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Wavelength Sharing Optimization for Integrated Optical Path and Optical Packet Switch

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ABSTRACT

In this paper, we address the issue of how to improve performance of integrated optical path and optical packet. For supporting ultra-high-speed traffic, integration of optical paths and packets in a switch is one of key techniques in New Generation Networks. However, the wavelength allocation for optical packets and optical paths has not been efficiently resolved yet because there lacks of a systematic model for evaluating performance of the integrated switch. This paper models the operation of the integrated switch as a system of two servers, one for optical paths and the other for optical packets. From the model, we utilize Newton method to find an optimal policy for sharing of wavelength resources. Afterwards, we propose an algorithm to dynamically allocate wavelength resources in an integrated switch. Finally, we evaluate performance of that algorithm.

Key words: Multiplexing, Queueing Theory, Optical Path, Optical Packet

1. INTRODUCTION

In recent times, the traffic of transmitting real-time images and videos is dominating internet traffic. Thus, the requirement of bandwidth is higher and higher. For example, let consider IPTV service, a key market driver for the next generation network service. A file containing one-hour-long uncompressed HDTV movie is about 675GByte. To transmit this file within about 1 minute, it requires 100GBps bandwidth. The optical network seems to be the most promising candidate to realize ultra-high-speed networks. The optical circuit switching (OCS) is usually used in optical networks. However, a pure OCS-based network has one critical drawback in their performance when the variance of file sizes transferred in a network is very large, which situation is very common to the Internet. In addition, it is well-known that circuit switching has low performance because it could not support many users simultaneously. On the other hand, packet switching has been indicated that more suitable for the Internet when compare with circuit switching. In traditional optical networks, although the packets are optical signals on the transmission channel, conversion processing is performed at the nodes to temporarily convert ar-

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riving optical signals to electrical signals. When the packets are placed on the next transmission channel, they are converted to optical signals again (O→E→O). This conversion leads to high cost and low performance. Recently, a new technical, namely optical packet switching (OPS), has been proposed to improve packet switching in optical networks. With OPS, the optical signals on the transmission channel are not converted to electrical signals at the nodes. Conversion processing is performed at the optical level as packets, which are placed on the next transmission channel (O→O→O).

The difference between packets and paths in optical networks just is the difference in means of providing information to end users. It is wasteful from the standpoint of service providers and telecommunication carriers, if each of these methods has separate control media and data transfer media. Hence, in order to resolve those problems, in these works, we propose to co-install an OPS with OCS. Integration of OCS and OPS has been considered in New Generation Network [1]. With this mechanism, wavelength resources are shared by two switching techniques. Because there is lack of a systematic model for operation of an integrated switch, wavelength resources are allocated for OCS and OPS based on fraction of each traffic demand [1]. However this static mechanism may not work well as shown in simulation result of this paper. Moreover, internet traffic typically varies. It is required to have a protocol to deal with changes of traffic. In this paper, we investigate the performance of integrated optical paths and optical packets. Similar to [2], [3], we estimate the average response time of transferring a file through an optical link to evaluate the performance. From the performance result, we optimize sharing mechanism of wavelengths between OCS and OPS. The paper is organized as follows:

- We refer to queueing theory in order to propose a systematic model for integrated path and packet switch in Section 2.
- From the mathematical model, we use Newton method to find an optimal policy for wavelength allocation. Afterwards, we will propose an algorithm in Section 3 to dynamically allocate wavelength resources to OCS and OPS.
- Section 4 analyzes performance of our algorithm. Simulation results will show that the operation of dynamic wavelength allocation can significantly outperform other methods.

2. PROBLEM FORMULATION

2.1 Operation of integrated optical path and optical packet switch

There are several integrated optical switch models. Figure 1 shows an active wavelength sharing of a switch. The detail of the switch operation is presented in [1]. In this mechanism, the wavelength bands entered from the fiber, which are presumed to be adjacent, are divided by the tunable long-pass filter, which determines changeable boundaries for wavelengths for many-wavelength packets and for OCS. λ_0 is assigned as the label for many-wavelength packets, and λ_1 to λ_W are used for OCS. The number of wavelengths used for OCS, W, is obtained from the upper limit for the number of ports in the optical switch. If some of λ_1 to λ_W wavelengths are not used by OCS, they are reused by incorporated in the payload part of many-wavelength packets even if they are between λ_1 and λ_W .

