Contention-based Reservation Protocol Using a Counter for Detecting a Source Conflict in WDM Single-hop Optical Network with Non-equivalent Distance

Makoto Sakuta, Yoshiyuki Nishino, and Iwao Sasase

Abstract: **We propose a new channel reservation protocol which can reduce message delay by using a counter for detection of a source conflict in a WDM single-hop network with non-equivalent propagation delay. A source conflict occurs when a source node has the right to transmit more than or equal to two messages simultaneously, which are transmitted using different wavelengths. In such a case, the source node has to newly obtain the right to transmit the message. In the proposed protocol, by using a source conflict counter a source node can detect a source conflict before a wavelength assignment is performed. Therefore, the source node can start a procedure to newly obtain the right to transmit the message which cannot be transmitted due to a source conflict. We analyze the throughput performance by taking the effect of a source conflict into account, and show that the approximate analysis and the computer simulated results are close. Also, from computer simulated results, we show that our proposed protocol can reduce mean message delay dramatically without degrading throughput performance as the offered load becomes large.**

Index Terms: **WDM, single-hop network, source conflict, throughput, message delay.**

I. INTRODUCTION

In recent years, wavelength division multiplexing (WDM) technology, which can utilize the bandwidth of optical fiber effectively by dividing it into several channels, is focused on. In the network using WDM technology, large capacity data transmission can be realized since users can transmit their packets using each different wavelength at the same time slot. A single-hop network, in which all nodes and the star coupler are connected with optical fibers, is known as an network which is effective for a small-scale LAN, since fast tuning devices are developed. Media access control protocols for a WDM single-hop network are roughly classified into TDMA schemes and the random access schemes. TDMA schemes cause an inefficient use of data channels under low and non-uniform traffic. Among the random access schemes, ALOHA protocol causes large degradation under high traffic load [1].

On the other hand, in the reservation scheme, a user makes reservation of a data channel only when he desires to communicate to other user. Hence, the reservation scheme has the advantage that data channels are effectively utilized. Channel reservation protocols in a single-hop network are widely studied [2]–[9]. The protocols, in which one of the channels is used as a control channel, are proposed [2]–[8]. In those protocols, the source node transmits a control packet prior to a data packet. Then, all nodes investigate a collision of control packets, and perform a wavelength assignment by using the identical algorithm. In [9], a channel reservation protocol in the network with non-equivalent propagation delay has been proposed. In the protocol, each node can handle variable-length messages, each of which consists of multiple data packets. When a control packet transmitted by a source node does not collide with other ones, the source node can obtain the right to transmit the message during a period which is equal to the message length. Also, all nodes have a counter for each wavelength, the value of which indicates the length of the queue formed by messages to be transmitted using the corresponding wavelength. The source node begins to transmit a message using the corresponding wavelength after a period which is equal to the value of the counter for the wavelength. In the protocol, when a message newly arrives at a source node at the beginning of a time slot, the source node transmits a control packet within the time slot, even if a wavelength assignment has not been performed with reference to the previous control packet transmitted by the source node. Therefore, it is possible that the source node obtains the right to transmit the new message using the wavelength, which is different from the wavelength which was used to transmit the previous message. Under the condition that each node has only one tunable transmitter for transmission of a message, the source node is not allowed to transmit more than or equal to two messages in one time slot. This is called a source conflict.

The scheduling scheme to avoid a source conflict has been proposed [10]. In [10], all nodes have the identical routing information table that indicates from which time slot the source node transmits a message, or which wavelength is used to transmit a message. Based on the routing information table, each node performs the wavelength assignment so as not to occur a source conflict. However, the scheme in [10] does not handle variable-length messages, and has not been adapted to the network with non-equivalent distance between the star coupler and nodes. When we consider non-equivalent distance between the star coupler and nodes and variable message length in addition to routing information in other wavelengths in that scheme, a wavelength assignment and scheduling are more and more com-

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plex. So, each node needs a very large-sized routing information table to perform a wavelength assignment.

