hierarchy architecture, as shown in Fig. 3.

Figure 3. LSP （Label Switching Path） Hierarchy



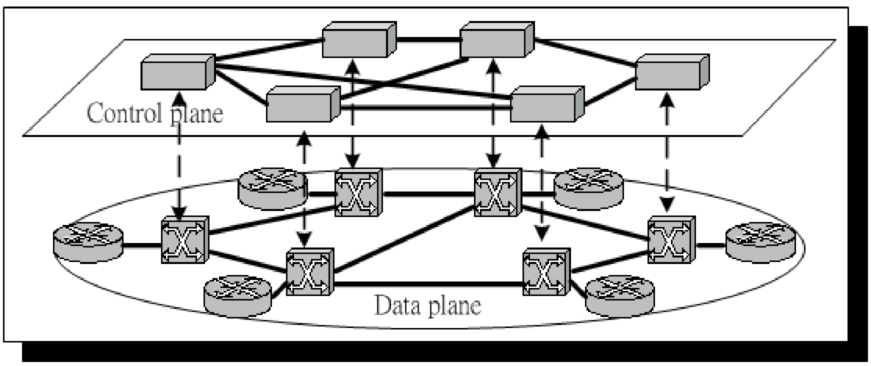
LSP is transmitted from the traditional IP network to the TDM network, and then through the physical layer of the photonic network. A natural hierarchy exists and dictates the order in which LSPs are nested. This hierarchy is based on the multiplexing capability of the LSP types that always start and terminate on similar equipment （For example, a lambda LSP originates and terminates on a device that supports lambdas.）The IP over WDM network architecture simplifies the traditional network architecture. It also increases the transmission speed and saves network resources. Therefore, GMPLS will directly apply to the architecture of IP over WDM. Besides, GMPLS expands current MPλS features （Klinkowski & Marciniak, 2001） to transmit IP packets more rapidly on the photonic network. In the application of MPλS, GMPLS offers Point-to-Point and Circuit-Switching （ lightpath ） connections （Murata & Kitayama, 2001）, such that the lightpath forms logical topology. Besides, the label swapping in the MPλS can be regarded as the wavelength converter in the WDM. The complexity of the computations is such that the logical topology design relies on a central controller entity to collect the long-term traffic statistics of the network and perform the relevant optimization to determine wavelength assignments.

III、Network Architectures and Algorithm Design

GMPLS includes four types of network architectures （Dixit & Ye, 2001; Banerjee et al., 2001） – the client-server model, the big fat router model, the peer-to-peer model, and the augmented model. Different network architectures handle addressing, signaling and routing in different ways. The peer-to-peer model is used in this paper.

1、Network Architecture

Figure 4. Peer-to-Peer Model



In the peer-to-peer model, each node contains information about the entire network, including network topology, the state of link, for example, to calculate the path more efficiently. The whole network architecture is divided into the control plane and the data plane to control and transmit signals, respectively. Another independent wavelength is used as a control channel to transmit network information and establish related resources more conveniently. As shown in Fig. 4, every node of the data plane corresponds to every node of the control plane in the peer-to-peer model, and OXC represented by every node contains its own status and that of the whole network. Once the network architecture changes or the resource status changes, algorithms such as OSFP or IS-IS can be used to update the network status very quickly. In a GMPLS network environment, a lightpath for transmitting the packet must be built quickly to transmit the optical packet.

2、Fuzzy Logic Control RWA（FLC RWA）Algorithm

The proposed algorithm dynamically allocates network resources and reserves partial bandwidth, based on the current network utilization status, to handle the large amount of bursty packets during transmission, resulting in data loss. In particularly, network resource reservation does not follow a certain model; an excess of reservation will waste network resources, and a lack of reservation will cause more severe data loss. Therefore, in this paper, the proposed fuzzy logic control RWA（FLC RWA） is dynamically adjusted in response to the network status to achieve the best quality of network transmission. In the early algorithms （Zhao et al., 2001; Fontaine & Smith, 1996; Shiomoto et al., 1998）, the average utilization of network transmission is adopted only to determine whether the network can be added to a new connection. This approach represents the easiest way to make such a decision, but sometimes fails to establish the connection precisely because the data flow fluctuates rapidly in a real network. The proposed algorithm considers the request bandwidth, average utilization for each wavelength and the coefficient of variance（C.V.） of data flow to determine new connections. If the average utilization is too high, then new connections cannot be established because of collisions; otherwise, new connections can be built smoothly to increase the wavelength utilization. C.V. represents the bursty events of packets because packets cannot be guaranteed to be transmitted as quickly as expected. The bandwidth reserved by the system must be under control to avoid collisions due to the bursty packets. If a threshold value is applied to reserve the bandwidth, then guarantee that the system resources will not be wasted is difficult.

Figure 5. Variable space is divided into five fuzzy sets.