2.2. Mathematical Model

Let's consider a scenario in which number of flows share a common bottleneck which is an optical link as shown in Figure 2. To multiplex multiple flows in the common link, we utilize an integrated switch has m wavelengths, x are used for OCS and y for OPS, so $x+y=m$. Assume that each wavelength has capacity of c (Mbps). The traffic arriving in the integrated switch is classified by fiber

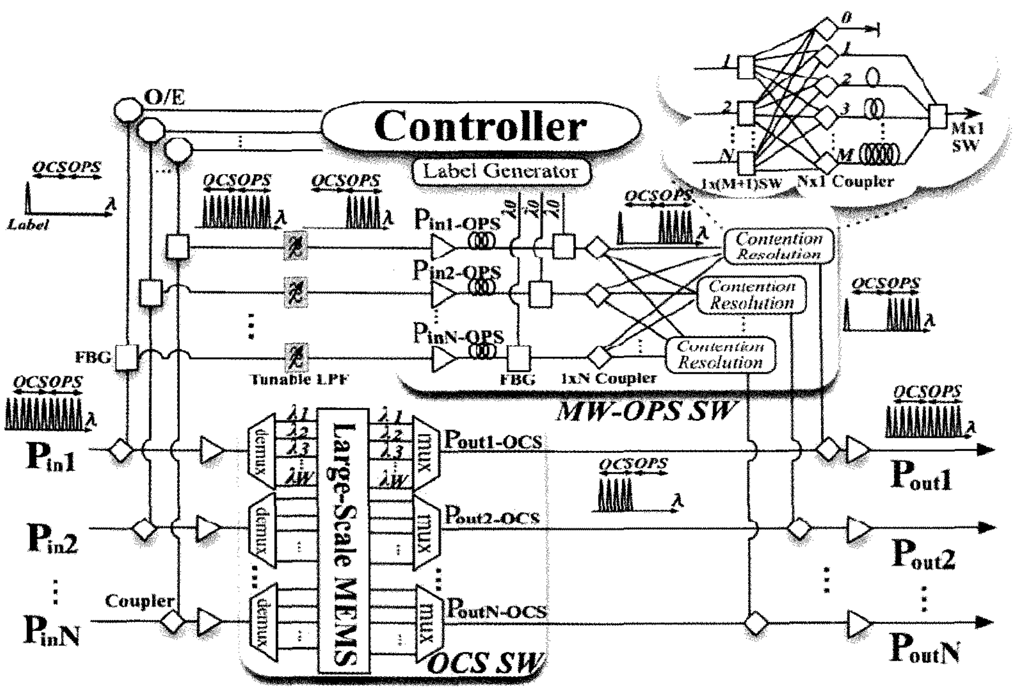

Fig. 1. Example of the Internal Configuration of an Integrated Packet and Path Node [1, Fig. 5.1.3.3.]

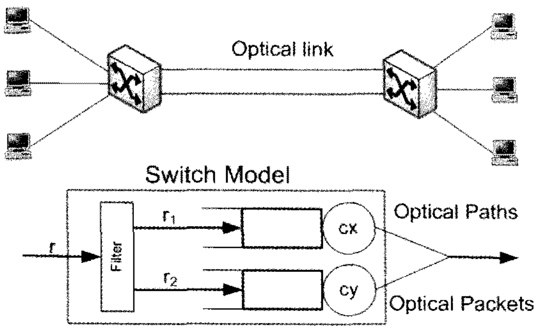

Fig. 2. Queuing Model

bragg grating (FBG), which is represented by a filter in the queueing model, into two kinds of traffics: optical paths (circuit switching) and optical packets (packet switching). It is said [4], [5] that circuit switching is more suitable for traffic that has long flow length while packet switching is more appropriate for traffic that has short flow length. Moreover, Shioda et al. pointed out circuit switching outperforms packet switching if the coefficient of variation of file size is smaller than 1. By contrast, packet switching is better if the coefficient is greater than 1. So by using FBG, we can direct traffic to a suitable switching technique. In this integrated switch, optical paths serve high quality multimedia traffic while optical packets serve other traffics such as data and low quality multimedia. Accordingly, OCS and OPS represent as two servers with capacity of cx and cy respectively in the queueing model.

