Master's Thesis

Title

Performance Evaluation of Optical Packet / Path Integrated Architecture for WDM-based Networks

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February 13th, 2008

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Abstract

Wavelength Division Multiplexing (WDM) technology, which carries multiple wavelength channels on a single fiber, is expected to accommodate the traffic volume for the current and future Internet. One approach for accommodating IP traffic on the wavelength division multiplexing (WDM) network is to construct a logical topology by establishing a set of lightpaths between nodes. The lightpath carries IP traffic and does not require any electronic packets processing at intermediate nodes, which reduces the load of packet processing at those nodes. Another approach is to utilize WDM networks as path switched networks. This approach can support applications that require high reliability and large bandwidth by establishing wavelength channels (called lightpath) between source and destination nodes on-demand basis. Applications requiring high reliability and large bandwidth such as grid computing services or digital cinemas become available recently. If we accommodate such applications using IP network, unexpected packet loss or packet delay may occur because of collision with other traffic. To prevent this, integration of packet and path switched networks is key to achieve high reliable and high bandwidth services in the Internet. In this thesis, we investigate the performance of optical packet / path integrated architecture in WDM-based networks. For this purpose, we develop an approximation analysis method to reveal how path network achieve effective network utilization and relax the load of packet switched network. Our method is based on M/M/1/K queuing system and iterative calculation. We verify the accuracy of our approximation analysis method and evaluate the throughput and packet loss rates of the integrated architecture by comparing with results of computer simulations. Our results indicate that the throughput of integrated architecture increases as the number of wavelengths assigned to path network increases, but throughput of integrated architecture decreases when all wavelengths are assigned to the path network.

Keywords

Wavelength Division Multiplexing, IP over WDM, Dynamic Path Setup, Reduced load approximation, queuing system, approximation analysis

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1 Introduction

The increase in the number of Internet users and the appearance of multimedia services such as video streaming have led to the rapid growth in Internet traffic. Until now, Internet traffic doubles each year [1]. New services such as grid computing, P2P will drive the traffic growth and bandwidth demands in the future. The answer to meet the bandwidth demand is centered on a new emerging technology, WDM (Wavelength Division Multiplexing). WDM technology allows transmitting multiple optical signals on different wavelengths on a single fiber, which dramatically increases the link bandwidth. There are several approaches to utilize WDM networks effectively.

One approach is to utilize WDM networks as packet switched networks, called IP over WDM [2–4]. In this method, wavelength channels, also known as lightpaths, are configured between each node and packets are transmitted on the lightpaths. The nodes consist of IP router and OXC (Optical Cross Connect) that bind an input wavelength channel to a specified output wavelength channel. Lightpaths are established by OXC in the first place and packets routing by IP router are transfered through the lightpaths. Photonic network works as layer 2 (data link layer) on OSI Reference Model and IP works as layer 3 (network layer) in this method. Therefore, IP over WDM has good compatibility with the Internet. However, applications requiring high reliability and large bandwidth such as grid services or digital cinemas become available recently. If you use such applications using IP network, it has possibilities to occur drop or delay of packets because of collision with other traffic. Hence, it is eligible way to divide traffic which requires high reliability and large bandwidth from other traffic. One possible approach to fulfill this is to use WDM technology where it can split wavelengths and assign different architecture to each wavelength.

Another approach to utilize WDM networks is to establish lightpaths [5–8]. The source node communicates with a destination node by signaling messages to configure OXCs along the route when a data transfer request arises at the source node. A lightpath is established when all OXCs along the route between a source node and a destination node. Then, the source node starts data transfer to the destination node through the established lightpath. In this case, there is no congestion and packet drop because only one flow can appropriate the large bandwidth lightpath. Furthermore, any transport mechanism can be applied to this method. So, it can support applications that require high reliability and large bandwidth. The drawbacks of this approach are lightpath setup delay. There is lightpath setup delay from time when data transfer request arises to time when data transfer can start.

Theses two approaches have advantages and drawbacks. Therefore, some integrated mechanisms such as TCP Switching have been researched [9–11]. TCP Switching is a network architecture that creates a separate circuit for each IP flow. It lets IP directly controls the creation or destruction of circuits. Integration of packet and path switched networks is key to achieve high reliable and high bandwidth services in the Internet. It is easy to integrate packet and path switched networks by using WDM technology. Wavelength channels can be dealt each other since each wavelength is independent from other wavelengths. Thus, it is feasible that packet switched architecture uses some wavelengths, while path switched architecture uses the remaining wavelengths.

Figure 1 shows a packet / path integrated network model we consider. The source node in the integrated network can select which network it uses. In order to utilize the integrated networks effectively, we must investigate the performance of integrated architecture. Therefore, it is necessary to reveal how path network achieve effective network utilization and relay the load of packet switched network. Especially, it is important to share wavelengths to packet and path networks optimally because wavelengths on fibers are limited.

In this thesis, we develop an approximation analysis method to reveal the throughputs and the data loss rates of integrated networks. Using our analysis method we reveal the optimal proportion of wavelength assignment to packet and path networks. We develop an approximation analysis method for packet network with UDP and TCP connections. The method is based on M/M/1/K queuing system and iterative calculation. It reveals the throughput and loss rate of each connection in the path network. Additionally, by combining it with the approximation analysis method for path network introduced in [14], the total throughput and data loss rate of integrated network are obtained. Furthermore, we verify the results of analysis by comparing with those of computer simulation. Then, we evaluate the throughputs and the drop rates of the integrated network by our approximation analysis method. As a result, the throughputs and loss rates obtained by our approximation analysis method are close to that of computer simulation. Moreover, our results show that the total throughputs of integrated networks increase, as the number of wavelength assigned to path network increase. However, the total throughputs decrease when all of wavelengths are assigned to path network because there is no support of packet network. It is also revealed that the throughputs of packet networks are not so high when the data transfer requests arrival rate is high. Because the path network works as a buffer agent.

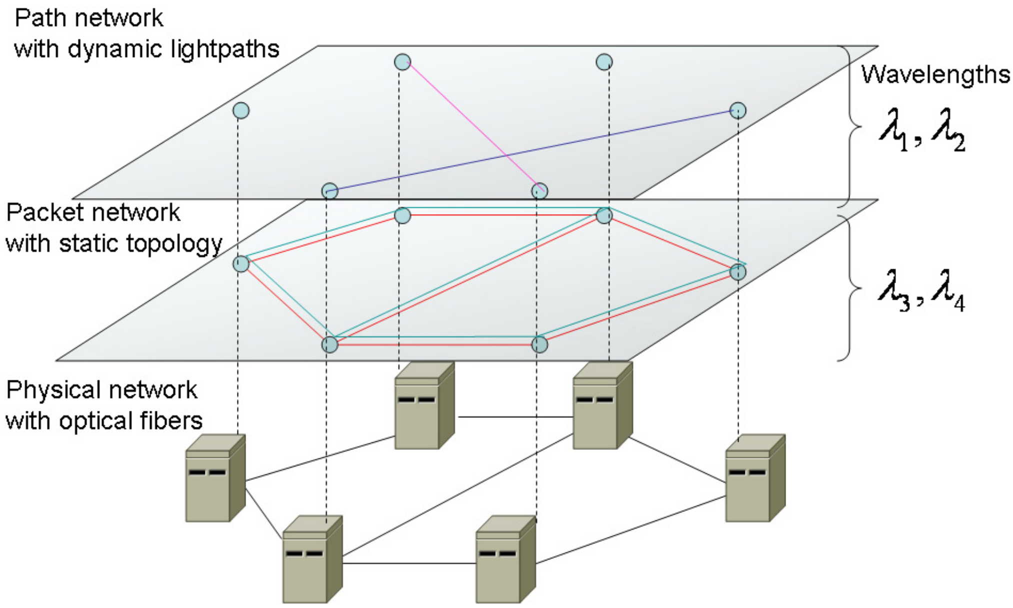


Figure 1: A model of packet/path integrated network

This thesis is organized as follows. In Section 2, we show attributes of IP over WDM architecture as packet network and distributed dynamic lightpath setup architecture as path network. After that, we explain integrated packet and path architectures. In Section 3, we show our analysis method for integrated networks. We explain both path network part and packet network part, and each case applied UDP and TCP to packet network part. Section 4 describes results of analysis and computer simulation. Comparing results of analysis and simulation, we verify our analysis method leads the throughput and data loss rate near by that of computer simulation. Finally we summarize our thesis in Section 5.

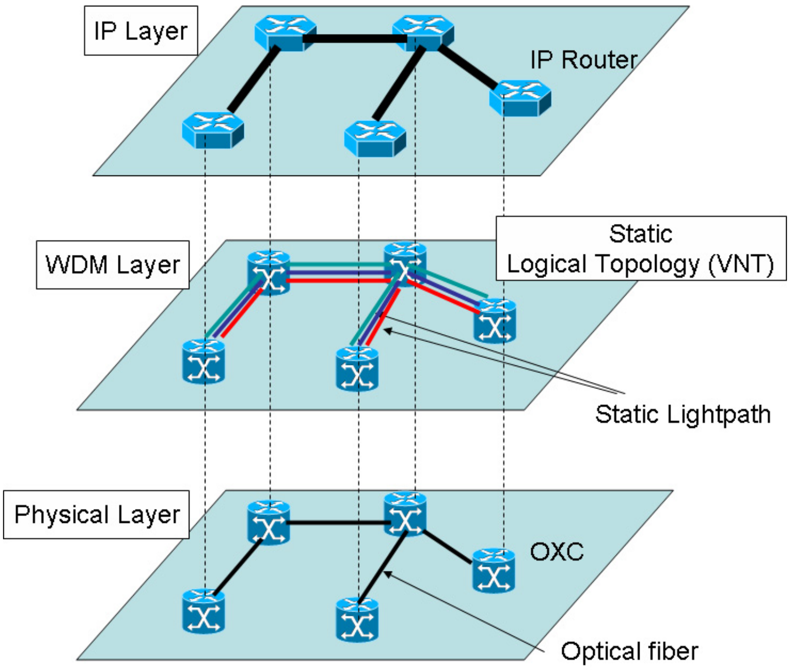


Figure 2: IP over Point-to-Point WDM

2 Packet / Path Integrated Architecture

There are mainly two types of architecture to utilize WDM network effectively. One is packet networks and another is path networks. In this section, we first describe two architectures on WDM networks. After that, we explain packet/path integrated architectures.