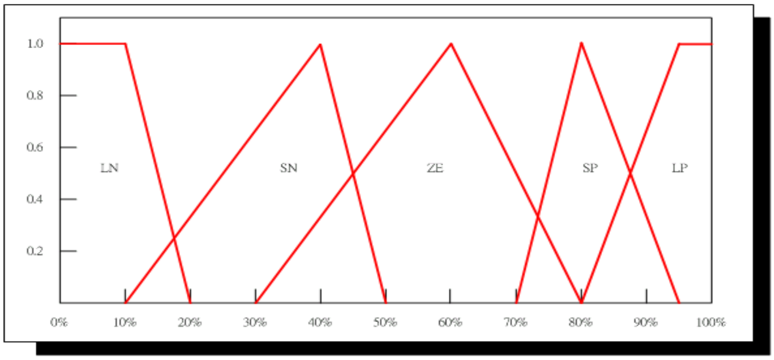
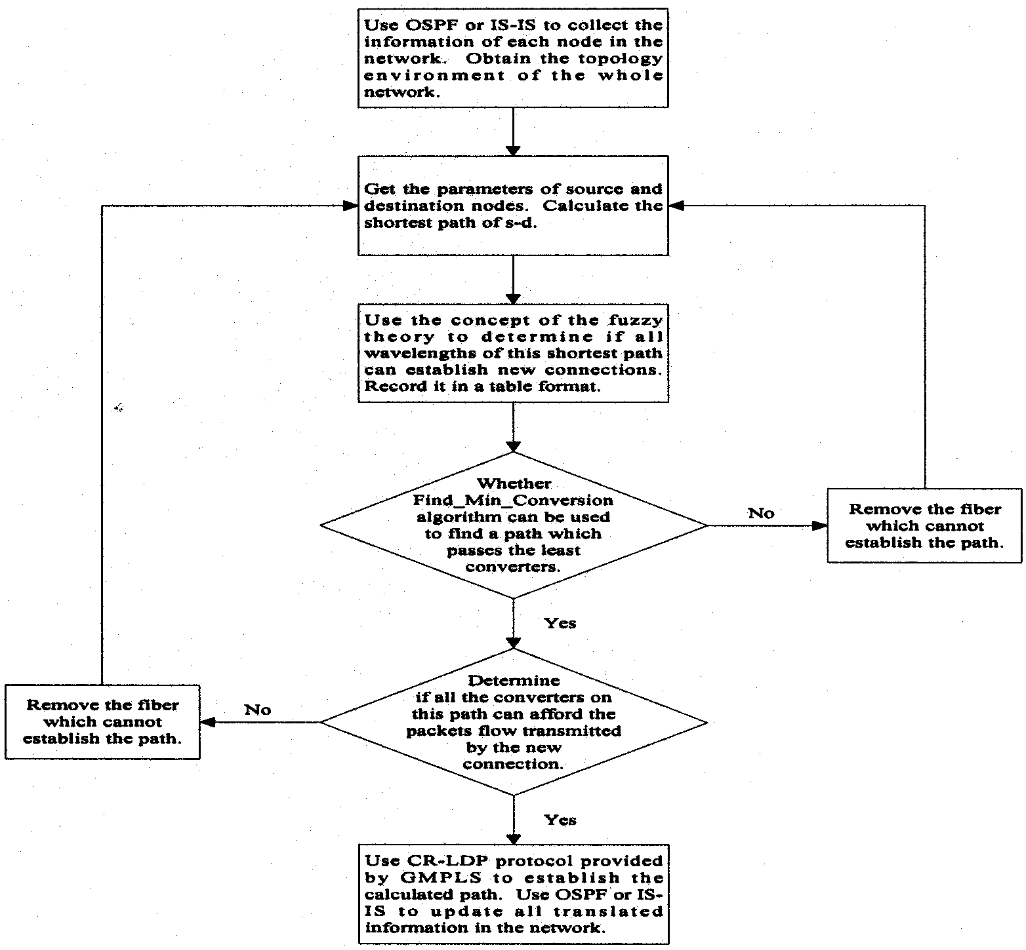


Figure 6. Flow chart of FLC RWA algorithm



Therefore, the fuzzy control is used here to dynamically reserve system resources to increase the utilization of network resources and solve the problem of suddenly increased data flow. Five fuzzy sets are used here, for request bandwidth, average utilization for each wavelength and its C.V., to divide the variable space（as shown in Figure 5）: very large （LP）, large （SP）, normal （ZE）, small （SN）, and very small （LN）（Yu, 2002）. Setting the fuzzy limit is also crucial to another key point in the proposed algorithm（Yu, 2002）. The membership functions of each variable space are as follows:

$$F_{LN}(x)=\begin{cases}1 & x\% \le 10\% \\ (-x)/10+2 & 10\% \le x\% < 20\%\end{cases}$$

$$F_{SN}(x)=\begin{cases}x/30-1/3 & 10\% < x\% \le 40\% \\ (-x)/10+5 & 40\% \le x\% < 50\%\end{cases}$$

$$F_{ZE}(x)=\begin{cases}x/30-1 & 30\% < x\% \le 60\% \\ (-x)/20+4 & 60\% \le x\% < 80\%\end{cases}$$

$$F_{SP}(x)=\begin{cases}x/10-7 & 70\% < x\% \le 80\% \\ (-x)/15+19/3 & 80\% \le x\% < 95\%\end{cases}$$

$$F_{LP}(x)=\begin{cases}x/15-16/3 & 80\% < x\% \le 95\% \\ 1 & 95\% \le x\%\end{cases}$$

Table 1 lists the fuzzy rules. If the value after defuzzificating is greater than the fuzzy limit, then this connection can be built. （1 implies that the connection is allowed; 0 represents that the connection is not allowed）.

