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A latency-aware scheduling algorithm for all-optical packet switching networks with FDL buffers

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Abstract Optical buffers implemented by fiber delay lines (FDLs) have a volatile nature due to signal loss and noise accumulation. Packets suffer from excessive recirculation through FDLs, and they may be dropped eventually in their routing paths. Because of this, packet scheduling becomes more difficult in FDL buffers than in RAM buffers, and requires additional design considerations for reducing packet loss. We propose a latency-aware scheduling scheme and an analytical model for all-optical packet switching networks with FDL buffers. The latency-aware scheduling scheme is intended to minimize the packet loss rate of the networks by ranking packets in the optimal balance between latency and residual distance. The analytical model is based on non-homogeneous Markovian analysis to study the effect of the proposed scheduling scheme on packet loss rate and average delay. Furthermore, our numerical results show how various network parameters affect the optimal balance. We demonstrate quantitatively how to achieve the proper balance between latency and residual distance so that the network performance can be improved significantly. For instance, we find that under a given latency limit and light traffic load our scheduling scheme achieves a packet loss rate 71% lower than a scheduling scheme that ranks packets simply based on latency.

Keywords Stochastic analysis · Multi-hop packet scheduling · Optical packet switching · Optical buffering · Fiber delay line buffers

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1 Introduction

All-optical packet switching is a promising scheme to meet high-capacity data transmission and avoid the bottleneck of optical-electrical-optical conversion. For all-optical packet switching, optical buffering implemented by fiber delay lines (FDLs) [2,6–9,11–14,17,19,20,24–26,28,29] is a solution to the output contention problem. Optical packets can be recirculated in FDLs to avoid output contention. Many optical switches with FDL buffers have been presented and their performances have been analyzed. Some proposed output buffer switches with FDL buffers [6,7,11,14]. Some proposed shared buffer switches with FDL buffers [12,19,20, 28,29], and some proposed hybrid buffer switches with FDL buffers [9,8]. They mainly focus on analyzing and reducing packet loss due to buffer overflow.

However, optical buffering implemented by FDLs has a volatile nature because of signal loss and noise accumulation from optical components of FDL buffers. As pointed out by [3,10,18,23,27], crosstalk and noise from optical links, optical switches, FDLs, semiconductor optical amplifiers (SOAs), and erbium-doped fiber amplifiers (EDFAs) are the main sources inducing signal loss and noise accumulation. Optical packets that are excessively recirculated in FDL buffers may be eventually dropped due to serious signal loss as well as noise accumulation. The excessive recirculation problem adversely degrades the performance of all-optical packet switching networks with FDL buffers. Unfortunately, using a great number of regenerators in each optical packet switch to solve this problem is economically infeasible at the present time. Many research works have been presented on reducing the local delay induced by packet recirculation within a optical switch or multiplexer [2,4,5,10]; however, they ignored the effect of latency (accumulated delay) across several optical switches.

In this paper, we propose a latency-aware scheduling scheme to mitigate the excessive recirculation problem. The latency-aware scheduling scheme is a multi-hop packet scheduling scheme [1,21], and regards the latency and the residual distance of a packet as two key parameters in packet scheduling over optical switches. The relative weight of latency and residual distance is summarized in a relative-distance factor. We optimize the relative-distance factor to rank packets in the optimal balance between latency and residual distance for minimizing packet loss. Furthermore, we provide an analytical model to calculate the packet loss rate and average delay of all-optical packet switching networks with our scheduling scheme. The analytical model is based on non-homogeneous Markovian analysis [21,29], and it can also be an analytical framework for similar networks by modifying the conditions of packet loss and the two key parameters.

The rest of this paper is organized as follows. In Sect. 2, we give a detailed description of the network model and the latency-aware scheduling scheme. In Sect. 3, we provide the analytical model for all-optical packet switching networks with FDLs. In Sect. 4, we validate the analytical results and study how to achieve the optimal balance between latency and residual distance. Finally, we conclude our discussion in Sect. 5.

2 Latency-aware scheduling scheme

2.1 Priority function Π

The latency-aware scheduling scheme is based on a priority function for handling packets. The priority function, Π, comprises two parameters: L is the latency in hops for a packet to traverse; and R is the residual distance in hops from the current locations to the destination, and

$$\Pi(R, L) = \frac{L}{R^{\rho}} \tag{1}$$

L and R, in fact, are the two key quantities for scheduling packets using the latency-aware discipline. Each packet is associated with a priority value given by $\Pi(R, L)$, such that a bigger value of $\Pi(R, L)$ denotes a higher transmission and preemption priority, and the priority value is updated slot by slot in the following manner. In the beginning, L and R are initialized with an estimated latency and residual distance for a new packet, respectively. At each slot, L will be incremented by one and R will remain unchanged if the packet experiences a FDL recirculation, but R will be decremented by one if the packet departs. Moreover, a queued packet may be eventually dropped due to excessive recirculation. We assume a queued packet will be dropped if the sum of its residual distance and latency is greater than the latency limit, denoted $L_{\max}$, because it will never reach the destined node.

In the above formulation, ρ, referred to as the relative-distance factor, controls the relative importance of the two parameters. R outweighs L if ρ is greater than one, while L outweighs R if ρ is smaller than one. In this fashion, we can also use the priority function to differentiate packets of real-time applications from best-effort ones. For example, packets of strict timing requirement are initialized with higher values of L and they will be assigned a higher rank accordingly for the subsequent routing.

Furthermore, the priority function is a general class of priority functions including many basic scheduling schemes. For instance, longest-latency-first (LLF) scheme is similar to a special cases of (1) with $\rho = 0$, where the packet with the longest latency is given the highest priority; longest-distance-first (LDF) and shortest-distance-first (SDF) schemes are similar to special cases of (1) with $\rho = -\infty$ and $\rho = \infty$, respectively. We will use these basic scheduling schemes to investigate how to determine the proper value of ρ for minimizing the packet loss rate in Sect. 4.

2.2 Major elements of the latency-aware scheduling scheme

We are concerned with the latency-aware scheduling scheme with the following functional requirements:

1. Rank packets in the optimal balance between latency and residual distance;
2. Maintain a queue on the FDL buffer that conforms to the results calculated by the priority function; and
3. Schedule packets to leave the output port according to the ranking and without contention.

It is worth mentioning that scheduling packets in FDL buffers is rather different from its electronic counterpart in RAM buffers. This is due to the fact that FDL buffers can hold a packet only for a small period of time given by the designated delay line. The queued packet must be moved to the specified switch output right before the delay time elapses. Furthermore, FDL buffers have a volatile nature that a packet exists in the buffer for the specified time period because of signal loss and noise accumulation from optical components of FDL buffers. As a consequence of this, packet scheduling in FDL buffers requires additional design considerations for avoiding contention among packets destined for the same output at the same time.