2.1 IP over WDM Architecture

Because of the majority of the Internet traffic is IP, it is an important task to develop network architectures which transport IP traffic on the WDM network. There are several alternatives for IP over WDM networks, IP over point-to-point WDM, IP over reconfigurable WDM, and IP over switched WDM [2]. Under the IP over point-to-point WDM architecture (Figure 2), the WDM is on each optical fiber link. That is, each wavelength on the fiber is treated as a physical link between conventional IP routers. The VNT is same as the physical fiber topology. Thus, multiple links of wavelength are provided between IP routers. In this case, the bandwidth of optical fiber links is actually increased by the WDM technology. However, it is insufficient to deal with increasing traffic demand because the bottle neck of the network shifts to electronic routers.

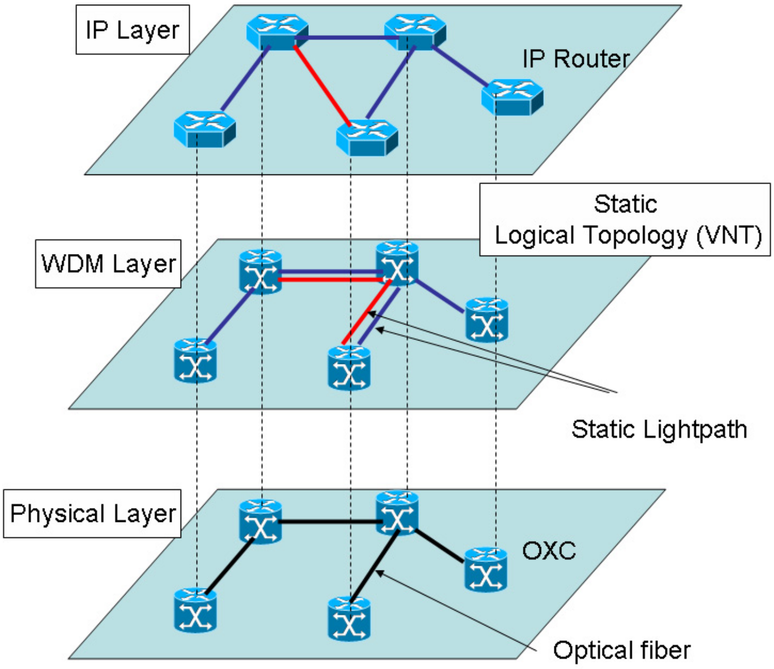


Figure 3: IP over WDM

In the IP over reconfigurable WDM architecture and IP over switched WDM (Figure 3), wavelength channels are configured in the WDM layer, and IP packets are transfered by the channels. Each intermediate node of the network has OXC and IP packets are transfered without any processing at each nodes. In this way, lightpaths reduce the load of IP routers. Reconfigurable WDM means VNT is configured as network state. On the other hand, switched WDM means VNT is pre-configured and it is static.

We consider IP over WDM as point-to-point WDM architectures in this thesis because we would like to know the performance of integrated networks with simple architecture at first.

Thus, the VNT equals topology of physical fiber in this thesis. When data transfer request arises at a source node, the data is packetization and the packets are transfered by IP like the Internet. Therefore IP over WDM has compatibility with the Internet.

However, normal IP cannot provides high reliability and large bandwidth to a connection. Because there are congestion, packets collision, forwarding processing delay and packet drop at routers and sharing bandwidth with many other connections Therefore, the flows which require high reliability and large bandwidth like digital cinema are unstable to transfer on IP network.

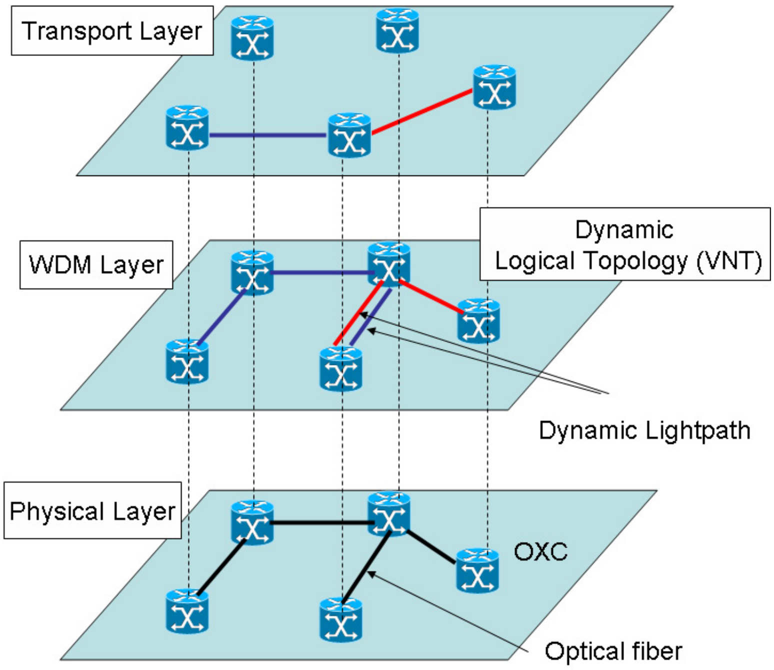


Figure 4: Dynamic Lightpath Setup Architecture

2.2 Dynamic Lightpath Setup Architecture

One approach to effectively utilize WDM networks is to transfer the data on-demand basis through wavelength reservation based on RSVP signaling (Figure 4). That is, when a data request arises at a source node, a wavelength is dynamically reserved between the source and destination nodes, and a lightpath is configured. The overview of dynamic lightpath setup with backward reservation method is as follows.

In backward reservation, the reservation of the network resource is performed more accurately. That is, the source node sends a PROBE packet before a wavelength reservation. A PROBE packet collects the information on usage of wavelength along the forward path, but no wavelength is reserved at this time. Along the forward path, the source node checks which wavelength is available in the next link and writes the information of available wavelength on a PROBE packet as available-list and sends the packet toward destination node. Every intermediate node which receives a PROBE packet examines that each wavelengths written in a PROBE packet is available or unavailable in the next link. If a wavelength is unavailable or in-use, the wavelength is removed from the available-list in a PROBE packet. When the destination node receives a PROBE packet, it

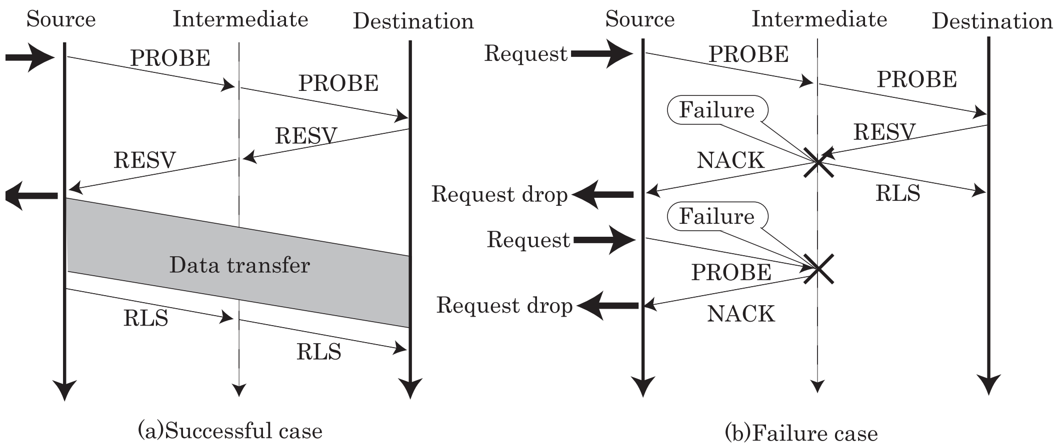


Figure 5: Backward signaling for lightpath establishment

will know that which wavelength is now available on the path between the source and destination. Based on this information, the destination node determines a wavelength for reservation, and then sends a RESV packet toward the source node. Figure 5(a) shows this successful case.

Although the reservation in backward scheme is more precisely due to PROBE-based reservation policy, the reservation failure is still unavoidable. There are two cases where the reservation failure occurs in backward scheme. The first one is the PROBE-failure. If there is no wavelength which is available through the entire path, an intermediate node is aware of it because there is no wavelength in a PROBE packet. In this case, the node returns a NACK packet and the source node notice the failure of lightpath establishment. The wavelength converter will be a powerful solution of this problem. But, applying the wavelength converters will produce another issue, i.e., facility cost. Note that, in this paper, we do not consider the wavelength conversion facilities. That is, a lightpath uses the same wavelength along the entire path, which is known as the wavelength continuity constraint. The second one is the congestion between RESV packets. Because of the propagation delay or OXC configuration delay, the information collected by a PROBE packet may be different from the current actual link state. There is no guarantee that a wavelength which was free until a few seconds ago is still available. In dynamic WDM networks, the link state changes from moment to moment. It is impossible for edge nodes to know the current actual link state exactly. If the destination node sends a RESV packet based on the outdated information, the reservation may be failure because the wavelength has been already reserved by the other lightpath establishment request. Figure 5(b) shows this case of reservation failure.