Table 1. Fuzzy Rules

	Request Bandwidth		Average Utilization		C.V.		Result
If	LP	and	*	and	*	then	0
If	SP	and	LP	and	*	then	0
If	SP	and	SP	and	*	then	0
If	SP	and	ZE	and	*	then	0
If	SP	and	SN	and	LP	then	0
If	SP	and	SN	and	SP	then	0
If	SP	and	SN	and	ZE	then	0
If	SP	and	SN	and	SN	then	0
If	SP	and	SN	and	LN	then	1
If	SP	and	LN	and	*	then	1

	Request Bandwidth		Average Utilization		C.V.		Result
If	ZE	and	LP	and	*	then	0
If	ZE	and	SP	and	*	then	0
If	ZE	and	ZE	and	LP	then	0
If	ZE	and	ZE	and	SP	then	0
If	ZE	and	ZE	and	ZE	then	0
If	ZE	and	ZE	and	SN	then	0
If	ZE	and	ZE	and	LN	then	1
If	ZE	and	SN	and	LP	then	0
If	ZE	and	SN	and	SP	then	1
If	ZE	and	SN	and	ZE	then	1
If	ZE	and	SN	and	SN	then	1
If	ZE	and	SN	and	LN	then	1
If	ZE	and	LN	and	*	then	1
If	SN	and	LP	and	*	then	0
If	SN	and	SP	and	LP	then	0
If	SN	and	SP	and	SP	then	0
If	SN	and	SP	and	ZE	then	0
If	SN	and	SP	and	SN	then	0
If	SN	and	SP	and	LN	then	1
If	SN	and	ZE	and	LP	then	0
If	SN	and	ZE	and	SP	then	0
If	SN	and	ZE	and	ZE	then	0
If	SN	and	ZE	and	SN	then	0
If	SN	and	ZE	and	LN	then	1
If	SN	and	SN	and	*	then	1
If	SN	and	LN	and	*	then	1
If	LN	and	LP	and	*	then	0
If	LN	and	SP	and	LP	then	0
If	LN	and	SP	and	SP	then	0
If	LN	and	SP	and	ZE	then	0
If	LN	and	SP	and	SN	then	0
If	LN	and	SP	and	LN	then	1
If	LN	and	ZE	and	LP	then	0
If	LN	and	ZE	and	SP	then	0
If	LN	and	ZE	and	ZE	then	0
If	LN	and	ZE	and	SN	then	0
If	LN	and	ZE	and	LN	then	1
If	LN	and	SN	and	*	then	1
If	LN	and	LN	and	*	then	1

In the flow chart of the Fuzzy Logic Control RWA （FLC RWA） algorithm, shown in Fig. 6, the path selection found by the shortest path algorithm uses fuzzy theory to deduce whether the wavelength can be added into a new connection.

IV、Simulation Environment, Results and Discussion

1、Simulation Environment

The simulation environment is based on the National Science Foundation Network （NSFNet） backbone network with GMPLS. An independent control channel is used to transmit and gather network information using OSPF or IS-IS protocols on the GMPLS network. The unique and independent memory space stores the network information gathered from each node. In the GMPLS network environment, each node has its independent database in which to store network information. The network information will be updated when the network status is changed（Kim et al., 2001）, to simulate the information renewing in a real network. The PMT algorithm （Zhao et al., 2001）, used in the ATM network to establish a virtual path in advance before transmitting data, is modified herein using GMPLS to determine whether to establish a new connection according to the network status. The modified equations are as follows.

$$X_i \le \hat{p}(C - R_p) \qquad (1)$$

$$\hat{p} = \frac{\overline{X}/S}{\left(R_{TP}/S\right)T_m} = \overline{X}/R_{TP}T_m \qquad (2)$$

, where X_i : Flows in unit time and wavelength （bps）

C : Bandwidth of the wavelength （bps）

R_p : Peak rate in a new connection （bps）

$\overline{X}$: Average flows in a wavelength （bps）

S : Number of the connection

R_{TP} : Total peak rate of all connections

T_m : 1 （Renewing and managing network status once in a second）

Table 2. Comparison of six different network statuses

Comparisons	Coefficient of Variance（~5%）	The utilization of each connection is high
		The utilization of each connection is low
	Coefficient of Variance（~30%）	The utilization of each connection is high
		The utilization of each connection is low
	Coefficient of Variance（~50%）	The utilization of each connection is high
		The utilization of each connection is low

The overall system performance is evaluated for six different network statuses shown in Table 2, in terms of the average request, the average no. of connection per wavelength, the wavelength utilization, the data loss rate, the average no. of connection failed to connect, and the transmission cost.

2、Simulation Results

The simulation assumes that each optical fiber carries four wavelengths and that the bandwidth in each wavelength is 1Gb/s. The flow processing capacity of the converter is only half of entire network capacity（Yoo, 1996）.（For the proposed WDM network architecture, if the entire bandwidth of the system is 20Gb/s, the converter can process 10Gb/s of data）. The scenario simulated herein includes two steps. The first step evaluates the appropriate Fuzzy Limits based on simulation results for the six different network statuses, and the centroid method is applied to obtain the defuzzification value between zero and one. If the value exceeds the Fuzzy Limit, then the connection can be established. The second step is to compare the system performance of FLC RWA algorithm with that of PMT （Zhao et al., 2001） for six network situations to show that the proposed FLC RWA algorithm can provide better network transmission.