3 Analytical model

In this section, we provide an analytical model to calculate the packet loss rate and average delay of all-optical packet switching networks with the latency-aware scheduling algorithm. The packet loss rate is defined as the probability that a packet is dropped in its routing path, and the average delay is defined as the expected value of the latency of a packet that is eventually transmitted to its destination. The analytical model is based on non-homogeneous Markovian analysis, and it can also be used on various scheduling schemes by replacing the priority function.

3.1 Network configuration

We consider an optical network constructed from synchronous photonic packet switches using FDL buffers. To make our analytical model tractable, we assume the optical network with homogeneous switches of N inputs and N outputs. Figure 1 shows an optical switch architecture for our study on packet scheduling.

The optical switch architecture is an output-buffer architecture. The output-buffered $N \times N$ switch is composed of N buffer-less switches of size $1 \times N$ and N output switches of size $(N + B) \times (B + 1)$. The buffer-less switches and the output switches are interconnected in a fully meshed manner, and the buffer-less switches make the lookup faster by photonic label lookup function [16] for the head of arriving packets. The output switch comprises a set of FDLs and a switching fabric as well as feedback connections. This is the place where packets are buffered and scheduled for departing the switch. Assuming B FDLs of equal length, the buffer size is equal to B and the switching fabric is of size $(N + B) \times (B + 1)$. The optical switch architecture makes the lookup faster and provides better throughput performance than input-buffer architecture because it does not suffer from head-of-line (HOL) blocking.

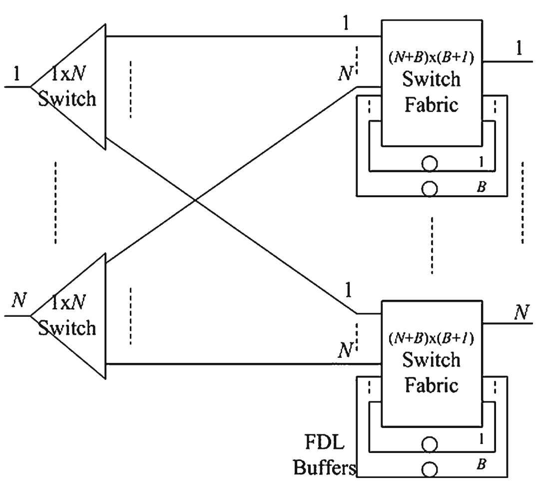

Fig. 1 An optical switch architecture for our study

3.2 Overview

Our analytical model considers an all-optical packet switching network with FDLs buffers in which a queued packet will be dropped if the sum of its residual distance and latency is greater than $L_{\max}$. Therefore, the model has additional considerations on the distributions of the latency and residual distance of queued and arriving packets. The model is based on the concept that these distributions are steady and in equilibrium. With this in mind, we construct a Markov chain model to calculate the packet loss rate and the average delay.

Let $P_{R_q,L_q}(r, l)$ be the steady state distribution of the latency and residual distance of a queued packet, and let $P_{R_q,L_q}(r, l)$ denote the one of the latency and residual distance of an arriving packet. Essentially, the Markov chain is a stochastic process with the Markov property, meaning that the next state depends only on the current state but not on any past states. According to the Markov property, we recursively update $P_{R_q,L_q}(r, l)$ and $P_{R_a,L_a}(r, l)$ until they converge, given their state transition probabilities. We list five main steps of our analytical model for easy to understand it:

1. Estimate a queue length distribution by a traditional queueing model, given an effective arrival rate;
2. Calculate state transition probabilities of $P_{R_q,L_q}(r, l)$ and $P_{R_a,L_a}(r, l)$, given the queue length distribution;
3. Update $P_{R_q,L_q}(r, l)$ and $P_{R_a,L_a}(r, l)$, given their state transition probabilities;
4. Recur to the second step until $P_{R_q,L_q}(r, l)$ and P_{R_a,L_a} (r, l) converge.
5. Calculate the packet loss rate and the average delay, given $P_{R_q,L_q}(r, l)$ and $P_{R_a,L_a}(r, l)$;

Furthermore, we are particularly interested in calculating the packet loss rate due to excessive recirculation, so we assume $B = \infty$ for simplifying the traditional queueing model. Through simulation, we find that the latency limit imposed by FDLs in fact plays a more important role in determining the packet loss rate than buffer overflow, if sufficient FDLs are provided. This will be verified in Sect. 4.3. Next, we present the details of these steps in the following subsections.

3.3 Queue length distribution

First of all, we estimate a queue length distribution, denoted $Q(n)$, for calculating state transition probabilities of P_{R_q,L_q} (r, l) and $P_{R_a,L_a}(r, l)$. We assume that new packets are generated independently at each queue with a generation rate, denoted λ_s, and each new packet is assigned an initial residual distance R_0 and latency L_0 with a general distribution, denoted $P_{R_0,L_0}(r, l)$. Since each node receives packets from its neighbor nodes and itself, we assume that the arrival process approximately forms a Poisson process with an overall arrival rate. Theoretically, the overall arrival rate per queue is

$$\lambda = \lambda_s + \lambda_s(E[R_0] - 1) \tag{2}$$

where $E[R_0]$ is the expected value of the initial residual distance of a new packet, and $\lambda_s(E[R_0] - 1)$ is the arrival rate from neighbor nodes.

However, a packet will be dropped if the sum of its residual distance and latency is greater than $L_{\max}$. Considering the effect of packet loss, we rewrite (2) to calculate the effective arrival rate, denoted λ_{eff}, and have

$$\lambda_{\text{eff}} = \lambda_s + \lambda_s(E[R_0] - 1 - P_{\text{loss}}E[R_{\text{loss}}]), \tag{3}$$

where P_{loss} is the packet loss rate and $E[R_{\text{loss}}]$ is the expected value of the residual distance of a dropped packet. The effective arrival rate from neighbor nodes is $\lambda_s(E[R_0] - 1 - P_{\text{loss}}E[R_{\text{loss}}])$. Thus, we can use an output queueing model from [15] with λ_{eff} to estimate $Q(n)$. The detail of the output queueing model is presented in Appendix A.