If it succeed to establish a lightpath, there are no congestion and packet drop because a established lightpath is leased for the connection which establishes the lightpath. This method provide high reliable and large bandwidth, dedicated channel for each connection.

But there are some disadvantages. First, data transfer cannot start immediately when the request arises because there is lightpath setup delay such as RSVP signaling and OXC configuration. If the data size is small, the influence of lightpath setup delay is large. Second, it cannot utilize the large bandwidth effectively, because a wavelength with large bandwidth is occupied by only one flow. Furthermore, the large bandwidth is cannot utilized while lightpath setup phase.

2.3 Models of Packet / Path Integrated Architecture

There are some related researches about packet / path integrated networks [10, 11, 13].

There are many types of packet / path integrated architectures because

One type is the network used for transfering data is determined by some policy and information such as the data size. In [11], a source node in the network can choice either packet network or path network. If the data size is larger than threshold, the data is transfered through path network. Otherwise, the data is transfered through packet network. This usage may be hold promise because path networks is superior for transfering large data and packet networks is superior for transfering small data. But in such network, it is difficult to determine the policy which network is used for data transfer because the network cannot know much information such as how the data size is large.

Another type of the integrated network is used preferentially for transfering data first and the other network is used for retrial as subsidiary. Furthermore, how the data transfer retry gives variety to types of integrated network usage.

In this thesis, we apply the type of sending data in the order corresponding to path network first and packet network second because of the simplicity and therefore, we can investigate the relationship between packet network and path network in the integrated network. In the network which a source node can choice either packet network or path network by some criteria, the criteria dominates the performance of the network. So it is difficult to investigate pure performance of these networks. Additionally, if it sends data through packet network first, it is unclear that how dropped packets are resend through path network.

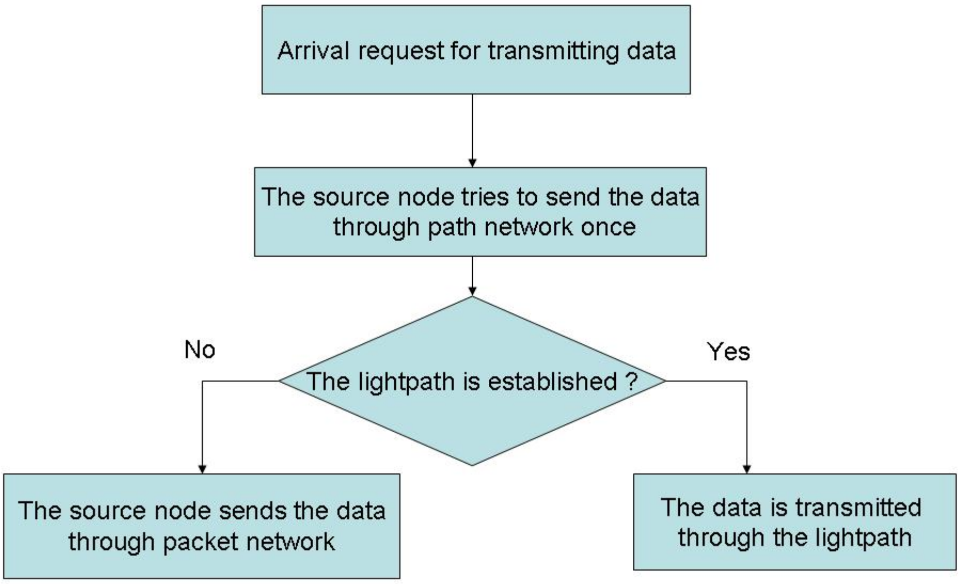


Figure 6: The flowchart of data transfer

3 Analysis Method

In this section, we explain our analysis method for packet / path integrated networks. At first, we show the network model we consider in this thesis. Then, we explain our analysis method. Our analysis method consists of two sub method for getting the throughputs and data loss rates of each path and packet networks. We consider both UDP and TCP connections. We show details of each sub method in Section 3.2.

3.1 Network Model

The networks we consider consist of nodes and optical fibers. The nodes consist of a IP router, a OXC and its controller because there are a packet network and a path network on a integrated network. The nodes are connected by optical fibers. The nodes have no wavelength conversion device. Therefore, a lightpath consists of same wavelength on all path along the route. One wavelength in the fibers is used to exchange control packets and other wavelengths are assigned to either packet or path network. A packet network and a path network have each own wavelengths and run independently. The switching architecture is based on that of introduced in [10].

In packet network on the integrated network, static lightpaths are configured on each fiber at the beginning. The VNT consists of these static lightpaths and the VNT equals physical fiber topology in this case. Data packets are transfered on this VNT. In path network, on the other hand, a lightpath is configured between source and destination nodes on demand by RSVP signaling and OXCs. The wavelength reservation method is backward reservation.

Our simple network model shows as figure 6. When data transfer request arises at a source node, the source node try to send the data through path network. If the source node succeeds to establish a lightpath between the source and the destination nodes, the data is transfered through the lightpath. Because of occupancy of the lightpath, the source node sends the data with all of bandwidth.

By contrast, if the source node fails to establish a lightpath because of collision of signaling messages or lack of utilizable wavelength, the source node sends the data through packet network like traditional packet networks.

3.2 Analysis Model

The network topology has J links and traffic demand are given. Each link has $W+1$ wavelengths, and one wavelength is assigned control plane. W_A wavelengths of remaining wavelengths are assigned to path network and W_P wavelengths are assigned to packet network. Thus, $W = W_A + W_P$. The set of All source and destination nodes pair is A Data transfer requests to each pair $a \in A$ of source and destination nodes arrive at the arrival rate of E_a. The requests arrive in accordance with the Poisson process. The bandwidth of a wavelength is b and propagation delay The data size is set to follow an exponential distributed with mean b/μ because lightpath holding time is set to follow an exponential distributed with mean $1/\mu$. The data is transfered along the predefined route R_a and the number of hops is h_a And we call each link on R_a as $a_1, a_2, ..., a_{h_a}$ by turns from upper reaches.

When a data transfer request is arrives on a source and destination pair a, the source node try to send the data through path network. So, we have beginning of analysis from path network. The analysis method for path network is based on [14]. In [14], the approximation analysis method for distributed dynamic lightpath setup network based on various reservation methods.

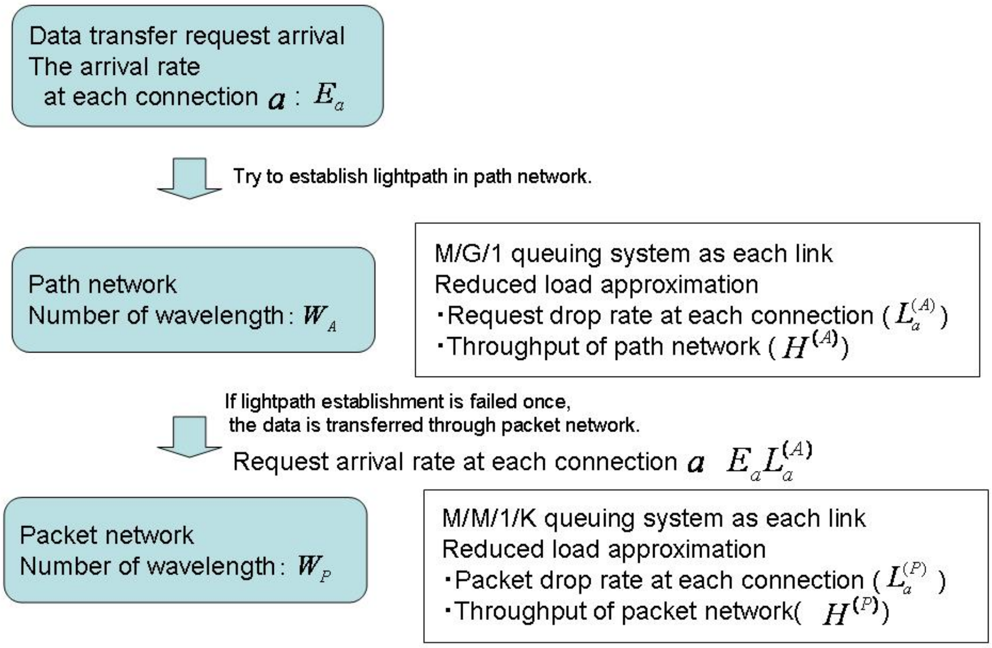


Figure 7: The analysis model for integrated network

We apply the approximation analysis method in [14] to analysis of path network. As a result of path network analysis, throughputs H_a and request drop rates L_a of each connection a. When a lightpath setup request is dropped in path network, the source node sends the data through packet network. Thus, we consider that data transfer requests arrive at each connection a according to a Poisson process with rate $E_a L_a$.