On the other hand, the protocol in [9] does not have to consider routing information in other wavelengths, since a wavelength utilized in a destination node is determined previously. So, the protocol has the advantage that each node does not need complex calculation to perform a wavelength assignment. However, in the protocol [9], a source conflict might occur. A source conflict is detected after a wavelength assignment is performed and a source node waits during a period which is equal to the value of the counter for the wavelength. The larger the offered load becomes, the larger the value of the counters becomes. Therefore, it is expected that mean message delay degrades dramatically as the offered load becomes large. Thus, the improvement of mean message delay performance for high load is important.

In this paper, we propose a new channel reservation protocol using a counter for a detection of a source conflict in a WDM single-hop network with non-equivalent distance. In the proposed protocol, in order to detect a source conflict before a wavelength assignment is performed, a source conflict counter is placed at each node. A source conflict counter has information about the message for which a source node makes reservation of a wavelengh most lastly. Each node investigates the value of the source conflict counter in conjunction with a collision of control packets. Even though a collision of control packets does not occur, the source node does not perform a wavelength assignment when a source conflict is detected. Thus, in the proposed protocol, when the source node can detect a source conflict by the counter, the source node does not need to wait during a period which is equal to the value of the counter for a wavelength. We analyze the throughput by taking the probability that a source conflict occurs in a node into account, and show the analytical result is close to the computer simulated one. Also, we compare the proposed protocol with the conventional one with regard to mean message delay performance by computer simulations. As a result, we show that our proposed protocol can reduce mean message delay dramatically without degrading throughput performance as the offered load becomes large.

II. PROPOSED CHANNEL RESERVATION PROTOCOL

In this section, we describe the system model and operation of the proposed protocol. In order to detect a source conflict before a wavelength assignment is performed, a source conflict counter is placed at each node. Each node investigates the value of the source conflict counter in conjunction with a collision of control packets. Even though a collision of control packets does not occur, the source node does not perform a wavelength assignment when a source conflict is detected. Therefore, in the proposed protocol, when the source node can detect a source conflict by the counter, the source node does not need to wait during a period which is equal to the value of the counter for a wavelength.

A. System Model

The network is composed by N nodes and the star coupler. Fig. 1 shows network structure with $N = 3$. Spectrum of optical fiber is divided into $M + 1$ wavelengths ($M < N$). In this paper, a data channel is defined as a channel between source and destination node. Available wavelengths are denoted as $\lambda_c, \lambda_1, \cdots, \lambda_M$. λ_c is used for reservation of a data channel as a control channel. $\lambda_1, \cdots, \lambda_M$ are assigned to data channels, and are used for each node to transmit data packets. Each node has one fixed transmitter and one fixed receiver which are tuned to λ_c, and has one tunable transmitter and one tunable receiver which can be tuned to any one of M wavelengths, or $\lambda_1, \cdots, \lambda_M$.

Fig. 2 shows structure of a control channel and data channels. In this paper, we define a period required to transmit one data packet as one time slot. Channels are divided into the control slot (CS) and the data slot (DS), respectively. Also, a CS is divided into $L(< N)$ minislots. A node generates a message which consists of multiple data packets. And, the node selects one of L minislots in a CS randomly, and transmits a control packet using a slotted ALOHA, which has the advantage that the number of nodes is not limited by the size of a slot. A control packet consists of a source address (SA) field, a destination address (DA) field, and a field for the number of data packets in the message (NPK). The star coupler broadcasts a control packet to all nodes. It is assumed that all slots are synchronized with respect to the star coupler.

In this paper, we focus on the network with non-equivalent distance between the star coupler and nodes. Generally, when we construct a network, distance between the star coupler and nodes differs at each node. Also, propagation speed of optical signals through an optical fiber varies by the physical environment such as temperature [11]. In the network with non-equivalent distance between the star coupler and nodes, the order of the packets arrived at the coupler is not the same as the order of the time that they start the transmission. Thus, for the different distance cases, the packet transmitted by the far node from the coupler would arrive at the destination later than the one transmitted by the node near the star coupler, as mentioned in [12]. So, we need the protocol which consider the non-equivalent distance between the star coupler and nodes.