（1）Optimal Fuzzy Limit vs. C.V.

Four initial values of Fuzzy Limit, say 0.9, 0.8, 0.7 and 0.6 are set. The system performance with these four initial Fuzzy Limits is compared in terms of the average request, the average no. of connection per wavelength, the wavelength utilization, the data loss rate, the average no. of connection failed to connect and the transmission cost. Transmission cost is defined as the cost of network resources used for data transmission （Yu, 2002）. The calculation of transmission cost is weighted by the average data loss rate, the average length of a connection and the number of converters. The average number of loss data in each connection has a weighting of three. The average length of each connection has a weighting of two. The average converters of each connection has a weighting of one. Furthermore, the transmitted distance may cause the transmission delay and will affect the speed of data transmission, so the weighted cost of the transmitted distance is greater than that of the converter. The value is two for the transmitted distance and one for the converter.

Figure 7 shows that the average utilization in each connection is between 80% and 90% and the C.V. is between 3% and 5% for different Fuzzy Limits - 0.9 in red, 0.8 in green, 0.7 in yellow, and 0.6 in blue. The results indicate that the utilization is high and the data flow is very stable in each connection. At a Fuzzy Limit of 0.6, the wavelength utilization and the number of connections in each wavelength exceed those at other Fuzzy Limits. In this case, the data loss rate is higher than the loss rate at other Fuzzy Limits, but the effect is relatively tiny （only 0.001%）. The transmission costs in terms of network resources for these four values of the Fuzzy Limit are almost the same. More stable lines of the transmission cost of the network resources on the figures correspond to a lower data loss rate. Hence, a Fuzzy Limit of 0.6 is suitable to this network status.

Figure 7. The average utilization in each connection of the network is between 80% and 90% and the C.V. is between 3% and 5%.

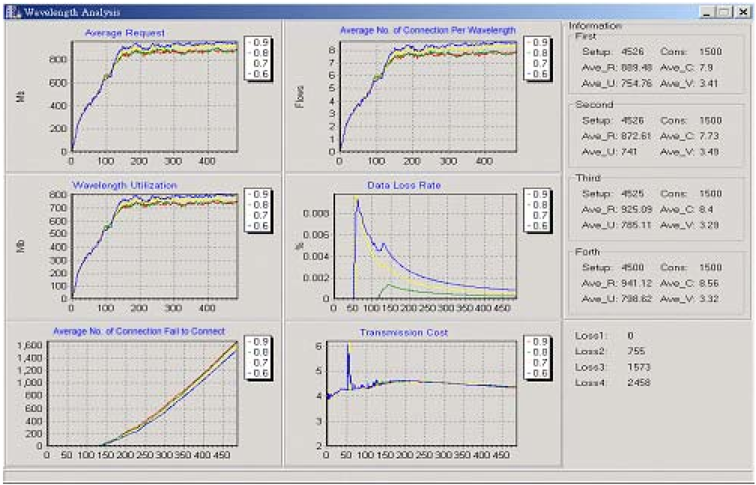


Figure 8. The average utilization in each connection of the network is between 50% and 60% and the C.V. is between 3% and 5%.

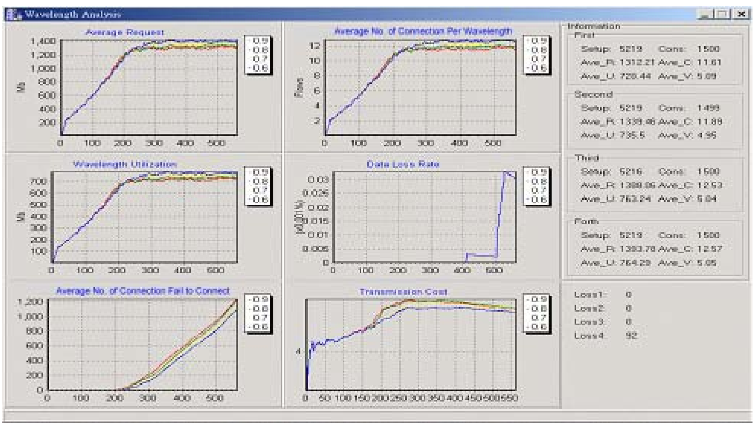
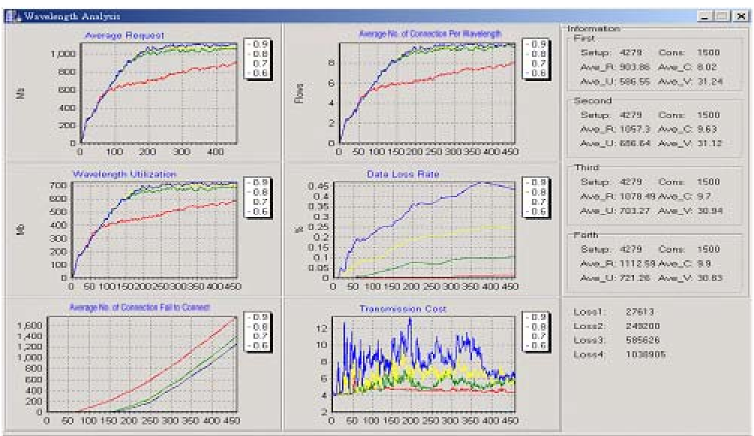