We consider both case all packets in packet network are transfered with UDP connection or TCP connection. In the case with UDP connections, we regards packets arrival to each link as according to a Poisson process and we consider each link as M/M/1/K queuing system. Thereby, packet drop rates of each link and each connection are revealed at given some condition about packet arrival rate at each link. But, to give the suitable condition is so difficult. So, we apply iterative calculation to the condition settings. If the given condition is not suitable, it updates the condition and recalculates. Thus, the results of calculation converge to that of static state. Consequently, we can get the throughputs and the drop rates each of path and packet networks. The total throughput of the integrated network is sum of the throughputs of path and packet networks.

3.3 Analysis Method

3.3.1 Analysis Method for Path network

We introduce the approximation analysis method for path network proposed in [14]

The overview of the method is follows.

(1) The request drop rates $L_a^{(A)}$ of each connection a are initialized as $L_a^{(A)} = 0 (a \in A)$, and the probability $q_j^{(A)}$ of some wavelength on the link j is not free are initialized as $q_j^{(A)} = 0 (j = 1, ..., J)$.

(2) We calculate a arrival rate $\Lambda_j^{(A)}$ of signal for wavelength reservation at each wavelength on the link j.

(3) We calculate a wavelength utilization time T_j which is from the time when the wavelength is reserved at link j to the time when the wavelength is released at link j for all links.

(4) We calculate the new probability $q_j'^{(A)}$ of some wavelength on the link j is not free in static state for all links.

(5) We calculate the new request drop rate $L'^{(A)}_a$ for all connections. If the request drop rates converge as $L^{(A)}_a \approx L'^{(A)}_a$, iteration phase is finished and go to next step. Otherwise, the request drop rates $L^{(A)}_a$ and $q^{(A)}_j$ are updated and return to step 2.

(6) We obtain the request drop rates of each connections.

The details are as follows.

Derivation of Λ_j and T_j

We focus a connection a. $\gamma^{(A)}_{a_i}$ means the request arrival rate of the ith link of the connection a. Similarly, α_{a_i} means the request arrival rate which succeed to establish lightpath finally, and β_{a_i} means the request arrival rate which fail to establish lightpath finally. Thus,

$$\gamma^{(A)}_{a_i} = \alpha_{a_i} + \beta_{a_i} \tag{1}$$

The probability of a wavelength is free on all links between the source and destination nodes is

$$\prod_{i=1}^{h_a}(1 - q^{(A)}_{a_i}) \tag{2}$$

The arrival rate at which a PROBE message received by destination node σ'_a is

$$\sigma'_a = E_a\left(1 - \left(1 - \prod_{i=1}^{h_a}(1 - q^{(A)}_{a_i})\right)\right) \tag{3}$$

Because we consider a wavelength selects randomly, the arrival rate of a RESERVE signal at the link a_{h_a} is

$$\gamma^{(A)}_{a_{ah_a}} = \sigma'_a \sigma'_{\text{select}} \tag{4}$$

σ'_{select} means the probability which a free wavelength is selected. So, σ'_{select} is inverse of expectation of the number of free wavelengths.

$$\sigma' \text{ select } = \sum_{k=0}^{W_A-1}(k+1)_{W_A-1}\mathrm{C}_k\left(\prod_{i=1}^{h_a}(1 - q^{(A)}_{a_i})\right)^k\left(1 - \prod_{i=1}^{h_a}(1 - q^{(A)}_{a_i})\right)^{(W_A-k-1)} \tag{5}$$

A RESERVE signal succeeds to reserve a wavelength if a RESERVE signal of the other connection is not received by the node. Thus,

$$\alpha_{a_{a_h}} = \gamma^{(A)}_{a_{h_a}}\prod_{k=1}^{h_a-1}\left(e^{-\Lambda^{(A)}_{h_{a_h}}(h_a-k+\frac{1}{2})D}\right) \tag{6}$$

$$\beta_{a_{a_h}} = \gamma_{a_{h_a}}^{(A)} - \alpha_{a_{h_a}} \tag{7}$$

Similarly, about each link along the route a_i,

$$\gamma_{a_{a_i+1}}^{(A)} = \gamma_{a_{a_i}}^{(A)} e^{-\Lambda_{a_i+1}^{(A)}(h_a-(i+1)+\frac{1}{2})D} \tag{8}$$

$$\alpha_{a_i} = \gamma_{a_i}^{(A)} \prod_{k=1}^{i-1} \left(e^{-\lambda_{a_k}^{(A)}(h_a-k+\frac{1}{2})D} \right) \tag{9}$$

$$\beta_{a_i} = \gamma_{a_i}^{(A)} - \alpha_{a_i} \tag{10}$$

s_j means the time from when a wavelength is reserved to when the wavelength is released in success case for lightpath establish. On the other hand, t_j means the time from when a wavelength is reserved to when the wavelength is released in failure case for lightpath establish.

$$s_{a_i} = iD - \frac{D}{2} + \frac{1}{\mu} \tag{11}$$

$$t_{a_i} = iD - \frac{D}{2} \tag{12}$$

Thereby, the request signaling arrival rate $\Lambda_j^{(A)}$ at each wavelength on link j and link utilization time T_j is calculated as,

$$\Lambda_j^{(A)} = \sum_{a_i=j} \gamma_{a_i}^{(A)} \tag{13}$$

$$\frac{1}{T_j} = \frac{\sum_{a_i=j} (\alpha_{a_i} s_{a_i} + \beta_{a_i} t_{a_i})}{\sum_{a_i=j} \gamma_{a_i}^{(A)}} \tag{14}$$

Derivation of $L_a^{(A)}$

The request drop rate $q_j^{(A)}$ at link j is described as,

$$q_j^{(A)} = \frac{\Lambda_j^{(A)}}{\Lambda_j^{(A)} + T_j} \tag{15}$$

S_a means the probability that the PROBE signal sended by the source node returns as NACK signal.

$$S_a = \left(1 - \prod^{h_a} i = 1(1 - q_{a_i}^{(A)}) \right)^{W_A} \tag{16}$$

Consequently, the request drop rate $L_a^{(A)}$ of connection a is calculated as

$$L_a^{(A)} = S_a + \left((1 - S_a) \left(1 - \prod_{k=1}^{h_a} e^{-\Lambda_{a_k}^{(A)} (h_a - k - \frac{1}{2}) D} \right) \right) \tag{17}$$

3.3.2 Analysis Method for Packet Network with UDP Connections

We explain our approximation analysis method for packet network with UDP connections. We consider packet arrival rate and processing time at each link is according to a Poisson process and model each link as M/M/1/K queuing system. K means buffer size at each link.

The overview of the method is as follows.

(1) We calculates data transfer request arrival rates $E_a^{(P)}$ to each connection a by $E_a^{(P)} = E_a L_a$, the result of path network analysis. And we initialize packet drop rates $L_a^{(P)}$ of each connection a as $L_a^{(P)} = 0$ and packet drop rates $q_j^{(P)}$ of each link j as $q_j^{(P)} = 0$.

(2) We calculates packet arrival rates $\Lambda_j^{(P)}$ at each link j.

(3) We calculates new packet drop rates $q_j'^{(P)}$ at each link j by analysis of M/M/1/K queuing system.

(4) We calculate new packet drop rates $L_a'^{(P)}$ of each connection a. If the packet drop rates of each connections converge as $L_a^{(P)} \approx L_a'^{(P)}$, iterative phase is finished and go to next step. Otherwise, packet drop rates at each link is updated as $q_j^{(P)} = q_j'^{(P)}$ and next iterative calculation starts from step 2.

(5) we calculate throughputs $H_a^{(P)}$ of each connection a with resulting packet drop rate $L_a^{(P)}$

(6) we calculate $H^{(P)}$ as sum of $H_a^{(P)}$.

The details of the method is as follows. We attention to a connection a. We caclurate The packet arrival rate γ_{a_i} of the ith link a_i as

$$\gamma_{a_i} = E_a^{(P)} \frac{b}{\mu} \prod_{l=1}^{i} \left(1 - q_{a_l}^{(P)} \right) \tag{18}$$

q_{a_i} is packet drop rate of the link a_i and b/μ is data size. There are some flows on a connection and each flow continue to send packets until all packets are transfered. So, the source node sends packets to the connection at rate $E_a^{(P)} b/\mu$ on static state.

The packet arrival rate $\Lambda_j^{(P)}$ at link j is

$$\Lambda_j^{(P)} = \sum_{a_i=j} \gamma^{a_i} \tag{19}$$

Then, we calculate new packet drop rate $q_j'^{(P)}$ by M/M/1/K queuing system as

$$q_j'^{(P)} = \frac{1-\Lambda_j^{(P)} d_j}{1-(\Lambda_j^{(P)} d_j)^{K+1}} (\Lambda_j^{(P)} d_j)^K \tag{20}$$

d_j is processing or propagation delay. If processing delay D_p is longer than propagation delay D,

Consequently, new packet drop rate $L_a'^{(P)}$ of the connection a is

$$L_a'^{(P)} = 1 - \prod_{i=1}^{h_a} \left(1 - q_{a_i}^{(P)}\right) \tag{21}$$

Then, if $L_a^{(P)} \approx L'(P)_a$ about all a, $L_a^{(P)}$ is packet drop rate of connection a in static state. Otherwise, $q_j^{(P)} = q_j^{(P)}$ for each link j and next iterative calculation starts.

Finally, the throughput of the connection a is

$$H_a^{(P)} = E_a^{(P)} \frac{bs}{\mu} \left(1 - L_a^{(P)}\right) \tag{22}$$

s means packet size. And Total throughput $H^{(P)}$ of packet network is

$$H^{(P)} = \sum_{a \in A} H_a^{(P)} \tag{23}$$

3.3.3 Analysis Method for Packet Network with TCP Connections

We explain analysis method for packet network with TCP connections. We apply relational expressions between throughput and packet loss rate under TCP Reno congestion control and iterative calculation with analysis of UDP. The overview is follows.