To simplify the analysis, let us suppose that the optical path traffic follows a Poisson arrival process with mean rate r_1 (number of entering flows/s). Each arrival is a requirement of transferring a file which has length of L_1. This traffic assumption is popularly used for network traffic in [2], [3]. To model OCS, we assume that the server takes one job at a time and serves each job to completion, at rate cx, before moving onto the next. Hence, the queueing model for optical path traffic is M/G/1 [4], [5]. There are two popular service disciplines: First Come First Serve (FCFS) and Shortest Job First (SJF). It is said [3], [4] that SJF has the smallest average response time among all nonpreemptive policies in an M/G/1 system, and so SJF represents the best-case performance for optical path policies. However, SJF requires knowledge of the amount of work required for each job. In this context, it means the integrated switch would need to know the duration of a flow before it starts, which is information not available in practice. Therefore, we consider FCFS as a simpler and more practical service discipline, since it only requires a queue to remember the arrival order of the flows. The average response time for M/G/1/FCFS is [5, p. 16]:

$$E(T_{CS}) = \frac{E(L_1)}{cx} + \frac{r_1 E(L_1^2)}{2(1-\rho_1)c^2x^2} \tag{1}$$

where T_{CS} is the response time in OCS, $\rho_1 = \frac{r_1 E(L_1)}{cx}$ is the optical path system load, and $E(.)$ denotes the average. This average response time includes two factors, one is the average processing time and the other is the average waiting time of a file. In the operation of integrated switch, if some optical path wavelength is idle, it can be used for OPS. Optical packet traffic is divided into small packets, so it does not take time to switch wavelength from OCS to OPS and vice versa. Consequently, the switching process does not affect M/G/1 model in OCS. Let σ be the fraction of path wavelengths reinforcing OPS. Because ρ_1 is also optical path utilization fraction, the $1-\rho_1$ the probability that optical paths are idle, then the capacity reinforced from OCS to OPS is $[\sigma(1-\rho_1)x]c$. Thus, the total capacity of OPS is $[\sigma(1-\rho_1)x+y]c$. Clearly, this operation can take full capacity of optical wavelength resources, then it can improve network performance.

$$E(T_{PS}) = \frac{E(L_2)}{[\sigma(1-\rho_1)x+y]c} + \frac{\rho_2 E(L_2)}{(1-\rho_2)[\sigma(1-\rho_1)x+y]c} \tag{2}$$

The optical packet traffic is a sequence of jobs, each represents the processing of a flow. For OPS, we use processor sharing (PrS) model [6] and so all jobs share the bottleneck link equally, and each makes progress at rate $\frac{[\sigma(1-\rho_1)x+y]c}{k}$, where k is the number of active flows. We presume number of flows also has Poisson distribution with mean rate r_2. Each flow is divided into small packets. The queueing model for optical packet traffic is assume to be M/G/1/PrS system [4-6]. The average response time is [6, p. 278]:
where T_{PS} is the response time in OPS, L_2 is a random variable representing length of a flow, and $\rho_2 = \frac{r_2 E(L_2)}{[\sigma(1-\rho_1)x+y]c}$ is the optical packet system load. Surprisedly, the result of average response time is the same as [7], [8] where M/M/1 queueing model is used for package switching. Similar to OCS, the first factor is the average processing time, and the last factor is the average waiting time.

Because all optical path traffic and optical packet traffic have Poisson distribution of arrival rates, then the aggregate traffic also has Poisson distribution with arrival rate of $r = r_1 + r_2$. From (1) and (2), the average response time for the integrated switch is:

$$E(T) = \frac{r_1}{r}E(T_{CS}) + \frac{r_2}{r}E(T_{PS}). \tag{3}$$

It is well known [4] that if system load is not less than 1 then response time will be infinity. So it is required that

$$\rho_1 < 1,$$
$$\rho_2 < 1.$$

Therefore, we find an optimal sharing point to minimize average response time as follows:

Minimize $E(T)$
Subject to $x+y=m$

$$\rho_1 = \frac{r_1 E(L_1)}{cx} < 1$$
$$\rho_2 = \frac{r_2 E(L_2)}{[\sigma(1-\rho_1)x+y]c} < 1 \tag{4}$$

Because $E(L_1^2) = E^2(L_1) + Var(L_1)$, where $Var(.)$ denotes variation, from (3), we have $E(T) = f(x)$, in which

$$f(x)=\frac{r_1}{r}\left\{\frac{E^2(L_1)-Var(L_1)}{2E(L_1)cx}+\frac{E^2(L_1)+Var(L_1)}{2E(L_1)[cx-r_1E(L_1)]}\right\}+\frac{r_2}{r}\frac{E(L_2)}{mc-r_1\sigma E(L_1)-r_2E(L_2)-(1-\sigma)cx} \tag{5}$$