Figure 8 shows that the average utilization decreases in each connection between 50% and 60%, and the C.V. varies between 3% and 5% for different Fuzzy Limits. The wavelength utilization is lower, but the data transmission is much more stable than in Fig. 7. The wavelength utilization and the number of connections at a Fuzzy Limit of 0.6 are higher than those at other Fuzzy Limits. However, the number of connections failed to connect is lower than those at other Fuzzy Limits, and the data loss rate is lower than 3.5×10^{-5}%. The influence on the transmission quality of whole network is tiny.

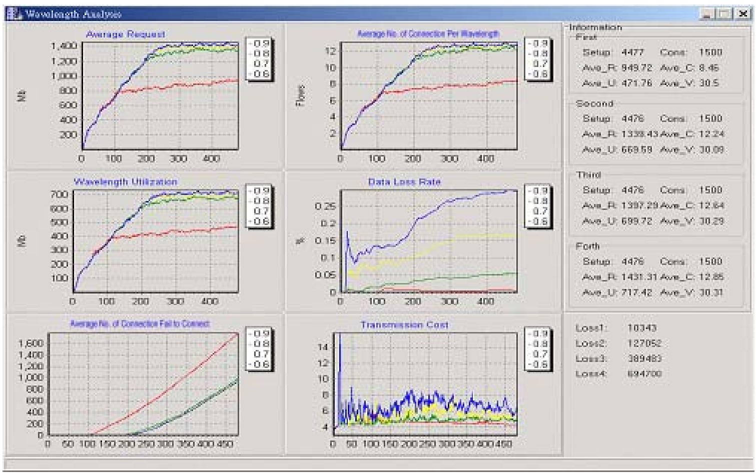
When C.V. increases, the data transmission becomes unstable. As shown in Fig. 9, the average utilization in each connection is between 60% and 70%, and its C.V. is between 30% and 35%, for various Fuzzy Limits. The results show that the average request bandwidth in each connection, the average number of connections and the wavelength utilization increase as the value of Fuzzy Limit is decreased. If the value of the Fuzzy Limit is lower, then the threshold of the connection is lower. The number of connections increases accordingly, but causing data loss. When the value of Fuzzy Limit is set to 0.6, the data loss rate reaches 0.4%. The transmission cost in terms of network resources will be increased thereafter. The same result is obtained when the value of Fuzzy Limit is set to 0.7 or 0.8. A Fuzzy Limit set to 0.8, 0.7 or 0.6 will consume more network resources than at 0.9, so, a Fuzzy limit of 0.9 is suitable for this network situation.

Figure 9. The average utilization in each connection of the network is between 60% and 70% and the C.V. is between 30% and 35%.



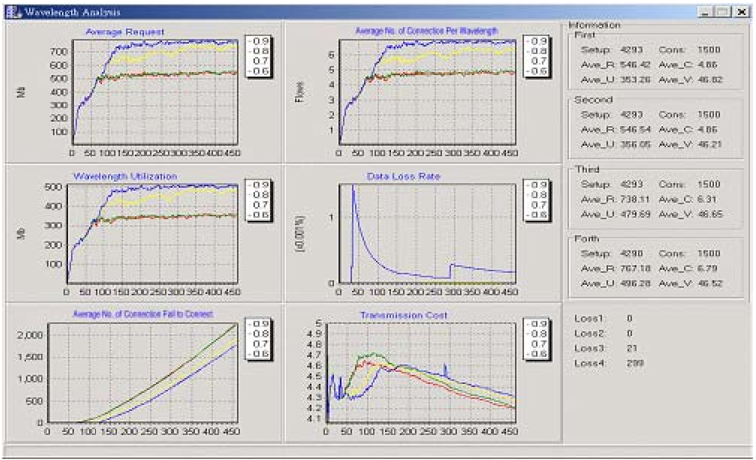
Similarly, when the average utilization of each connection is decreased to 50%, and the C.V. is maintained between 30% and 35%, as shown in Fig. 10, the average utilization of each connection becomes lower and the data flow is unstable. The results are similar to those shown in Fig. 9. The average request bandwidth in each wavelength, the average number of connections and the wavelength utilization increase as the value of the Fuzzy Limit is decreased. If the value of the Fuzzy limit is set to 0.8, 0.7 or 0.6, then the transmission cost in terms of network resources will exceed that at 0.9. Hence, a Fuzzy Limit of 0.9 is the most suitable in such a network status.

Figure 10. The average utilization in each connection of the network is around 50% and the C.V. is between 30% and 35%.



From the results in Fig. 7 to 10, the setting of the Fuzzy Limit depends strongly on the C.V.. For instance, the C.V. between 3% and 5% is suitable for the value of the Fuzzy Limit set to 0.6, and the C.V. between 30% and 35% is suitable for the value of the Fuzzy Limit set to 0.9 in any network status.

Figure 11. The average utilization in each connection of the network is between 60% and 70% and the C.V. is between 45% and 55%.