(1) The packet sending rate is initialized as $r = 1$

(2) We calculates data transfer request arrival rates $E_a^{(P)}$ to each connection a by $E_a^{(P)} = E_a L_a$, the result of path network analysis. And we initialize packet drop rates $L_a^{(P)}$ of each connection a as $L_a^{(P)} = 0$ and packet drop rates $q_j^{(P)}$ of each link j as $q_j^{(P)} = 0$.

(3) We calculates packet arrival rates $\Lambda_j^{(P)}$ at each link j.

(4) We calculates new packet drop rates $q_j'^{(P)}$ at each link j by analysis of M/M/1/K queuing system.

(5) We calculate new packet drop rates $L_a'^{(P)}$ of each connection a. If the packet drop rates of each connections converge as $L_a^{(P)} \approx L_a'^{(P)}$, iterative phase is finished and go to next step. Otherwise, packet drop rates at each link is updated as $q_j^{(P)} = q_j'^{(P)}$ and next iterative calculation starts from step 2.

(6) We calculate throughputs $H_a^{(P)}$ of each connection a with resulting packet drop rate $L_a^{(P)}$. Besides, we calculate TCP throughputs $H_a'^{(P)}$ of each connection a by relational expression between throughput and packet loss rate under TCP congestion control introduced in [15]. If the throughputs converge as $H_a^{(P)} \approx H_a'^{(P)}$, iterative phase is finished and go to next step. Otherwise, packet sending rate is updated as $r_{\text{next}} = r + 1$ and next iterative calculation starts.

(7) we calculate $H^{(P)}$ as sum of $H_a^{(P)}$.

The details are as follows.

In this method, two methods for getting throughputs are applied. One is approximation analysis with UDP connections we described, and another is relational expression between throughput and packet loss rate under TCP congestion control introduced in [15]. If the results of the two methods is same, it is performance of static state.

First of all, packet sending rate is set as 1. Although there are parallel flows on a connection, we consider these flows is one flow. In the UDP approximation analysis with packet sending rate r, b/μ is replaced by r. Then, the throughputs $H_a^{(P)}$ and packet loss rates $L_a^{(P)}$ of each connection is found in UDP connections sending packets at rate r.

On the other side, we calculate the throughputs of each connection under TCP congestion control by packet loss rate $L_a^{(P)}$ it can be calculated by following expression introduced in [15]

$$H_a'^{(P)} = \frac{\sqrt{\frac{3}{2}}s}{h_a D \sqrt{L_a^{(P)}}} \tag{24}$$

Finally, the total throughput is calculated by convergent throughput $H_a^{(P)}$ as

$$H^{(P)} = \sum_{a \in A} H_a^{(P)} \tag{25}$$

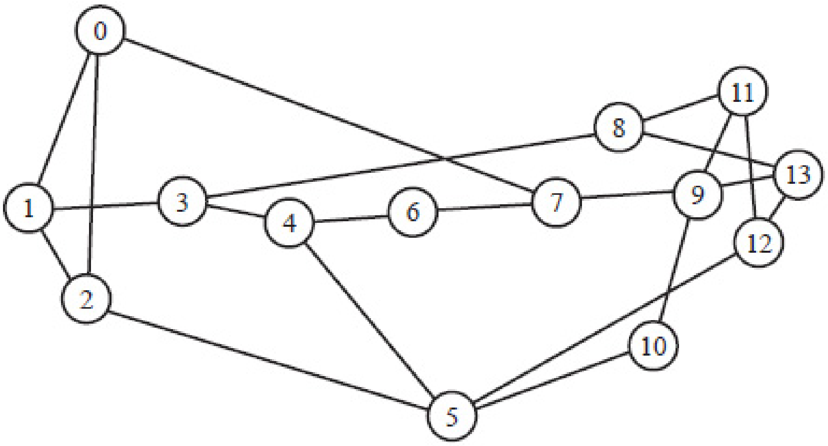


Figure 8: NSFNET topology

4 Results and Discussions

4.1 Parameter Settings

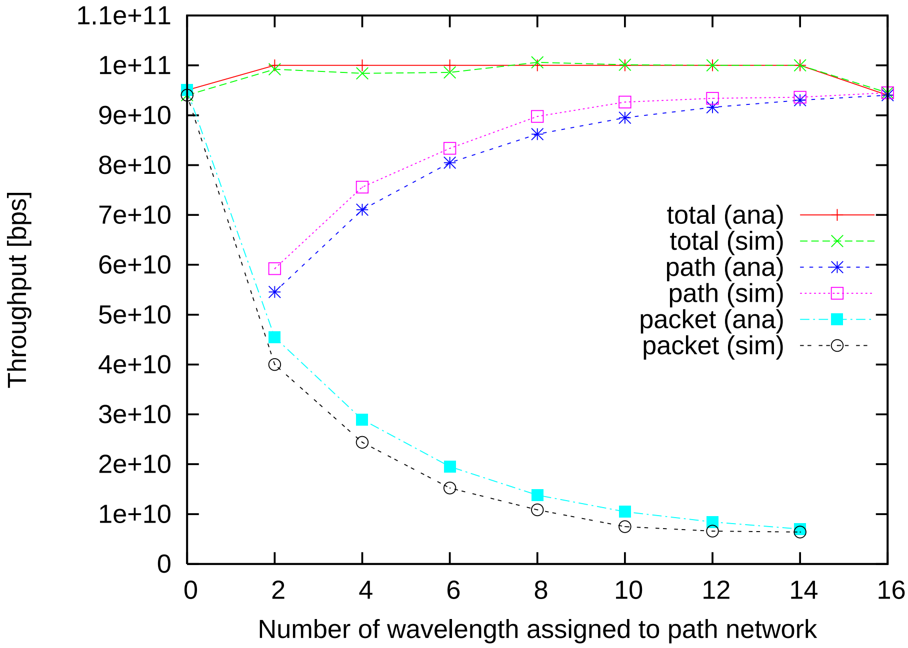
We evaluate the performance of the proposed approximation analysis method in Section 4 on the NSFNET (Figure 8) that has 14 nodes and 21 bidirectional links. A bidirectional link has an uni-directional optical fiber that multiplexes $16+1$ wavelengths in each direction and one wavelength is assigned to control channel. The transmission capacity of each wavelength is set to 10 Gbps. The link propagation delay is 10 ms per a link and OXC configuration delay is 20 ms per a link. The processing capacity of IP router is set to 40 Gbps, and data size is exponentially distributed with a mean value of 1 Gbyte. Thus, the holding time of path network is exponentially distributed with a mean value of 0.1 second. The size of packets is 1500 byte, and each link has queue which length is 10 packets. IP traffic flows between each node pair a arrive according to Poisson process with the average rate $\epsilon \times m_a$, where $M = m_a$ is traffic demand matrix and ϵ is scale factor of the traffic demand matrix. We use the traffic demand matrix shown in the reference [4]. In Table 1, we show this traffic demand matrix. The route of each connection is static minimum hop path, and VNT in packet network is same as physical fiber topology.

In the computer simulation with UDP connection, the UDP packets sending rate is 100 Mbps.

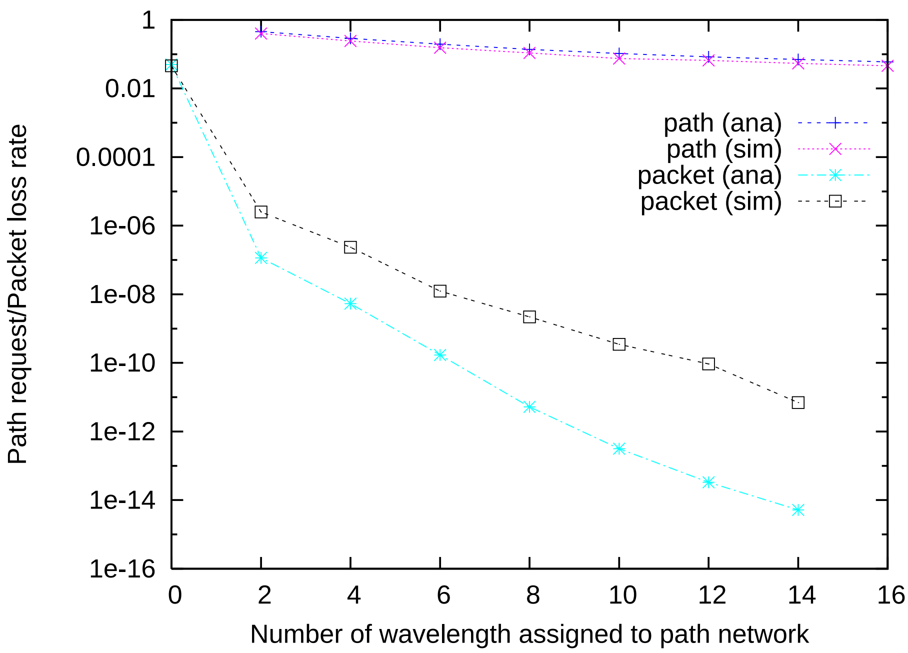
Figure 9: European Optical Network (EON) topology