So the problem (4) becomes minimization of $f(x)$ with respect to only one variable x. Note that x is an integer and $1\le x\le m-1$, then we can use the following two steps to achieve the optimal solution:

Step 1: Using Newton iterative [9] to find the continuous optima

$$\bar{x}(t+1)=[\bar{x}(t)-\frac{f'(\bar{x}(t))}{f''(\bar{x}(t))}]^1_{(m-1)} \tag{6}$$

where $[\cdot]^1_{(m-1)}$ is the projection on $[1,m-1]$. This iterative can generate the continuous optima $\bar{x}^*$.

Step 2: Choosing one of two integers as the integer optima

$$x^*=\begin{cases}\lfloor\bar{x}^*\rfloor, & If\ f(\lfloor\bar{x}^*\rfloor)<f(\lceil\bar{x}^*\rceil)\\ \lceil\bar{x}^*\rceil, & otherwise\end{cases} \tag{7}$$

where $\lfloor\cdot\rfloor$ and $\lceil\cdot\rceil$ denote the lower integer and upper integer of a continuous variable respectively.

Table 1. Notation summary

Symbol	Description
m	Number of wavelengths of the integrated switch
c (Mbps)	Capacity of each wavelength
x	Number of wavelengths for optical paths
y	Number of wavelengths for optical packets
$E(.)$	The average
r_1(flows/s)	Arrival optical path rate
r_2(flows/s)	Arrival optical packet rate
ρ_1	Optical path system load
ρ_2	Optical packet system load
L_1(MB)	Length of optical path flow
L_2(MB)	Length of optical packet flow
σ	Fraction of path wavelengths reinforcing optical packets
T(s)	Overall response time
T_{CS}(s)	Response time of optical paths
T_{PS}(s)	Response time of optical packets

3. DYNAMIC WAVELENGTH ALLOCATION ALGORITHM

We will discuss how to implement the above two steps in the integrated switch. From (5), we need to know some parameters such as number of wavelengths m, capacity of each wavelength c, and traffic statistics such as average traffic rates r_1 and r_2, average flow lengths $E(L_1)$ and $E(L_2)$, and $Var(L_1)$ to implement the process of two steps (6) and (7). m and c are local parameters in the integrated switch. Although traffic statistics are not local information, they can be measured by observing traffic that arrives in the switch. In practice, traffic may vary in time. Thus, we need to update traffic statistics frequently and dynamically allocate wavelengths according to changes of traffic.

In this paper, we use a popular method, namely exponential moving average, to handle changes of traffic statistics. For example, we need to monitor a parameter Z. At a slot time t, the observed data for Z is Z_t . The previous exponential moving average of Z is $E_{t-1}(Z)$. Let N be the monitor window, i.e., we have the exponential moving average of Z at slot time t is

$$E_t(Z)=\frac{(N-1)E_{t-1}(Z)+Z_t}{N}.$$

The exponential moving averages of traffic statistics are used to computer function $f(x)$, derivative $f'(x)$, and hessian $f''(x)$ in (5) and (6). And then we develop the algorithm in Table 2 to dynamically allocate wavelengths for traffic demand of OCS and OPS. In this algorithm, the integrated switch observes traffic input and estimate moving

Table 2. Dynamic wavelength allocation algorithm

Input: Traffic statistics; m; c

$E_t(L_1) \Leftarrow \frac{(N-1)E_{t-1}(L_1)+L_{1t}}{N};$

$E_t(L_2) \Leftarrow \frac{(N-1)E_{t-1}(L_2)+L_{2t}}{N};$

$E_t(r_1) \Leftarrow \frac{(N-1)E_{t-1}(r_1)+r_{1t}}{N};$

5: $E_t(r_2) \Leftarrow \frac{(N-1)E_{t-1}(r_2)+r_{2t}}{N};$

$E_t(r) \Leftarrow E_t(r_1)+E_t(r_2);$

$Var_t(L_1) \Leftarrow \frac{(N-1)Var_{t-1}(L_1)+Var_tL_1}{N};$

while $|f'(\bar{x})| > \delta$ do

$\bar{x} \Leftarrow \bar{x} - \frac{f'(\bar{x})}{f''(\bar{x})};$

10: end while

if $f(\lfloor \bar{x} \rfloor) < f(\lceil \bar{x} \rceil)$ then

$x^* \Leftarrow \lfloor \bar{x} \rfloor;$

else

$x^* \Leftarrow \lceil \bar{x} \rceil;$

15: end if

$y^* \Leftarrow m - x^*;$

Output: x^* and y^*;

average of traffic statistics in each duty cycle (lines 1-7). Afterward, the switch optimally allocate wavelengths for each kind of traffic such that the average response time is minimized by using Newton method (lines 8-15).