In the network shown in Fig. 1, it takes d_i slots for the packet transmitted by node $i (1 \leq i \leq N)$ to reach the star coupler, and a propagation delay of node i is denoted as d_i. A propagation delay of the farthest node k from the star coupler is d_k, and maximum round-trip propagation delay is denoted as $R = 2d_k$. In the protocol, before the system is made use of, the propagation delays of other nodes are measured in advance, and each node keeps the values of propagation delays of all nodes. While the system is made use of, each node uses the measured values.

Tunable receivers of all nodes are previously tuned to one of M wavelengths. The pattern to allocate a wavelength to a tunable receiver of a node is updated regularly [9]. All nodes have the counter $\mathrm{GQ}_j (1 \leq j \leq M)$ for wavelength λ_j. The value of GQ_j indicates the length of the queue formed by messages to be transmitted using λ_j. The value of GQ_j decreases one by one every time slot if it is not equal to zero.

The counter GQs can be updated at each node without being aware of the context of other nodes, and the consistencies of the counter GQs are maintained. In order to maintain the consistencies of the counter GQs, node i stores a set of control packets

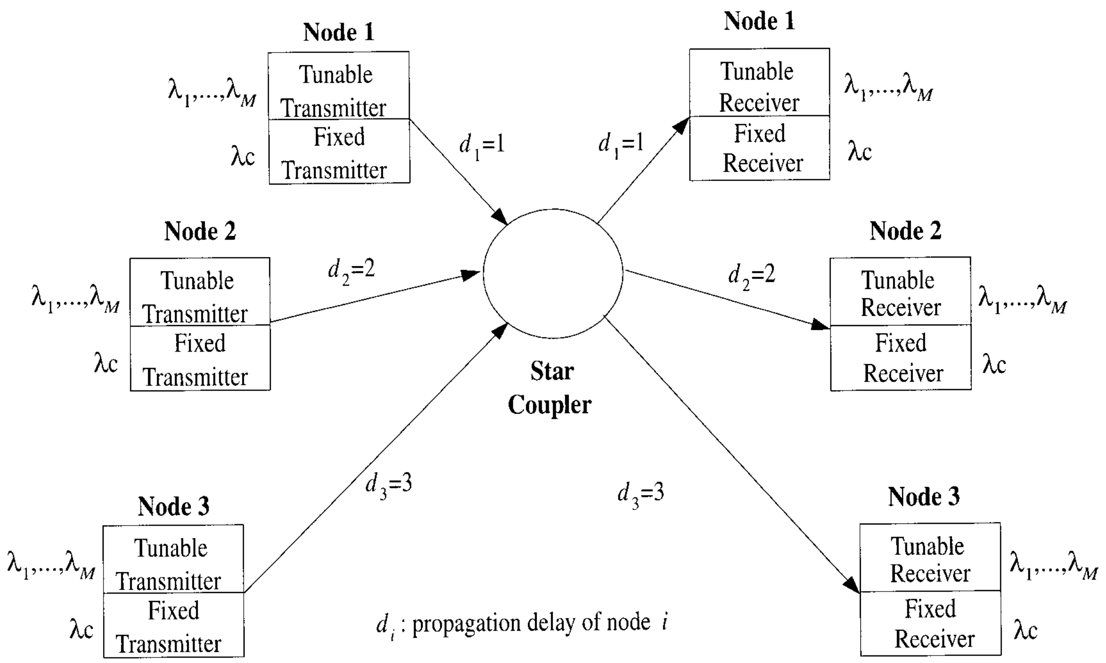

Fig. 1. Structure of WDM single-hop network($N = 3$).