3.4 Updating $P_{Rq,Lq}(r, l)$

For updating $P_{R_q,L_q}(r, l)$, we need to calculate state transition probabilities of $P_{R_q,L_q}(r, l)$. The state transition probabilities depend on the transmission probabilities of a queued packet. Let $p_x(r, l)$ be the transmission probability of a queued packet with $\Pi(r, l)$. Thus, we have

$$p_x(r, l) = \frac{n_{x,\Pi(r,l)}}{n_{q,\Pi(r,l)}}. \tag{4}$$

$n_{x,\Pi(r,l)}$ is the expected number of departing packets with $\Pi(r, l)$ in a queue. Among the queued packets with $\Pi(r, l)$, a packet will be chosen to transmit from a queue at the current slot if the queue has no queued and arriving packets with a higher priority than $\Pi(r, l)$. Let $Pr_q(u_q)$ be the probability function that the queue has u_q queued packets with the same priority $\Pi(r, l)$ and no queued packet with a higher priority than $\Pi(r, l)$. Let $Pr_a(u_a)$ be the probability function that the queue has u_a arriving packets with the same priority $\Pi(r, l)$ and no arriving packet with a higher priority than $\Pi(r, l)$. We use $Pr_q(u_q)$ and $Pr_a(u_a)$ to compute $n_{x,\Pi(r,l)}$ by

$$\begin{aligned} n_{x,\Pi(r,l)} &= \sum_{u_q} Pr_q(u_q) \sum_{u_a} Pr_a(u_a) \\ Pr_q(u_q) &= \sum_{n=1}^{\infty} Q(n) \binom{n}{u_q} p_e(r, l)^{u_q} \\ &\quad (1 - p_g(r, l) - p_e(r, l))^{n-u_q} \\ Pr_a(u_a) &= \sum_{i=1}^{N} A(i) \binom{i}{u_a} p_{ae}(r, l)^{u_a} \\ &\quad (1 - p_{ag}(r, l) - p_{ae}(r, l))^{n-u_a}, \end{aligned} \tag{5}$$

where $u_a + u_q \geq 1$; $p_e(r, l)$ and $p_g(r, l)$ are the probabilities that a queued packet has a priority higher than $\Pi(r, l)$ and equal to $\Pi(r, l)$, and $p_{ae}(r, l)$ and $p_{ag}(r, l)$ are the probabilities that an arriving packet has a priority higher than $\Pi(r, l)$ and equal to $\Pi(r, l)$, respectively. They can be calculated by (6), given $P_{R_q,L_q}(r, l)$ and $P_{R_a,L_a}(r, l)$.

$$\begin{aligned} p_e(r, l) &= \sum_{\Pi(r',l')=\Pi(r,l)} P_{R_q,L_q}(r', l') \\ p_g(r, l) &= \sum_{\Pi(r',l')>\Pi(r,l)} P_{R_q,L_q}(r', l') \\ p_{ae}(r, l) &= \sum_{\Pi(r',l')=\Pi(r,l)} P_{R_a,L_a}(r', l') \\ p_{ag}(r, l) &= \sum_{\Pi(r',l')>\Pi(r,l)} P_{R_a,L_a}(r', l') \end{aligned} \tag{6}$$

$n_{q,\Pi(r,l)}$ is the expected number of queued packets with $\Pi(r, l)$ in a queue. For computing $n_{q,\Pi(r,l)}$, we consider how many queued and arriving packets with the same priority $\Pi(r, l)$ at the current slot. Let $Pr'_q(u_a)$ be the probability function that the queue has u_q queued packets with the same priority $\Pi(r, l)$ and $Pr'_a(u_a)$ be the probability function that the queue has u_a arriving packets with the same priority $\Pi(r, l)$. Thus, $n_{q,\Pi(r,l)}$ can be calculated by

$$\begin{aligned} n_{q,\Pi(r,l)} &= \sum_{u_q} Pr'_q(u) \sum_{u_a} Pr'_a(u_a)(u_q + u_a) \\ Pr'_a(u_a) &= \sum_{i=1}^{N} A(i) \binom{i}{u_a} p_{ae}(r, l)^{u_a} (1 - p_{ae}(r, l))^{n-u_a} \\ Pr'_q(u_q) &= \sum_{n=1}^{\infty} Q(n) \binom{n}{u_q} p_e(r, l)^{u_q} (1 - p_e(r, l))^{n-u_q}, \end{aligned} \tag{7}$$

where $u_a + u_q \geq 1$ and $A(i)$ is the probability that the number of arriving packets at the queue is i during a given slot. Finally, we compute $p_x(r, l)$ by (4), given $n_{q,\Pi(r,l)}$ and $n_{x,\Pi(r,l)}$.

The state transition probabilities of $P_{R_q,L_q}(r, l)$ include the three following cases: a queued packet departs, a queued packet is dropped, and a queued packet experiences a FDL recirculation. For a queued packet in state (r, l) where $L_{\max} - l > r \geq 1$, it will transit to state (r', l') where $(r', l') = (r, l + 1)$, with probability $1 - p_x(r, l)$, if it experiences a FDL recirculation. Correspondingly, it departs with probability $p_x(r, l)$. The rate of packet arriving a queue equals the rate of packets leaving the queue in equilibrium, so we simplify the case by assuming that a queued packet in state (r, l) departs with probability $p_x(r, l)$ and a packet arrives the queue with steady state distribution $P_{R_a,L_a}(r, l)$. Furthermore, when a queued packet in state (r, l) where $L_{\max} - l = r$, it will depart with probability $p_x(r, l)$ or be dropped with probability $1 - p_x(r, l)$. Thus, the state transition probabilities from $P_{R_q,L_q}(r, l)$ to $P_{R_q,L_q}(r', l')$ can be computed by

$$\begin{cases} 1 - p_x(r,l) + p_x(r,l)P_{R_a,L_a}(r',l') \\ \quad (\text{if } L_{\max} - l > r \geq 1 \text{ and } (r',l') = (r,l+1)) \\ p_x(r,l)P_{R_a,L_a}(r',l') \\ \quad (\text{if } L_{\max} - l > r \geq 1 \text{ and } (r',l') \neq (r,l+1)) \\ (1 - p_x(r,l))P_{R_a,L_a}(r',l') + p_x(r,l)P_{R_a,L_a}(r',l') \\ \quad (\text{if } L_{\max} - l = r). \end{cases} \tag{8}$$

Let P_q denote the vector version of $P_{R_q,L_q}(r,l)$, and let T_q be the transition probability matrix constructed from the state transition probabilities. According to the Markov property, we recursively update P_q by $P_q = P_q T_q$ until P_q converges. However, $P_{R_q,L_q}(r,l)$ depends on $P_{R_a,L_a}(r,l)$ as indicated in (8), so we need to recursively update $P_{R_q,L_q}(r,l)$ and $P_{R_a,L_a}(r,l)$ at the same time. In the next subsection, we will present how to recursively update $P_{R_a,L_a}(r,l)$.