In the following simulations, the C.V. is increased to see how the Fuzzy Limit is affected. In Fig. 11, the C.V. is raised to between 45% and 55% and the average utilization of each connection is between 60% and 70%. When the value of Fuzzy Limit is set to 0.6, the average number of connections and the average wavelength utilization are higher than those at other Fuzzy Limits, and fewer connections failed to connect. The data loss rate is 0.001% lower than those at other values of Fuzzy Limit, but the transmission quality of the network is unaffected. Hence, the Fuzzy Limit of 0.6 is suitable in this network situation. Following the same procedure, when the average utilization of each connection is decreased around 50% and the C.V. is maintained between 45% and 55% （as shown in the Fig. 12）, the results are similar to those in Fig. 11. When Fuzzy Limit is set to 0.6, the average number of connections and the average wavelength utilization are higher than other values of Fuzzy Limit, but the number of connections failed to connect is lower. The data loss rate does not affect the transmission quality of the network. Table 3 shows the relationship between C.V. and the recommended Fuzzy Limit, which is further discussed in （Yu, 2002）.

Figure 12. The average utilization in each connection of the network is around 50% and the C.V. is between 45% and 55%.

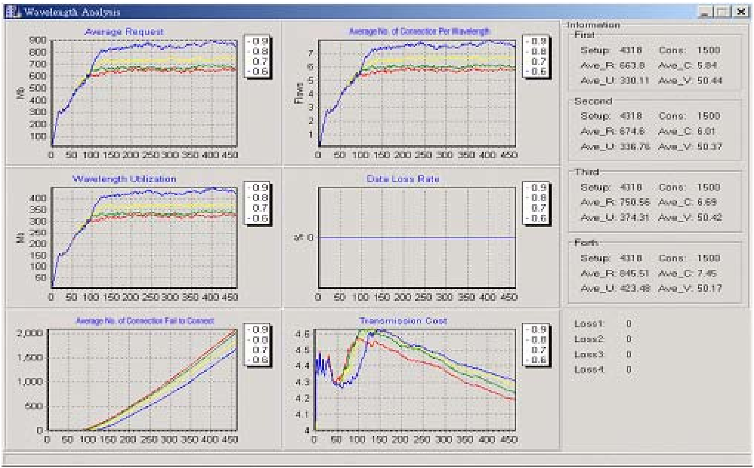


Table 3. Relationship between C.V. and Recommended Fuzzy Limit

C.V.	Recommended Fuzzy Limit
Under 10%	0.6
10%~35%	0.9
35%~45%	0.8
45%~55%	0.6

（2）Performance Comparison of FLC RWA Algorithm and PMT

In the second step, the performance of the FLC RWA algorithm is compared with that of PMT in six network situations. The transmission cost in the network resource is calculated using weightings, as in Section 4.2.1. The influence of the transmission cost on network resources is more visible. However, the initial values Fuzzy Limits are based on the simulation results from the first step.

Figure 13. The average utilization in each connection of the network is between 80% and 90% and the C.V. is between 3% and 5%.

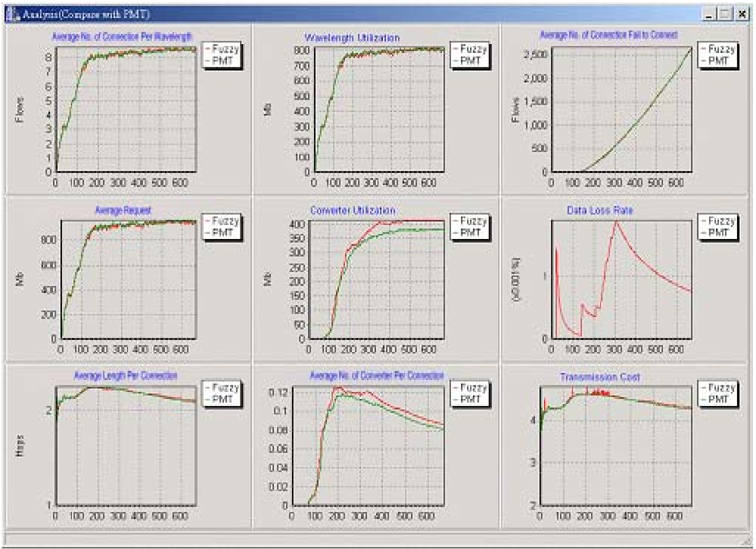
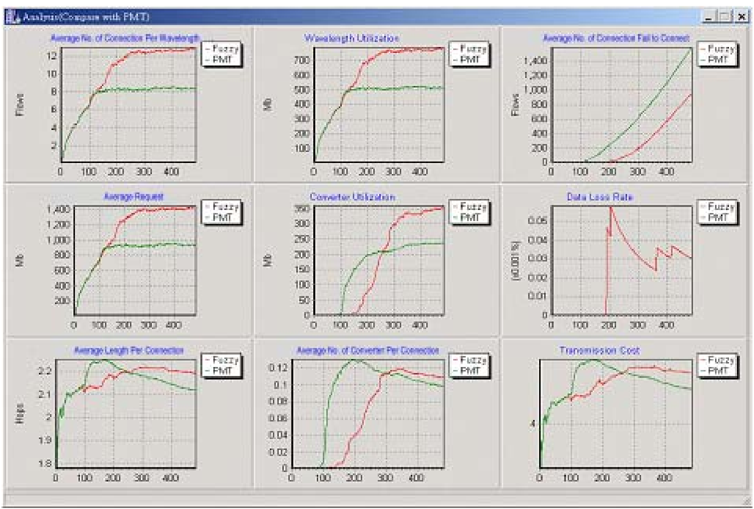