4. NUMERICAL ANALYSIS

Let's analyze the performance of our proposed algorithm. Our network scheme is shown in Figure 2. Assume that the optical link has 100 wavelengths, each has capacity of 10GBps. The optical path traffic has average flow length of 1GB and variance of $(250MB)^2$. Clearly, the coefficient of variation of this traffic is $\frac{1}{4}$, then this traffic should be served by optical paths. The optical packets serve a long-tailed traffic that has average flow length of 1MB and variance of $(10MB)^2$. Aggregate throughput of the integrated switch is

$$\Theta = r_1L_1 + r_2L_2.$$

And the system load of the integrated switch is

$$\rho = \frac{\Theta}{mc}.$$

In this simulation, the system load is assumed to be 0.3. The fraction of optical path is

$$\eta_1 = \frac{r_1L_1}{\Theta}.$$

Let's consider some kinds of traffic, each has fraction of optical path 1%, 5%, 10%, 20%, 30%, 90%, 95%, and 99% respectively. Figure 3 shows the dependence of response time on how many wavelengths are used for OCS. For each kind of traffic, there exists an optimal number of wavelengths, which are allocated for OCS, minimizing response time. We can employ the algorithm in Table 2 to find the optima.

To evaluate the algorithm, we show its convergence to the optima in Figure 4. As shown, the optima is achieved very fast, in several steps. When there is some change in traffic, for example, he fraction of optical path traffic changes, our algorithm can dynamically allocate number of wavelengths for optical paths within several steps according to the change of traffic. This simulation result shows that to optimize response time, the fraction of wavelengths allocated to optical paths

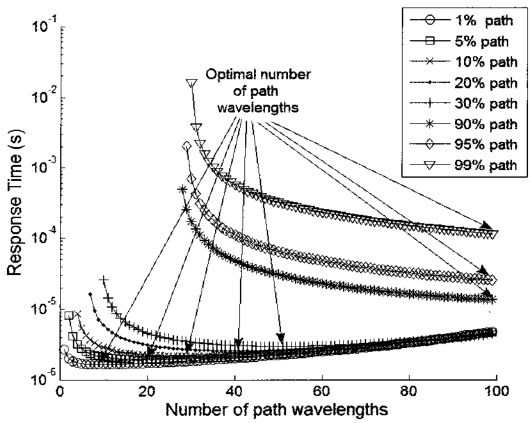

Fig. 3. Response time vs. Number of path wavelengths.

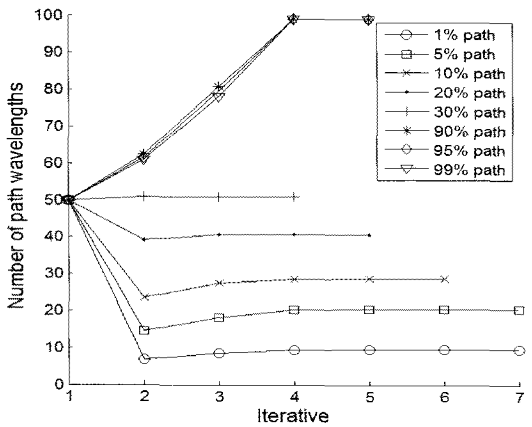

Fig. 4. Convergence of the algorithm.

should not equal to fraction of optical path traffic.

We can find an optimal policy for sharing of wavelength resources to minimize response time. On the other hand, for each number of path wavelengths, we can also determine maximal link utilization of the integrated switch such that the response time is kept under a given value. Figure 5 shows the relationship between the maximal link utilization of the integrated switch and number of path wavelengths with assumption that the limited response time is 10ms, 1ms, and 0.1ms respectively. If an offered traffic exceeds the maximal link utilization, the response time constraint is violated. For example, when the limited response time value is 0.1ms and the number of path wavelengths is 60, if the arrival traffic is 900 GBps, which is *smaller than maximal link utilization*, we can guarantee that the response time will be less than 0.1ms. By contrast, if the arrival traffic is 1000GBps, the average response time is over 0.1ms.