Table 1: The traffic demand matrix for NSFNET topology

0	33.029	32.103	26.008	0.525	0.383	82.633	31.992	31.174	0.568	0.358	0.544	0.651	0.16
0.546	0	0.984	0.902	0.866	0.84	0.013	62.464	0.475	0.001	0.342	0.925	0.656	0.501
35.377	0.459	0	0.732	0.272	0.413	28.242	0.648	0.909	0.991	56.15	23.617	1.584	0.935
0.739	0.225	0.296	0	0.896	0.344	0.012	84.644	0.293	0.208	0.755	0.106	0.902	0.715
0.482	96.806	0.672	51.204	0	0.451	0.972	0.814	0.225	0.694	0.504	0.704	0.431	0.333
0.456	0.707	0.626	0.152	0.109	0	0.804	0.476	0.429	0.853	0.28	0.322	90.503	0.212
0.042	0.067	0.683	0.862	0.197	0.831	0	0.585	67.649	56.138	0.896	0.858	73.721	0.582
0.616	0.64	0.096	97.431	0.308	0.441	0.299	0	0.161	0.49	0.321	0.638	82.231	0.376
0.768	0.323	0.676	0.359	0.019	50.127	12.129	0.65	0	0.483	45.223	58.164	0.894	0.613
0.037	0.318	0.367	2.981	0.976	0.629	0.525	0.293	0.641	0	33.922	0.228	0.995	71.905
12.609	0.479	0.146	0.174	0.181	0.072	23.08	0.671	0.634	0.759	0	0.725	0.592	0.445
0.887	0.004	1.614	0.471	0.12	0.263	0.585	0.086	0.157	95.633	42.828	0	0.527	0.021
9.019	0.569	0.936	0.975	81.779	0.573	0.738	0.41	0.49	0.948	0.154	0.145	0	0.436
20.442	0.515	0.719	0.089	39.269	49.984	0.72	0.863	0.858	0.49	0.106	0.765	0.059	0



(a) Throughput



(b) Loss rate

Figure 10: Throughput and loss rate of integrated networks; The case for UDP connections

4.2 Performance of Integrated Network with UDP connections

Figure 10(a) shows the each throughput of the path and the packet networks and total throughput with UDP connections in approximation analysis and computer simulation at data transfer request rate of 100 requests per second.

As a result, the results of approximation analysis come near that of computer simulation. All differences of results are within small range. Thus, our approximation analysis method is effective to deal with integrated networks.

At the number of wavelength assigned to path network is 0, it is the case of only packet network and at the number of wavelength assigned to path network is 16, it is the case of only path network. As a result, the total throughputs of two case are inferior to integrated network. Therefore, the integrated networks are effective to increase total throughput.

As the number of wavelength assigned to path network, the throughput of path network increase and that of packet network decrease. The difference of the increase and the decrease degree influences to the total throughput. In this case, the total throughput increase gradually as increasing the number of wavelength assigned to path network, and it is achieved full throughput at the case the wavelength assigned to path network is in the range from 8 to 14.

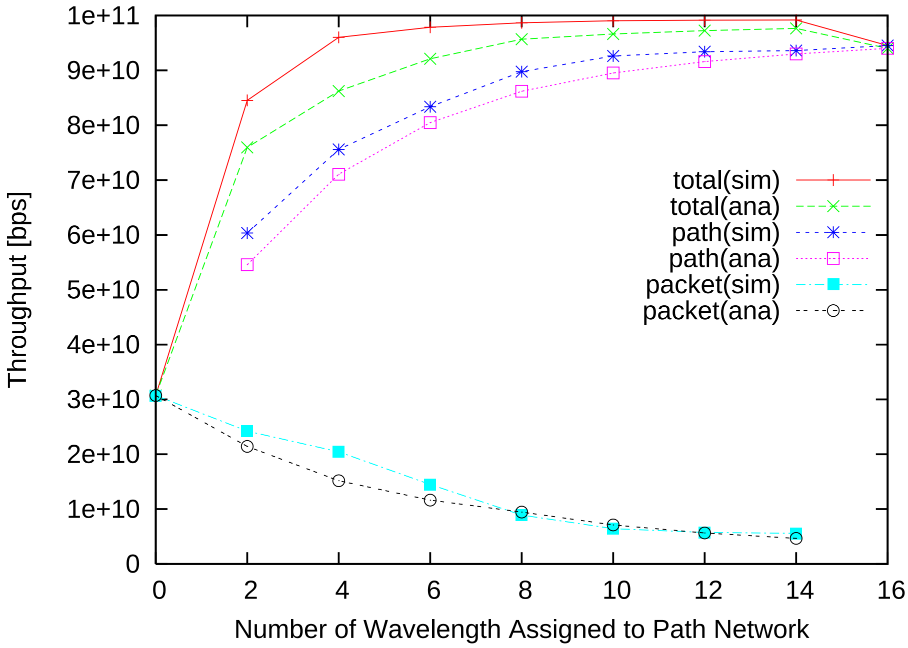
Figure 10(b) shows the loss rate of path request and packet.

In the case only packet network, the packet loss rate is about 0.04 and it is high rate. However, in the case few wavelengths are assigned to path network, the loss rate decrease near 0.

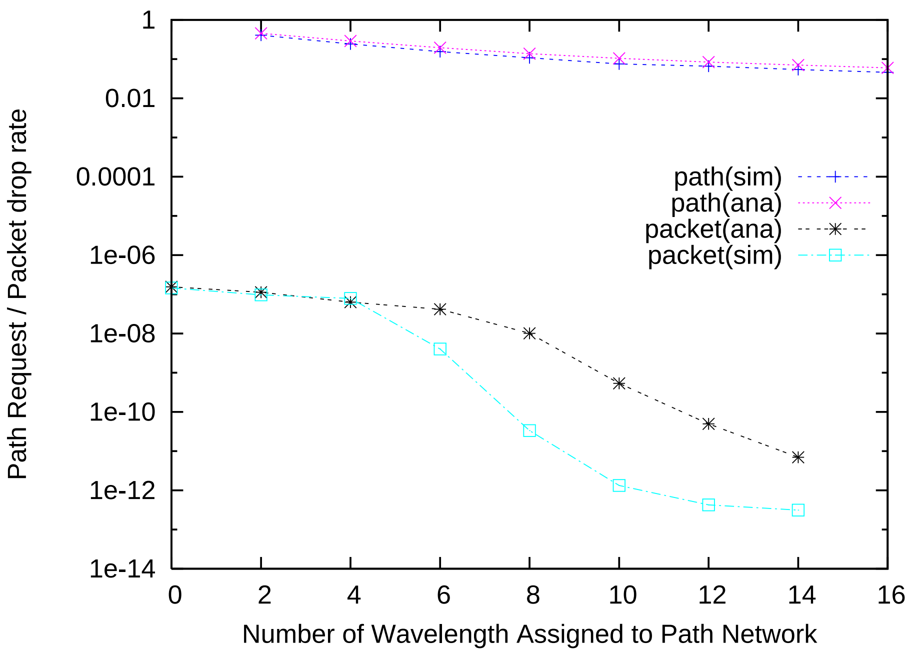
In this case, the performance of path network is high compared to packet network because processing capacity of IP routers is low. Similarly, the performance of path network is dominated by OXC configuration delay.

4.3 Performance of Integrated Network with TCP connections

Figure 11 shows the throughputs and the loss rates of approximation analysis and computer simulation. The differences of results are within small range. The throughputs and packet loss rate of packet network are low because of congestion control mechanism. The throughputs of approximation analysis of each network are lower side of that of computer simulation. Thus, the difference of the total throughput is a little bit large. However, it is not a important problem because the total throughput of analysis is safety side, which is lower side of computer simulation too.



(a) Throughput



(b) Loss rate

Figure 11: Throughput and loss rate of integrated networks; The case for TCP connections

4.4 Discussions

We investigate the effects of each parameter such as request arrival rate, OXC configuration delay and data size (holding time) on integrated networks with UDP and TCP connections with EON Topology. For EON topology, we randomly generate a traffic matrix according to exponential distribution.

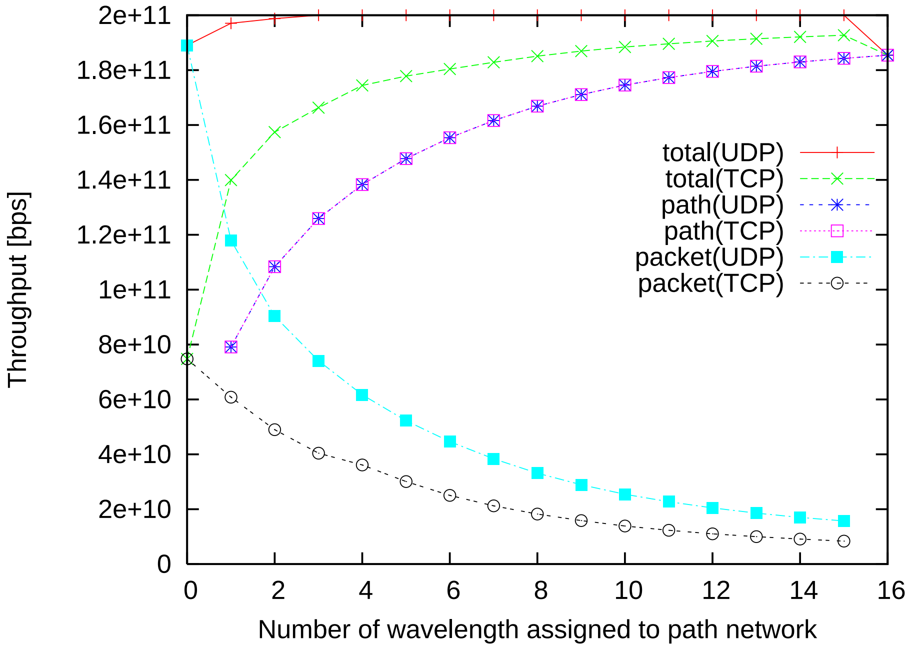
In Figure 12, the throughputs and the loss rates of integrated networks with settings as follows. The request arrival rate is 200 requests per second, the OXC configuration delay is set to 20 ms and the average data size is 1 Gbytes. Thus, the average holding time of a lightpath in path network is 100 ms.