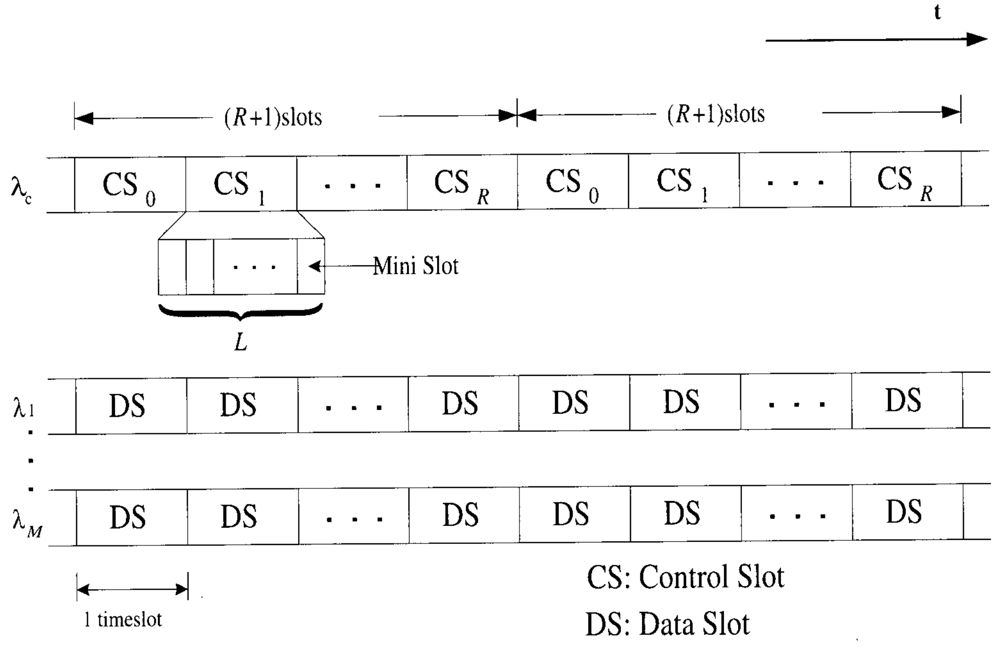

Fig. 2. Structure of control channel and data channels.

in latency buffer during $2(d_k - d_i)$ slots from the time that node i receives a set of them. Then, node i investigates a collision of control packets and updates the counter GQ. The duration of $2(d_k - d_i)$ slots is called a propagation latency of node i. We describe why the parameter of $2(d_k - d_i)$ is used as a propagation latency of node i.

Fig. 3 shows an example of propagation latencies in the network shown in Fig. 1. In the figure, node 3, 2, and 1 transmit control packet A, B, and C at the time slot 0, 1, and 2, respectively. Those control packets simultaneously arrive at the star coupler at time slot 3, and node 1, 2, and 3 receive a set of control packets at time slot 4, 5, and 6. From Fig. 1 and Fig. 3, we can find that a control packet transmitted by node $k(=3)$ at time slot 0 arrives at the point that a distance from the star coupler is equal to d_i at time slot $d_k - d_i$. For example, control packet A is at the same distance from the star coupler as control packet C at time slot $d_3 - d_1 (=2)$. When a node performs a wavelength assignment, the node investigates a collision of control packets which arrive at the star coupler simultaneously. Therefore, in order to maintain the consistencies of the counter GQs, node i has to investigate a collision of control packets after $(d_k - d_i)$ slots from the time that node k does. Also, we consider the sit-