Fig. 13 shows that the average utilization in each connection is between 80% and 90% and the C.V. is between 3% and 5%. In the high utilization and stable data flow network state, the results of the FLC RWA algorithm （red curve） and PMT （green curve） are very close, and the transmission costs are almost the same. Although the data loss rate of the FLC RWA algorithm is 0.001% higher than PMT, transmission quality is unaffected because the FLC RWA algorithm permits more connections. （The FLC RWA algorithm establishes 3583 connections, and PMT establishes 3567 connections.）

The average utilization of each connection is decreased around 50% to determine whether the data flow is stable. As shown in Fig. 14, the average connection of each wavelength and the utilization of the FLC RWA algorithm exceed those of PMT because the FLC RWA algorithm evaluates the current network status, which the wavelength utilization is low and the data flow is stable. Therefore, other connections share the redundant bandwidth to reserve bandwidth for rapidly changing traffic, also reducing the number of connection failed to connect. As the number of connections for the FLC RWA algorithm before 250 units time exceeds that of the PMT, the system performance parameters, such as the average length of connections, the average number of converters, the converter utilization and transmission cost, for the FLC RWA algorithm are lower than those of the PMT. For the FLC RWA algorithm, the connection of the network saturates after 250 units of time (PMT saturates the network earlier). When the number of connections for the FLC RWA algorithm is higher than that of the PMT, the system performance parameters for the FLC RWA algorithm, such as average length of connections, transmission cost in terms of the network resources are higher than those of the PMT.

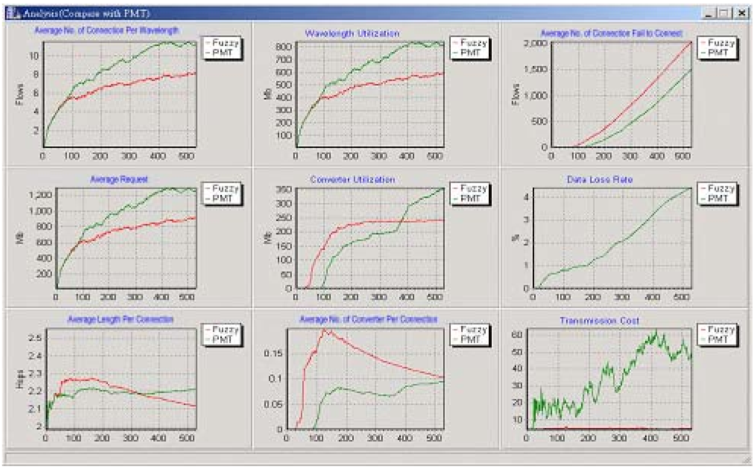
Figure 14. The average utilization in each connection of the network is between 50% and 60% and the C.V. is between 3% and 5%.



Next, the C.V. of the data flow is increased between 30% and 35%, and the average utilization in each connection is between 60% and 70%. In the state with high wavelength utilization and an unstable data flow, as shown in Fig. 15, the average number of connections and wavelength utilization for PMT exceed those for the FLC RWA algorithm and the number of connection failed to connect for the

PMT is lower than that for the FLC RWA algorithm. However, the data loss rate for PMT is 4%, but for the FLC RWA algorithm is 0%. Therefore, the transmission cost is 49.26 for PMT, but only 4.42 for FLC RWA. Hence, the network performance of the FLC RWA algorithm is better than that of the PMT algorithm given this network status.

Figure 15. The average utilization in each connection of the network is between 60% and 70% and the C.V. is between 30% and 35%.



If the average utilization of each connection is decreased（as shown in Fig. 16）, then the data loss rate of PMT is higher than that of the FLC RWA algorithm. Hence, PMT, using the average data flow to determine the routing, cannot adjust efficiently the number of connections based on network status. This will also cause an overabundance of connections, and increase the data loss rate. The C.V. is increased to 50%, and each connection tested at both higher and lower utilization （as shown in Fig. 17） to prove this assumption.

Fig. 17 shows that the average utilization of each connection is between 60% and 70%, and the C.V. is between 45% and 55%. Clearly both the number of connections and the wavelength utilization in PMT are very high, which are close to the maximum values supportable by the network bandwidth. However, the data loss rate may reach 13%, far from that obtained by the FLC RWA algorithm （=0%）. Furthermore, the transmission cost in terms of network resources may reach 156.3 with PMT, almost 36 times that reached using the FLC RWA algorithm （=4.34）. When the average utilization of connections is around 50% （as shown in Fig. 18）, the results are similar. The transmission cost of the network with PMT is 84.26, almost 19 times of that with the FLC RWA algorithm （=4.37）.

Figure 16. The average utilization in each connection of the network is around 50% and the C.V. is between 30% and 35%.