In Figure 12(a) shows the throughputs in the standard case. The throughput of the network with TCP connections inferior to that of the network with UDP connections because of congestion control mechanism. Therefore, the packet loss rate is under 1e-06 in all area shown by Figure 12(b). The packet loss rate of the network with UDP connections is high under 0 or 2 wavelengths are assigned to path network because the traffic through bottleneck links exceeds the capacity and there is no congestion control mechanism. At the view of the time require for transmission of all data, low throughput and high loss rate with re-transmission lead to lengthen the time.

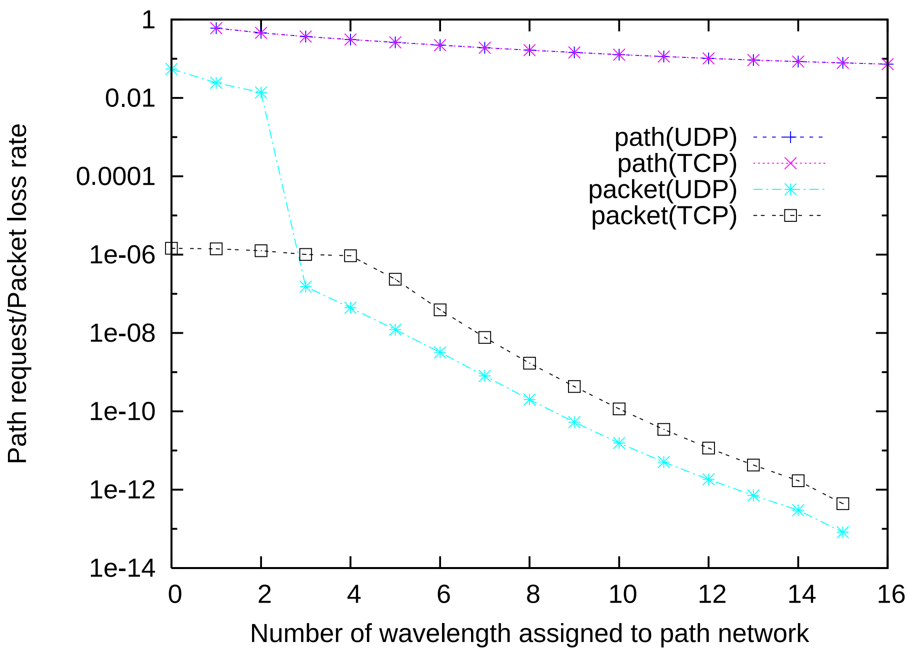
In Figure 13, the request arrival rate increased to 400 requests per second from standard case. Thus, Figure 13 shows us the results of high arrival rate case. In this case, the loss rate of UDP network keeps high rate over all range because path network drops much of traffic, and the arrival rate for packet networks is also high. On the other hand, the loss rate of TCP network keeps low level because of congestion control mechanism. Therefore, compared with the throughput of UDP network, that of TCP network is stable against difference of number of wavelength. That means it is ineffective to assign many wavelengths to a packet network with TCP connections in high arrival rate case.

Compaired with the case the request arrival rate is 200 the throughtputs of path network are influenced by the change of the request arrival rate. However, the throughputs of packet networks are not so high because the path network works as a buffer agent.

The performance of path network is dominated by OXC configuration delay. Figure 14 shows the a high OXC configuration delay case which set to 200ms. The other parameters are same with standard case. In this case, the performance of path network is low, and hence, the request arrival

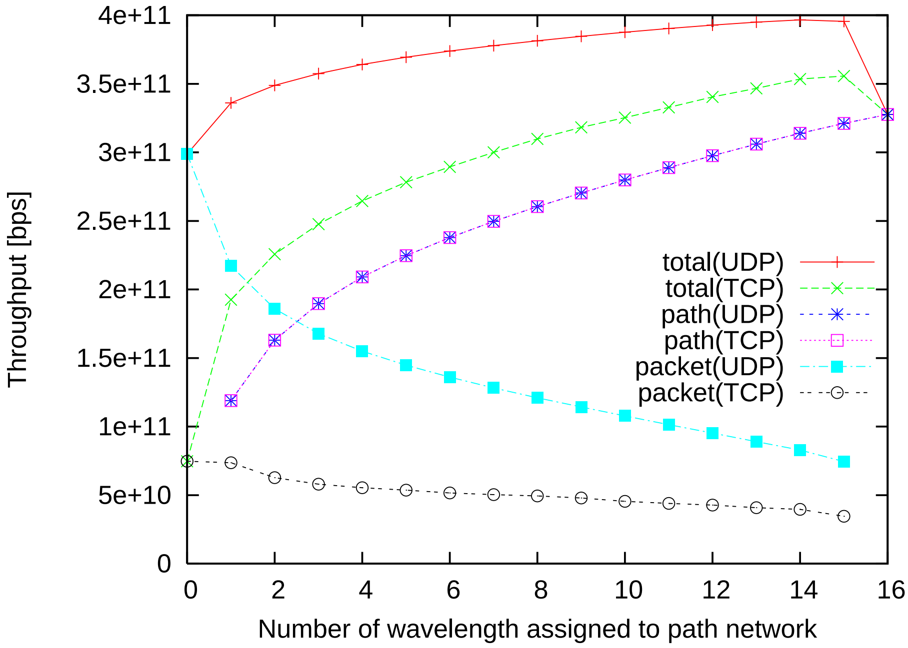


(a) Throughput

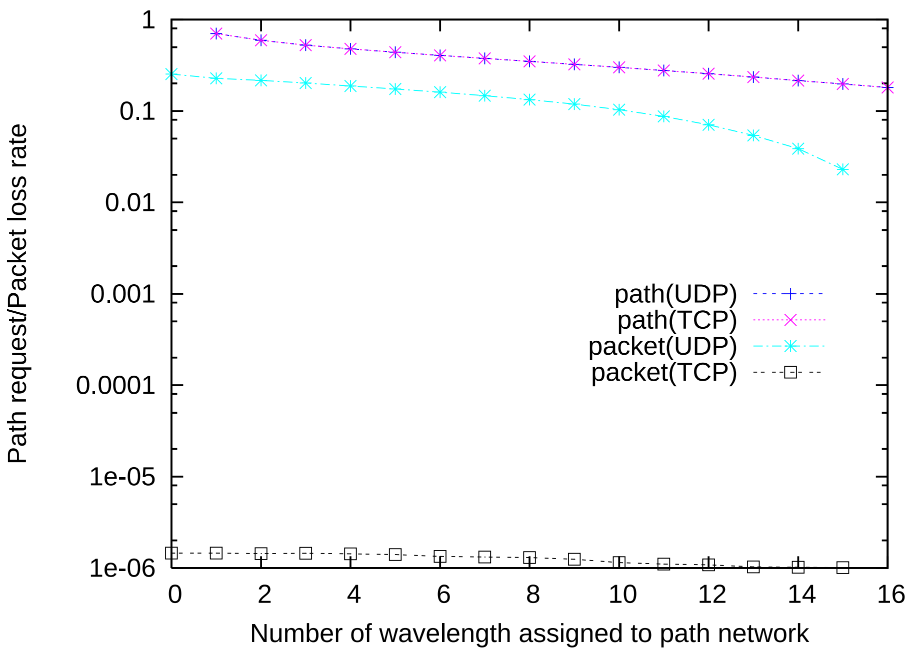


(b) Loss rate

Figure 12: Throughput and loss rate of integrated networks (Request arrival rate: 200 request / sec, OXC configuration delay: 20 ms, holding time: 0.1 sec)