3.5 Updating $P_{R_a,L_a}(r,l)$

Like updating $P_{R_q,L_q}(r,l)$, we calculate state transition probabilities of $P_{R_a,L_a}(r,l)$ for updating $P_{R_a,L_a}(r,l)$. The state transition probabilities depend on the departure probability that an arriving packet enters a queue and leaves it. Let $P_{d,\Pi(r,l)}(k)$ denote the departure probability that an arriving packet with $\Pi(r,l)$ is delayed for k slots in a queue and leaves it. $P_{d,\Pi(r,l)}(1)$ is equal to $p_x(r,l)$, because this situation occurs only when an arriving packet immediately leaves the queue without delay. $P_{d,\Pi(r,l)}(k)$ is equal to $[1 - \sum_{i=1}^{k-1} P_{d,\Pi(r,l)}(i)]p_x(r,l+k-1)$ for $L_{\max} - l - r \geq k \geq 2$, because this situation occurs only when the arriving packet is delayed for k slots and it departs eventually. Thus, we can compute $P_{d,\Pi(r,l)}(k)$ by

$$\begin{aligned} &P_{d,\Pi(r,l)}(1) = p_x(r,l) \\ &P_{d,\Pi(r,l)}(k) = [1 - \sum_{i=1}^{k-1} P_{d,\Pi(r,l)}(i)]p_x(r,l+k-1) \\ &P_{d,\Pi(r,l)}(\infty) = 1 - \sum_{i=1}^{L_{\max}-l-r+1} P_{d,\Pi(r,l)}(i), \end{aligned} \tag{9}$$

where $P_{d,\Pi(r,l)}(\infty)$ denotes the loss probability that an arriving packet with $\Pi(r,l)$ is eventually dropped in the queue.

There are the three cases of the state transition probabilities of $P_{R_a,L_a}(r,l)$: an arriving packet leaves the queue, an arriving packet arrives its destination, and an arriving packet is dropped. For an arriving packet in state (r,l), where $L_{\max} - l - r + 1 \geq k \geq 1$, it will transit to state (r',l') where $(r',l') = (r,l+k)$, with probability $P_{d,\Pi(r,l)}(k)$, if it is delayed for k slots and leaves the queue. Correspondingly, it is dropped with probability $P_{d,\Pi(r,l)}(\infty)$. In equilibrium, the rate of packet leaving the network equals the rate of new packets arriving the network. Therefore, we simplify the case by assuming that an arriving packet departs with probability $P_{d,\Pi(r,l)}(k)$ and a new packet arrives the queue with $P_{R_0,L_0}(r,l)$. Furthermore, when a arriving packet in state (r,l) where $r = 1$, it will leave the network, no matter no matter whether it arrive its destination or be dropped. Thus, the state transition probabilities from $P_{R_a,L_a}(r,l)$ to $P_{R_a,L_a}(r',l')$ can be computed by

$$\begin{cases} P_{d,\Pi(r,l)}(k) + P_{d,\Pi(r,l)}(\infty)P_{R_0,L_0}(r',l') \\ \quad (\text{if} L_{\max} - l - r + 1 \geq k \geq 1, \\ \quad (r',l') = (r-1,l+k) \text{ and } k = l' - l) \\ P_{d,\Pi(r,l)}(\infty)P_{R_0,L_0}(r',l') \\ \quad (\text{if } L_{\max} - l - r + 1 \geq k \geq 1 \text{and} r' \neq r-1) \\ P_{R_0,L_0}(r',l'). \\ \quad (\text{if } r = 1) \end{cases} \tag{10}$$

Let P_a denote the vector version of $P_{R_a,L_a}(r,l)$, and let T_a be the transition probability matrix. According to the Markov property, we recursively update P_a by $P_a = P_a T_a$ until P_a converges. In the next subsection, we will show how to recursively update P_a and P_q at the same time and calculate P_{loss}, R_{loss}, and the average delay, denoted L_s.

3.6 Computing P_{loss}, R_{loss}, and L_s

The previous two subsections have presented how to iteratively update P_a and P_q, respectively. In fact, P_a and P_q have a dependency on each other and they have to be updated at the same time. In this subsection, we present a computational method used to update P_a and P_q simultaneously. The computational method consists of the seven following steps:

- Step 1: Estimate $Q(n)$.
- Step 2: Compute $p_x(r,l)$.
- Step 3: Construct T_q.
- Step 4: Let $P_q = P_q T_q$.
- Step 5: Compute $P_{d,\Pi(r,l)}(k)$.
- Step 6: Construct T_a.
- Step 7: Let $P_a = P_a T_a$.
- Repeat from Step 2 until P_q and P_a converge.

In the computational method, we use $P_{R_0,L_0}(r,l)$ to initialize $P_{R_q,L_q}(r,l)$ and $P_{R_a,L_a}(r,l)$, respectively, and then calculate $p_x(r,l)$ for constructing T_q and T_a. P_q and P_a are updated by $P_q = P_q T_q$ and $P_a = P_a T_a$. Finally, we repeat these steps until P_q and P_a converge.

After P_a and P_a converge, we can calculate the packet loss rate by an absorbing Markov chain using the state transition probabilities of $P_{R_a,L_a}(r,l)$. Let $P_s(r,l)$ denote the steady state distribution of the latency and residual distance of a new packet. Since a new packet with an initial state (r_0,l_0) will reach the destination with a final state $(0,l)$ or be dropped in the routing path, the absorbing Markov chain has two types of absorbing states, $P_{\text{loss}}(r,l)$ and $P_s(0,l)$. $P_{\text{loss}}(r,l)$ is the packet loss probability that a new packet is dropped along the routing path with the final state (r, l), and $P_s(0, l)$ is the probability that a new packet arrives its destination with the final state $(0, l)$. Considering the two types of absorbing states, we modify (10) to (11) for the state transition probabilities from $P_s(r, l)$ to $P_s(r', l')$, $P_{loss}(r, l)$, or $P_s(0, l')$.

$$\begin{cases} P_{d,\Pi(r,l)}(k) \\ \quad (\text{if } L_{\max} - l - r + 1 \geq k \geq 1, \\ \quad (r', l') = (r-1, l+k) \text{ and } k = l' - l) \\ P_{d,\Pi(r,l)}(\infty) \\ \quad (\text{if } (r', l') \rightarrow \text{loss}) \\ 1 - P_{d,\Pi(r,l)}(\infty) \\ \quad (\text{if } r = 1 \text{and} (r', l') \rightarrow \text{success}). \end{cases} \tag{11}$$

Let P_s be the vector version of $P_s(r, l)$ and T_s be the transition probability matrix. According to the Markov property, we recursively update P_s by $P_s = P_s T_s$ until P_s converges, and then we compute P_{loss}, R_{loss}, and L_s by

$$\begin{aligned} P_{\text{loss}} &= \sum P_{\text{loss}}(r, l) \\ R_{\text{loss}} &= \sum P_{\text{loss}}(r, l) r \\ L_s &= \sum P_s(0, l) l. \end{aligned} \tag{12}$$

Especially to deserve to be mentioned, the maximum number of recursively updating P_s is a small number that is equal to $L_{\max}$. The maximum number of recursively updating P_s occurs only when a new packet with an initial state $(r, 0)$ arrives its destination with the final state $(0, L_{\max})$. Furthermore, the absorbing Markov chain is homogeneous because $P_{d,\Pi(r,l)}(k)$ is given and constant. [22] provides an alternative solution to the homogeneous Markov chain.