Because our protocol always works in the optimal point, we can achieve a smaller response time than other methods in Figure 6. In this simulation, we compare our dynamic wavelength allocation in an integrated switch with three other schemes: an integrated switch with static wavelength allocation, a switch with only optical paths, and a switch with only optical packets. In static wavelength allocation scheme, wavelength resources are allocated for OCS and OPS based on long-term traffic statistics. So the number of wavelengths allocated for OCS in static scheme is

$$x_S = [\frac{r_1 L_1}{\Theta}].$$

This mechanism cannot adapt its operation when there are changes in traffic demand which usually happens in practice. There is another scheme which is similar to static wavelength allocation. In [2], the authors use integrated optical

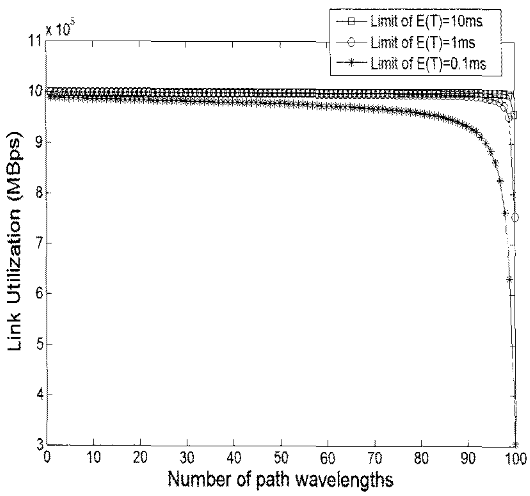

Fig. 5. Link utilization vs. Number of path wavelengths.

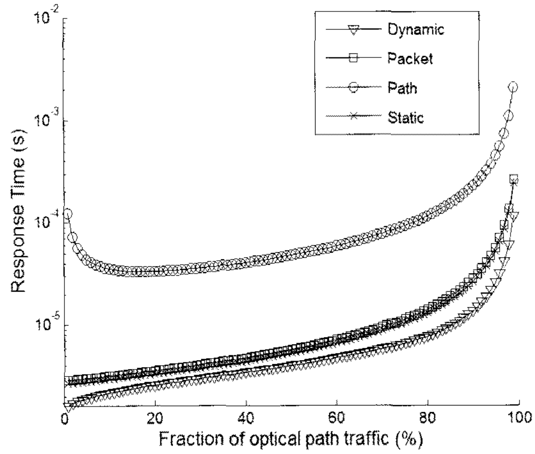

Fig. 6. Comparison of dynamic wavelength allocation and other methods.

path and electrical packet networks. However, capacity of electrical network is much lower than optical networks. Therefore, this scheme is not suitable in a scenario in which fraction of long-tailed traffic is high. Figure 6 shows that optical path has the worst performance among four protocols. In case of the switch with only optical paths, this switch is suitable for optical path traffic. Therefore, firstly, when the fraction of optical path traffic is increased, the response time is decreased. However, if we continue increasing optical path traffic fraction, the average flow length is increased significantly that leads to the average response time increasing. The integrated switch with static wavelength allocation outperforms both optical paths and optical packets because it can take full advantage of both two kinds of switching methods it uses appropriate switching technique for each kind of traffic, i.e., optical paths for long flow and low variation coefficient and optical packets for long-tailed traffic. And our protocol outperforms static scheme because it works in optimal point, and it can temporarily use idle optical path wavelength to intensify optical packets.

5. CONCLUSION

This paper inquires into operation of an integrated optical path and optical packet switch. We use queueing theory with two serves to model the integrated switch, one for optical paths and the other for optical packets, and combine with utilizing the Newton method to find an optimal policy for sharing of wavelength resources. And then, we propose an algorithm to dynamically allocate wavelength resources for the integrated switch. The simulation shows that our protocol outperforms other methods. Accordingly, the performance of the integrated switch is improved.

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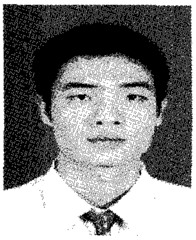

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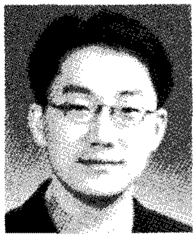

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