(a) Throughput

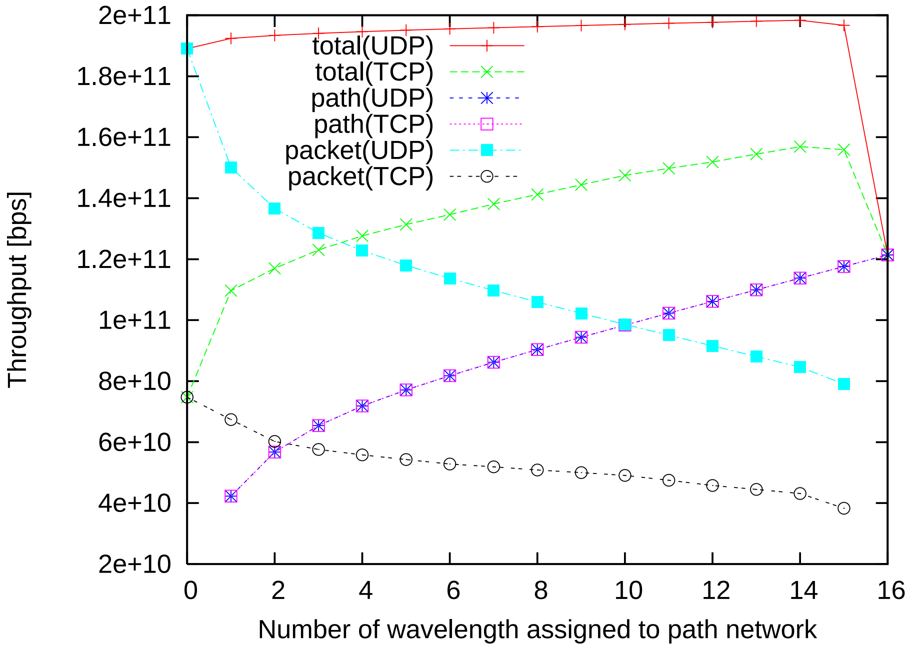


(b) Loss rate

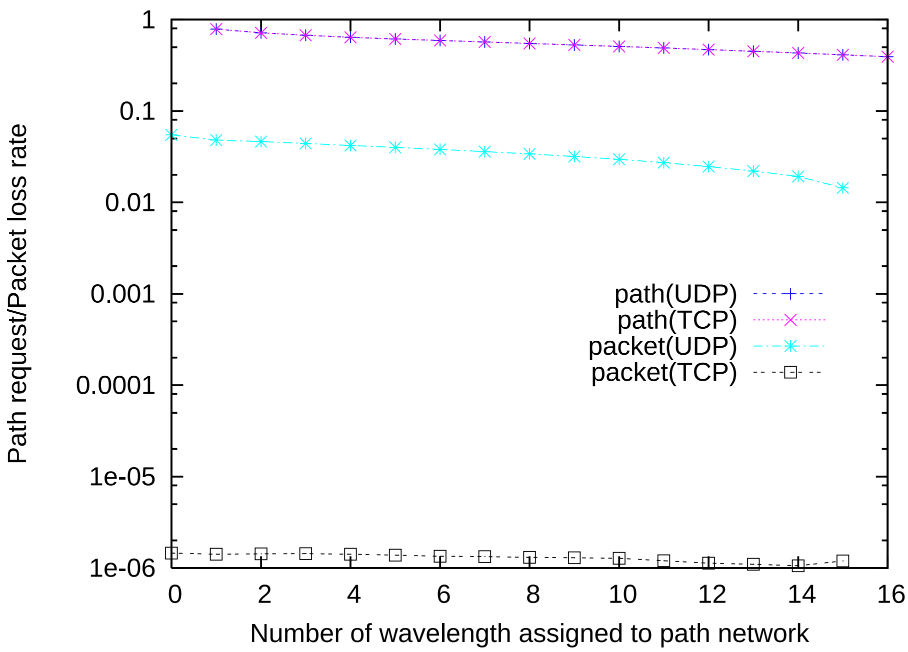
Figure 13: Throughput and loss rate of integrated networks (Request arrival rate: 400 request/sec, OXC configuration delay: 20 ms, holding time: 100 ms)

rate to packet network is high.

The path network cannot bring out the merits with transfering small data because the loss with lightpath setup delay become larger than the case transfering large data relatively. Figure 15 shows the performance of each network in the case which the data size is small which set to half of standard case. In this case, the performance of path network is lower than standard case and that of packet networks crossly increase. However, the step of increasing or decreasing throughput as wavelength is almost same as that in the standard case. Therefore, the pattern of results is steady.

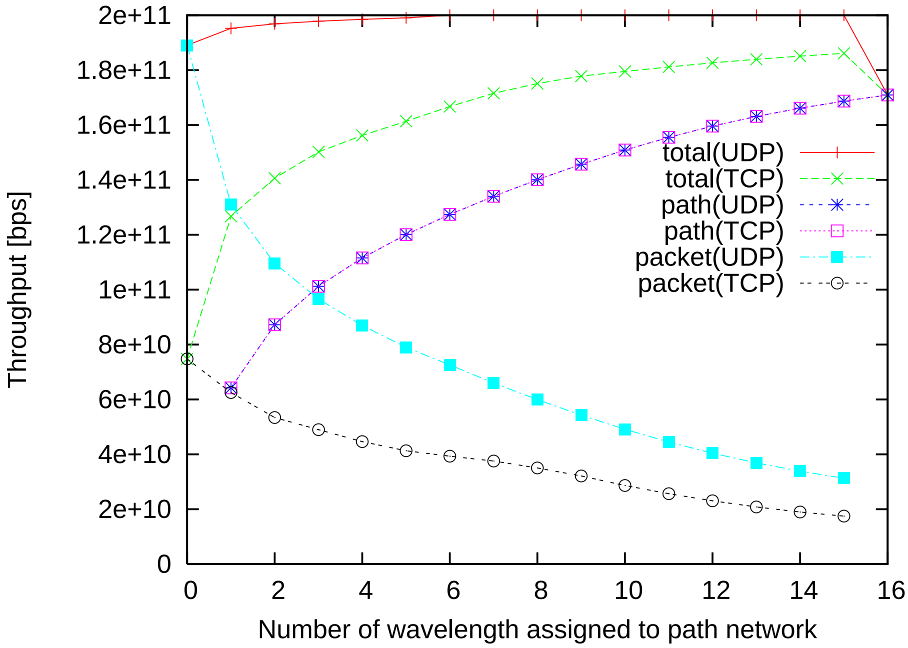


(a) Throughput

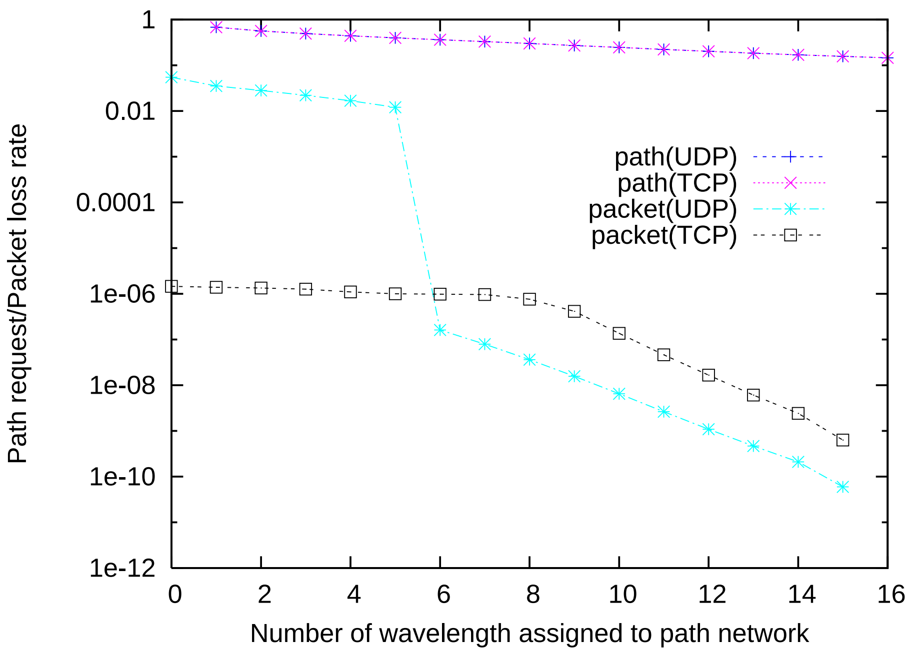


(b) Loss rate

Figure 14: Throughput and loss rate of integrated networks (Request arrival rate: 200 request/sec, OXC configuration delay: 200 ms, holding time: 100 ms)



(a) Throughput



(b) Loss rate

Figure 15: Throughput and loss rate of integrated networks (Request arrival rate: 200 request/sec, OXC configuration delay: 20 ms, holding time: 50 ms

5 Conclusion

One approach to utilize WDM networks effectively is to utilize WDM networks as packet switched networks because IP over WDM has good compatibility with the Internet. However, applications requiring high reliability and large bandwidth such as grid services or digital cinemas become available recently. On the other hand, path network can fulfill this. Though the drawbacks of this approach is lightpath setup delay. To correspond to diversity of traffic pattern in recent years, it is a solution to integrate packet networks and path networks. It is easy to integrate packet and path switched networks by using WDM technology.

We have developed an approximation analysis method for optical packet / path integrated networks. We consider the network as first transmission tried through path network and sends data through packet network if the first trial is failed. Our approximation analysis method is consists of approximation analysis of path network and that of packet network. The approximation analysis method of path network is the method introduced in [14]. The approximation analysis method of packet network is based on M/M/1/K queuing system and iterative calculation.

We evaluate the accuracy of our approximation analysis method by comparing with computer simulations. As a result, the difference between the results of our approximation analysis and that of computer simulation is small.

We then evaluate the throughputs and data loss rates of packet / path integrated network by our approximation analysis method. The results show that the greater the wavelengths assigned to path network, the greater the total throughputs of integrated networks. However, the total throughputs of integrated networks decrease when all wavelengths are assigned to path networks because there is no support of packet networks. It is also revealed that the throughputs of packet networks are not so high when the data transfer request arrival rate is high, because the path network works as a buffer agent.

Acknowledgements

I would like to express my sincere appreciation and great respect to Professor Masayuki Murata of Osaka University, who was my supervisor and has given me tremendous advice and inspiration throughout my studies and in the preparation of this thesis.

All works of this thesis would not have been possible without the support of Assistant Professor Shin'ichi Arakawa of Osaka University. He has always provided me with appropriate guidance and invaluable advice. I am also indebted to Associate Professor Naoki Wakamiya who have given me helpful advice and support.

Finally, I thank Yuki Koizumi, Yuichi Kiri, Yusuke Sakumoto and many other friends and colleagues in the Department of Information Science and Technology of Osaka University for their support.

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