Finally, we consider the issue that significant packet loss may have a direct impact on the effective traffic load, when packets start to be dropped; the transmission queue becomes shortened and the effective traffic load is reduced. Some analytical models overestimate the packet loss rate because they do not consider this impact. When the effective traffic load is reduced because of packet loss, the packet loss rate is also reduced. For enhancing accuracy, we recursively updates λ_{eff} and P_{loss} to avoid overestimating the packet loss rat, and present the complete steps of our analytical model using a double-loop structure:

- Step 1: Estimate $Q(n)$, given λ_{eff}.
- Step 2: Compute $p_x(r, l)$.
- Step 3: Construct T_a.
- Step 4: Let $P_a = P_q T_q$.
- Step 5: Compute $P_{d,\Pi(r,l)}(k)$.
- Step 6: Construct T_a.
- Step 7: Let $P_a = P_a T_a$.
- Repeat from Step 2 until P_q and P_a converge.
- Step 8: Calculate P_{loss}, R_{loss}, and L_s.
- Repeat from Step 1 until P_{loss} converges.

In addition, we present a little modification in Appendix B, because the new packets in state $(r_0, 0)$ exist only in the arrival traffic. When these packets arrive a queue, the state will change from $(r_0, 0)$ to $(r_0, 1)$. These packets need to be handled especially.

4 Numerical analysis and simulation

In this section, we employ our analytical and simulation model to examine how the relative weights assigned to the latency and the residual distance of a packet affect the performance of packet loss rate and average delay in our scheduling scheme. First, we validate our analytical model by comparing the analytical and simulation results. Second, we use LLF, LDF, and SDF schemes to investigate effects of extreme values of ρ on the performance. Last, we find out how to determine the optimal value of ρ through numerical analysis for minimizing the packet loss rate.

4.1 Simulation model

Our simulation model employs a multi-stage network with one hundred nodes as shown in Fig. 2, where each stage is composed of N nodes and each node is directly connected with all nodes of the previous stage and the next stage. In this multi-stage network, optical packets are randomly routed following the left-to-right or right-to-left, and they are not exchanged between the nodes of the same stage. Let $R_{\max}$ denote the maximum residual distance in hops for a packet to traverse. Each packet is assigned a random routing path, an initial residual distance R_0 and an initial latency L_0, such that the route length has a uniform distribution between one and $R_{\max}$. Furthermore, the initial latency is equal to zero.

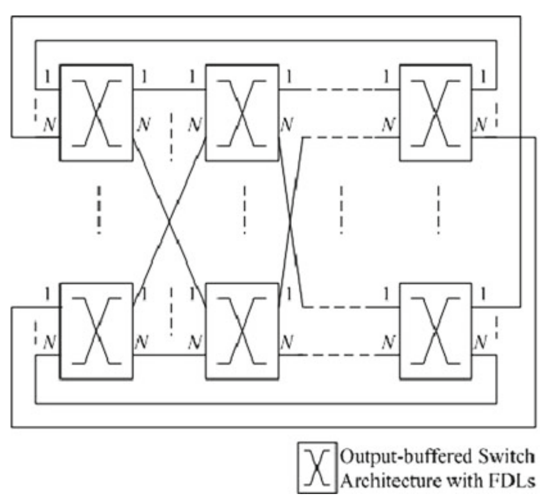

Fig. 2 A multi-stage network for our simulation

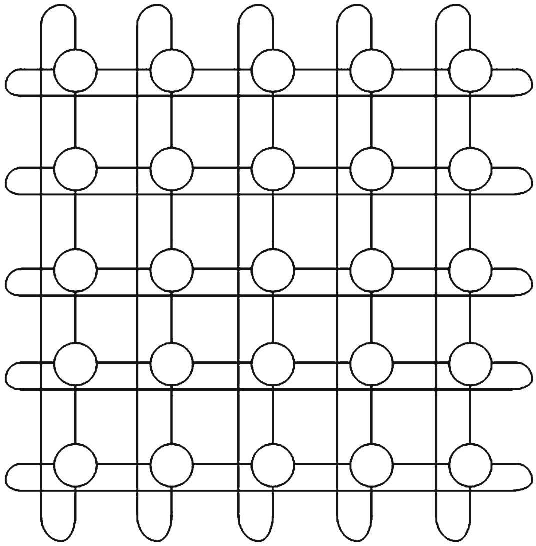

Fig. 3 A Bi-dimensional Manhattan Street network

In addition to the multi-stage network, we also study our scheme on a Bi-dimensional Manhattan Street network as shown in Fig. 3, where each internal node directly connects to its four neighbors. We have consistent results on the Bi-dimensional Manhattan Street network and the multi-stage network. For brevity, we abridge the discussion on the Bi-dimensional Manhattan Street network.

4.2 Analytical verification

In this subsection, we validate our analytical model by comparing the analytical and simulation results. We assume that $R_{\max} = 10$, $B = \infty$, and $N = 10$, and compute the packet loss rate and the average delay for a series of λ, ranging from 0.1 to 0.8. The traffic load follows the overall arrival rate per queue λ from (2), and $A(i)$ follows (14).

As mentioned previously, our analytical model can be used to calculate the packet loss rate and the average delay of all-optical packet switching networks with our scheduling scheme. Figures 4 and 5 illustrate average delays and packet loss rates of the analytical and simulation results with various relative-distance factors. They show that the analytical results are in good agreement with the simulation results in terms of packet loss rates and average delay. Note that the analytical results are considerably close to the simulation results under heavy traffic load. This is because our analytical model has considered the effect of significant packet loss on $Q(n)$ and λ_{eff}. The simulation and analytical results verify the accuracy of our analytical model. Furthermore, Figs. 4 and 5 also show that the relative-distance factor has a significant impact on packet loss rate and average delay.