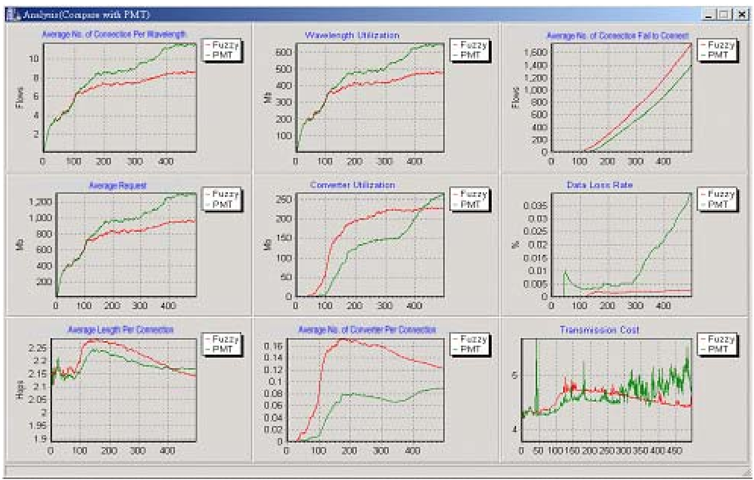


Figure 17. The average utilization in each connection of the network is between 60% and 70% and the C.V. is between 45% and 55%.

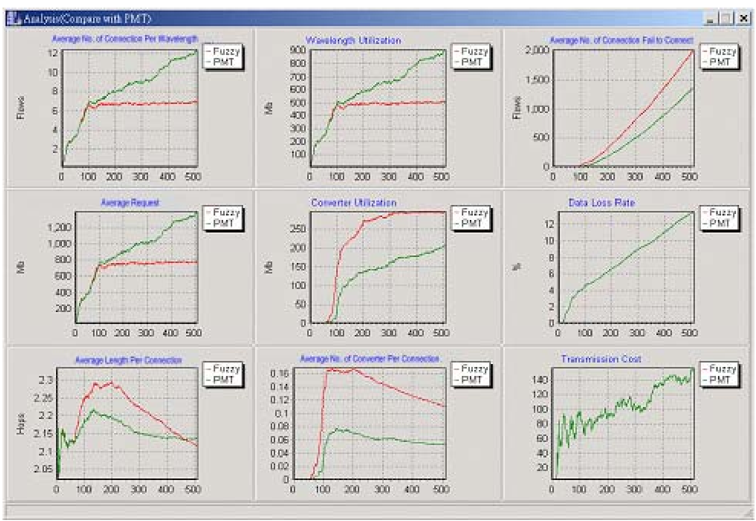
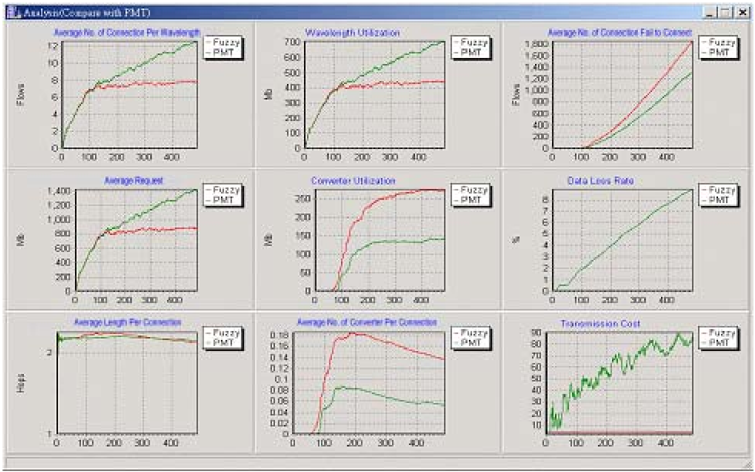


Figure 18. The average utilization in each connection of the network is around 50% and the C.V. is between 45% and 55%.



V、Conclusion

The architecture of IP with GMPLS over DWDM simplifies the traditional IP network architecture; increases the quality of transmission, and saves network resources. This paper proposed a dynamic FLC RWA scheme using a fuzzy logic control to achieve the best quality of network transmission. The proposed algorithm dynamically allocates network resources and reserves some bandwidth based on the current network status, which includes the request bandwidth, average utilization for each wavelength and the coefficient of variance（C.V.）of data traffic. The scenario simulation has two purposes – the first is to evaluate and set the appropriate Fuzzy Limits; and the other is to compare the performance of the FLC RWA algorithm with the periodic measurement of traffic （PMT）, which uses only the average wavelength utilization to determine whether the connection can be established. Based on the relationship between the C.V. and the recommended Fuzzy Limit, the simulation results show that the proposed FLC RWA algorithm can provide better network transmission quality. Therefore, when the utilization of bandwidth is low, the excessive bandwidth can be shared with other connections; when the utilization of bandwidth is high, partial resources can be reserved to handle abrupt change of data flow. Determining the C.V. of network flow can prevent the need to continue to establish new connections under unstable flow, which would result in excessive data loss and increased transmission cost. In future networks, the trend will be to maintain the QoS of packet transmission, regardless the bandwidth size. In fact, the use of RSVP-TE or CR-LDP in GMPLS provides a mechanism for establishing connections of QoS, so such connections can guarantee the quality of transmission. Furthermore, the priority of each connection is considered during fuzzy determination, which protects the quality of transmission in different network situations.

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