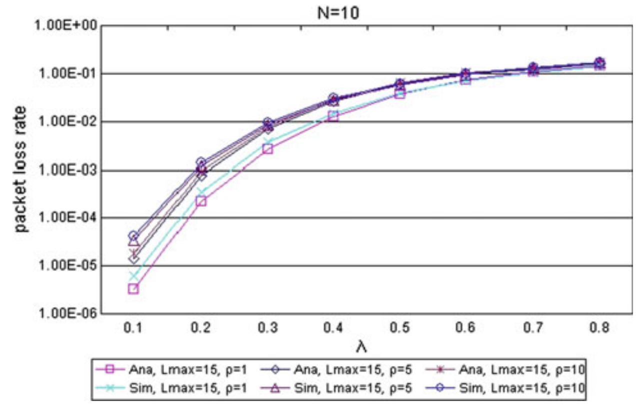

Fig. 4 Packet loss rates of analytical and simulation results with various relative-distance factors

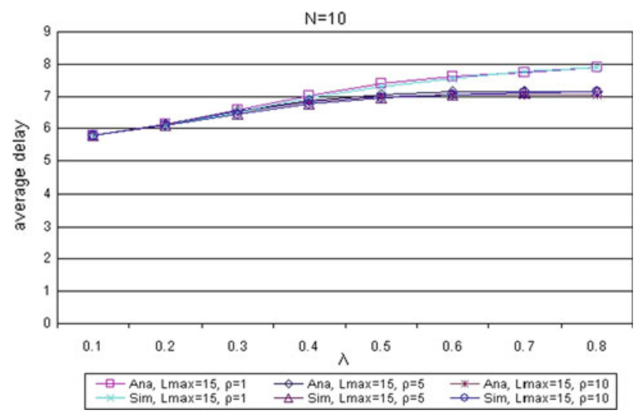

Fig. 5 Average delays of analytical and simulation results in our scheduling scheme with various relative-distance factors

4.3 Effects of extreme values of ρ

In this subsection, we examine effects of extreme values of ρ on the performance of packet loss rate and average delay. We use LLF, LDF, and SDF schemes to investigate the effects of extreme values of ρ for minimizing the packet loss rate as well as the average delay. The LLF, LDF, and SDF schemes are similar to special cases of (1) with $\rho = 0$, $\rho = -\infty$, and $\rho = \infty$, respectively. Through simulation, we intend to observe how the performance is varied by these schemes under various loading conditions. The observations can then help us estimate the operating range of ρ for minimizing the packet loss rate as well as the average delay. Figures 6, 7, 8 illustrate packet loss rates and average delays of simulation results in the three schemes and the first-in-first-out scheduling scheme (FIFO).

Figure 6 shows that LLF outperforms LDF, SDF, and FIFO in terms of packet loss rate. This is because a queued packet will be dropped if the sum of its residual distance and latency is greater than $L_{\max}$, and a queued packet with a long latency is easier to transmit than one with a short latency in LLF.

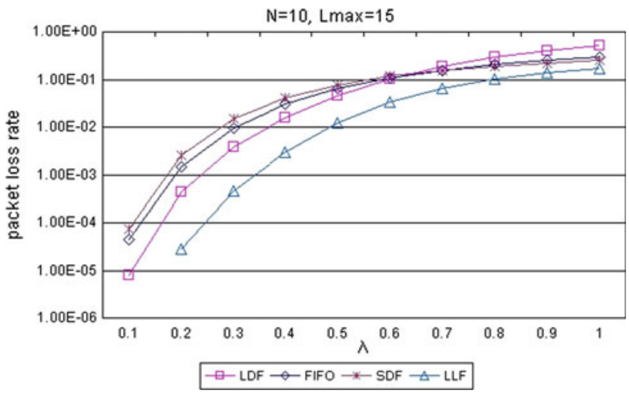

Fig. 6 Packet loss rates of simulation results in different schemes with $B = \infty$

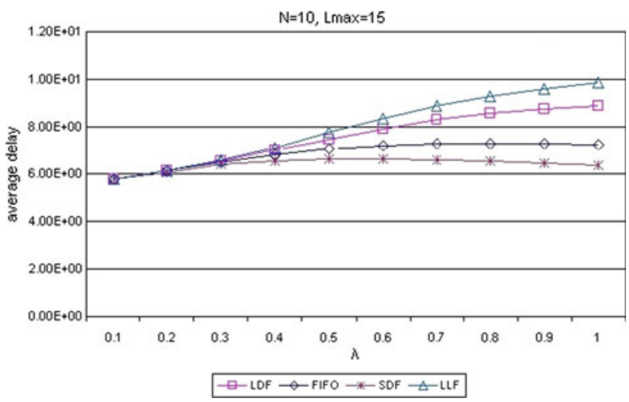

Fig. 7 Average delays of simulation results in different schemes with $B = \infty$

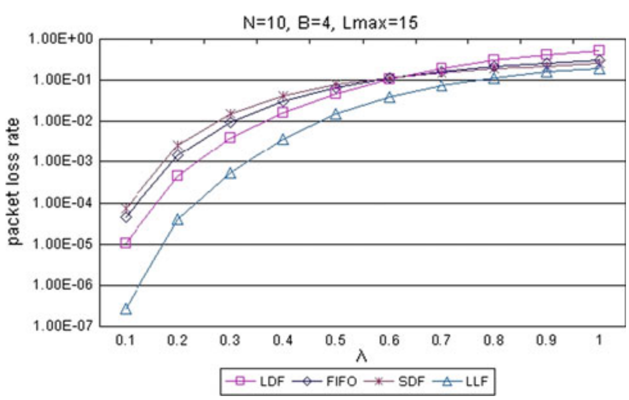

Fig. 8 Packet loss rates of simulation results in different schemes with $B = 4$

LLF reduces the packet loss rate, but Fig. 7 shows it also increases the average delay.

Next, Fig. 6 shows that LDF outperforms SDF and FIFO in terms of packet loss rate under low traffic load, but doing the opposite under heavy traffic load. Under low traffic load, LDF is similar to LLF, because a new packet with a long initial residual distance usually has a long latency when it has reached the destined node. However, a queued packet with a short residual distance is difficult to transmit even if it has a long latency. This causes an adverse effect on packet loss rate when the traffic load is heavy and the network is congested. By contrast, a queued packet with a long residual distance is difficult to transmit in SDF, so SDF achieves larger R_{loss} than LDF. According to (3), larger R_{loss} can considerably reduce effective traffic load as well as packet loss. Furthermore, Fig. 8 shows the consistent results under $B = 4$, and Fig. 7 shows that SDF also reduces the average delay. Therefore, SDF can reduce both the packet loss rate and the average delay under heavy traffic load.

Figures 6 and 8 verify that $L_{\max}$ imposed by FDLs in fact plays a more important role in determining the packet loss rate than the buffer size, if sufficient FDLs are provided. Comparing Fig. 6 with Fig. 8, they show that the packet loss rate due to buffer overflow is 96% lower than the packet loss rate due to excessive recirculation in LDF when $\lambda = 1.0$ and $B = 4$. The packet loss rates due to buffer overflow and excessive recirculation both increase with λ but the packet loss rate due to buffer overflow can be reduced significantly if sufficient FDLs are provided.

4.4 Optimal balance between latency and residual distance

According to the results of the previous subsection, we make two important observations for minimizing the packet loss rate. First, LLF (i.e., $\rho = 0$) and LDF (i.e., $\rho = -\infty$) can reduce the packet loss rate but increase the average delay when the traffic load is light. Second, LLF and SDF (i.e., $\rho = \infty$) can reduce the packet loss rate when the traffic load is heavy. In particular, SDF can also reduce the average delay. Therefore, we should use a negative ρ to combine the effect of LLF and LDF under low traffic load for minimizing the packet loss rate, and use a positive relative-distance factor to combine the effect of LLF and SDF under heavy traffic load.

Now, we intend to determine the proper value of ρ in our scheduling scheme for achieving the optimal balance between latency and residual distance. Figures 9, 10 and 11 illustrate packet loss rates of simulation results in our scheduling scheme with various ρ and $B = 4$. We compute the packet loss rate for a series of ρ, ranging from -1 to 1. These results help us find the optimal balance between latency and residual distance for minimizing the packet loss rate.

In the case of light traffic load and $L_{\max} = 15$, Fig. 9 shows that the optimal value of ρ is equal to -0.5 when $\lambda = 0.2$; the optimal value of ρ is equal to -0.4 when $\lambda = 0.3$ and $\lambda = 0.4$. Therefore, we know that using a negative relative-distance factor to combine the effect of LLF and LDF on packet loss rate is truly effective under low traffic load.

In the case of heavy traffic load and $L_{\max} = 15$, Fig. 10 shows that the optimal value of ρ is equal to -0.3 when $\lambda = 0.7$; the optimal value of ρ is equal to -0.2 when $\lambda = 0.8$

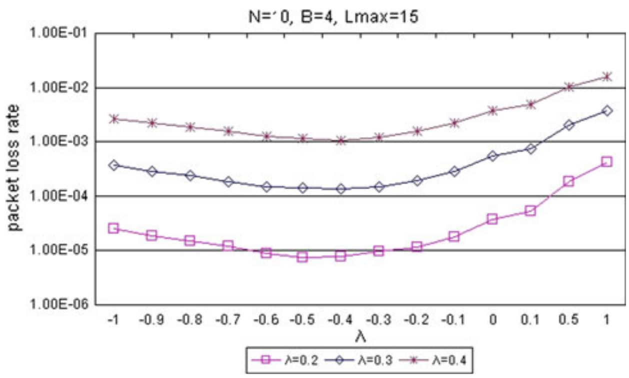

Fig. 9 Packet loss rates of simulation results under low traffic load and $L_{\max} = 15$

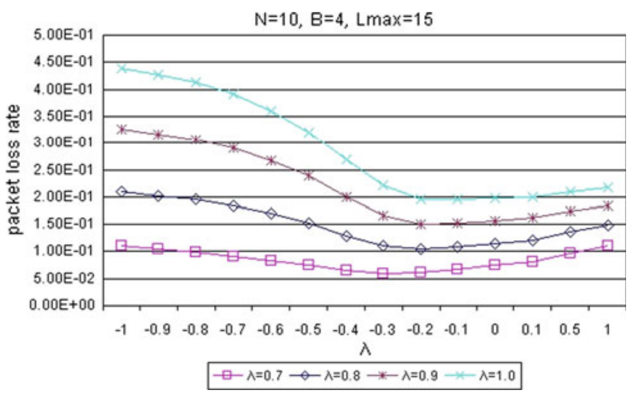

Fig. 10 Packet loss rates of simulation results under heavy traffic load and $L_{\max} = 15$

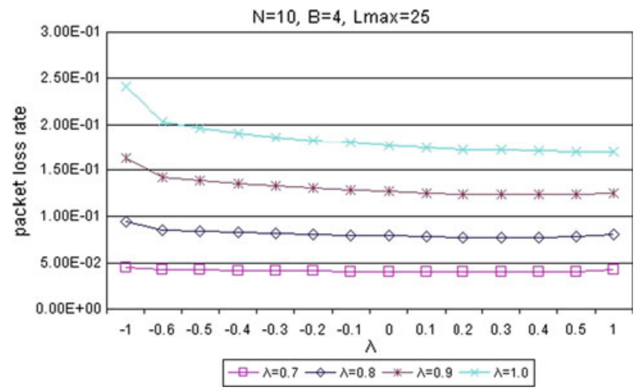

Fig. 11 Packet loss rates of simulation results under heavy traffic load and $L_{\max} = 25$

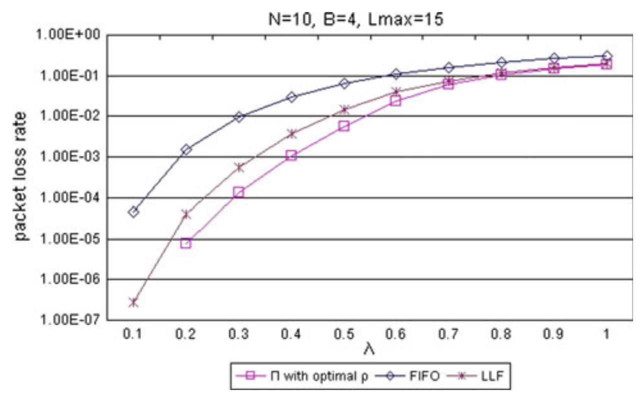

Fig. 12 Packet loss rates of simulation results with different priority functions under $L_{\max} = 15$

and $\lambda = 0.9$; the optimal value of ρ is equal to -0.1 when $\lambda = 1.0$. Obviously, the optimal value of ρ increases with λ.

Furthermore, Fig. 11 illustrates packet loss rates of simulation results in our scheduling scheme under heavy traffic load and $L_{\max} = 25$. It shows that the optimal value of ρ is equal to 0.3 when $\lambda = 0.7$ and $\lambda = 0.8$; the optimal value of ρ is equal to 0.5 when $\lambda = 0.9$ and $\lambda = 1.0$. Comparing Fig. 11 with Fig. 10, a wide $L_{\max}$ results in that the optimal value of ρ increases. This is because a wide $L_{\max}$ reduces the packet loss rate due to excessive recirculation but the one due to buffer overflow. When the packet loss rate due to buffer overflow increases, our scheduling scheme needs a greater relative-distance factor to reduce the effective traffic load, according to the effect of SDF (i.e., $\rho = \infty$). In the extreme case where the network traffic is highly stressed, a great relative-distance factor should be used.

Consequently, we can optimize ρ to minimize the packet loss rate based on the following observations:

1. The optimal value of ρ is a negative number under low traffic load;
2. The optimal value of ρ increases with λ;
3. The optimal value of ρ increases with $L_{\max}$.

We dynamically adapt the value of ρ based on the three observations to minimize the packet loss rate. Figure 12 shows that our scheduling scheme outperforms FIFO and LLF in terms of packet loss rate. Our scheduling scheme is very effective for reducing packet loss when the traffic load is light. Under light traffic load, our scheduling scheme achieves a packet loss rate 71% lower than the one of LLF. Even if the traffic load is heavy and equal to 0.9, the packet loss rate of our scheduling scheme is still 4% lower than the one of LLF in Fig. 12.

5 Conclusions

We have proposed a latency-aware scheduling scheme and an analytical model for all-optical packet switching networks with FDL buffers. We focus on the optimization of a relative-distance factor, ρ, which represents the relative weights assigned to the latency and the residual distance of a packet to determine its priority in the latency-aware scheduling scheme. The optimal value of ρ minimizes the packet loss rate of the all-optical packet switching networks. The proposed analytical model is based on a non-homogeneous

Markov chain using a double-loop structure. We use the analytical model to analyze the performance of our scheduling scheme in terms of packet loss rate and average delay. Furthermore, the proposed analytical model is accurate and suitable for a wide range of network configurations in multi-stage networks and Bi-dimensional Manhattan Street networks, as well as other packet generation patterns.

Our numerical results show how various network parameters affect the choice of ρ for minimizing the packet loss rate. In the case of light traffic load, the latency is a more important factor and the optimal value of ρ is a negative number. The optimal value of ρ increases (i.e., the importance of the residual distance increases) as the traffic load or the latency limit increases. The effects of residual distance and latency on the performance are different from common heuristics. Our study demonstrates quantitatively that the latency-aware scheduling scheme with the optimal value of ρ can lead to significant reduction in packet loss rate.

Appendix A

Let $Q(n)$ denote the steady state probability that the queue length is n. The following equations can compute the steady state probabilities,

$$\begin{aligned} Q(0) &= \frac{(1-\lambda_{\text{eff}})}{A(0)} \\ Q(1) &= \frac{(1-A(0)-A(1))}{A(0)} q_0 \\ Q(j) &= \frac{(1-A(1))}{A(0)} q_{j-1} - \sum_{i=1}^{j} \frac{A(i)}{A(0)} q_{j-i}, \quad \text{if } j>1 \end{aligned} \tag{13}$$

where $A(i)$ is the probability that the number of arriving packets at the queue is i during a given timeslot. $A(i)$ is different from the one of [15], because arriving packets come from neighbor nodes and the node itself in our network configuration. Since the arriving packets come from the node itself with a stable generation rate λ_s, we have

$$\begin{aligned} A(i) &= Pr[A=i] \\ &= \binom{N}{i} \left(\frac{\lambda_{\text{eff}}-\lambda_s}{N}\right)^i \left(1-\frac{\lambda_{\text{eff}}-\lambda_s}{N}\right)^{N-i} (1-\lambda_s) \\ &\quad + \binom{N}{i-1} \left(\frac{\lambda_{\text{eff}}-\lambda_s}{N}\right)^{i-1} \left(1-\frac{\lambda_{\text{eff}}-\lambda_s}{N}\right)^{N-i+1} \lambda_s, \end{aligned} \tag{14}$$

where N denotes the number of input/output ports. In addition, we also can use various distributions to generate packets. For example, if the packet generation follows a Poisson distribution with a generation rate λ_s, (14) will be

$$\begin{aligned} A(i) &= Pr[A=i] = \\ &\sum_{k=0}^{i} \binom{N}{i-k} \left(\frac{\lambda_{\text{eff}}-\lambda_s}{N}\right)^{i-k} \\ &\left(1-\frac{\lambda_{\text{eff}}-\lambda_s}{N}\right)^{N-i-k} \frac{\lambda_s^k e^{-\lambda_s}}{k!}, \end{aligned} \tag{15}$$

where k is the number of arriving packets from the node itself.

Appendix B

We modify some equations for handling the new packets with $(r_0, 0)$ especially. Firstly, let $A'(i)$ denote the number of arriving packets from the neighbor nodes. According to (14), we have

$$A'(i) = \binom{N}{i} \left(\frac{\lambda_{\text{eff}}-\lambda_s}{N}\right)^i \left(1-\frac{\lambda_{\text{eff}}-\lambda_s}{N}\right)^{N-i}. \tag{16}$$

These packets will arrive and directly depart a queue when the queue has no arriving packets with higher priorities and the queue is empty, so we can calculate $p_x(r_0, 0)$ for these packets by

$$p_x(r_0, 0) = Q(0)A'(0)\lambda_s', \tag{17}$$

where λ_s' denotes the generation rate of these packets.

Next, we modify (6) for the other packets. Since the packets with the lowest priority do not exist in a queue and exist only in the arrival traffic, we modify (6) to (18) for the other packets.

$$\begin{aligned} p_e(r,0) &= \sum_{\Pi(r',0)=\Pi(r,0)} P_{R_q,L_q}(r',l') \\ p_g(r,l) &= \frac{\sum_{\Pi(r',l')>\Pi(r,l)} P_{R_q,L_q}(r',l')}{1-p_e(r,0)} \quad \text{if } l \neq 0 \text{ and } l' \neq 0 \\ p_e(r,l) &= \frac{\sum_{\Pi(r',l')=\Pi(r,l)} P_{R_q,L_q}(r',l')}{1-p_e(r,0)} \quad \text{if } l \neq 0 \text{ and } l' \neq 0 \\ p_{ag}(r,l) &= \sum_{\Pi(r',l')>\Pi(r,l)} P_{R_a,L_a}(r',l') \\ p_{ae}(r,l) &= \sum_{\Pi(r',l')=\Pi(r,l)} P_{R_a,L_a}(r',l'). \end{aligned} \tag{18}$$

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