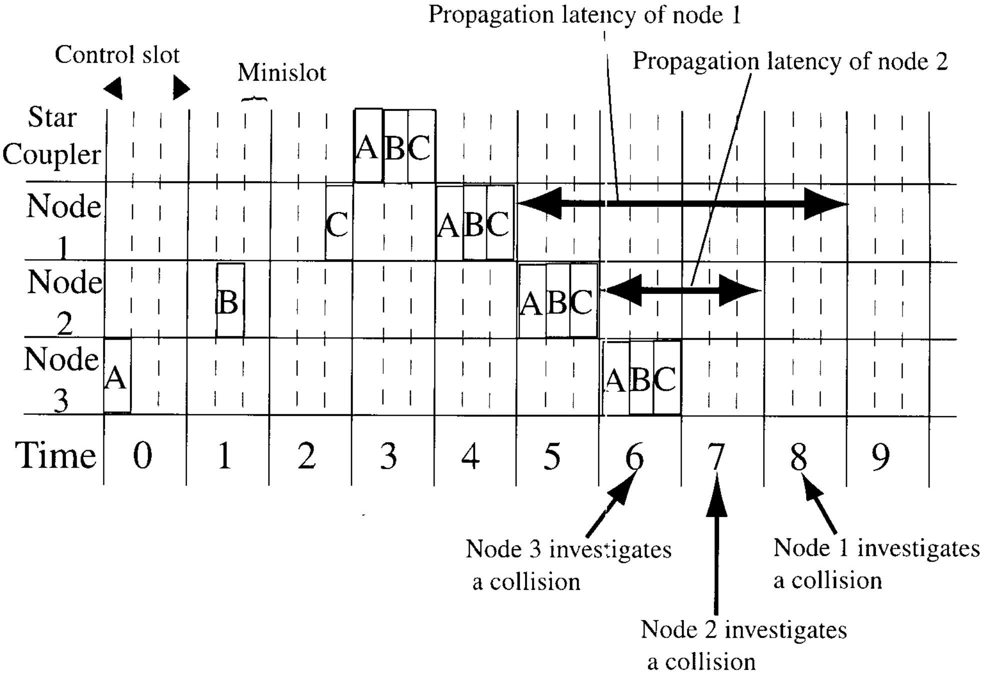

Fig. 3. An example of propagation latencies.

uation that the farthest node k from the star coupler investigates a collision of control packets at time slot t. Node i receives a set of control packets at time slot $t-(d_k-d_i)$. Hence, node i needs to store a set of control packets in the latency buffer during $2(d_k-d_i)$ slots from the time that node i receives a set of control packets. In Fig. 3, node $k(=3)$ receives a set of control packets and investigates a collision of control packets at time slot $t(=6)$. Node 1 receives a set of control packets at time slot 4, and investigates a collision of them at time slot 8. Thus, the parameter of $2(d_k-d_i)$ slots is used as a propagation latency of node i. Also, node k investigates a collision after $2(d_k-d_k)(=0)$ slots from the time that node k receives a set of them. That is, node k receives a set of control packets at time slot t, and investigates a collision of them within time slot t.

The consistencies of the counter GQs are maintained by propagation latencies, and the counter GQs can be updated at each node without being aware of the context of other nodes. Therefore, management overheads for being aware of the context other nodes are not required.

B. Operation of the Proposed Protocol

In this section, we describe an operation of the proposed protocol. As shown in Fig. 2, the control channel is divided into R+1 slot and xth control slot is denoted as $\text{CS}_x(0 \leq x \leq R)$. Node i, which generates a message, transmits a control packet using a minislot in CS_x at the beginning of time slot t with probability $p_{i,x}$, or puts off transmitting a control packet until time slot $(t+R+1)$ with probability $1-p_{i,x}$. Initially, $p_{i,x}=1$ is set. When more than or equal to two control packets are transmitted using the same minislot, they collide each other. When the control packet transmitted by node i at time slot t collides with other control packets, node i selects one of L minislots randomly again and retransmits the control packet at time slot $(t+R+1)$ with probability $p_{i,x}$, or puts off retransmitting it until time slot $(t+2(R+1))$ with probability $1-p_{i,x}$. Also, node i updates $p_{i,x}$ based on a collision ratio of the control packet before the beginning of next CS_x [9]. The updated value of $p_{i,x}$ is used for retransmission. Now, ratio of the number of minislots in which a collision occurs and L is denoted as β. If $0 \leq \beta \leq \Delta_L$, node i divides $p_{i,x}$ by parameter $q(0<q\leq 1)$. If $\Delta_U \leq \beta \leq 1$, node i multiplies $p_{i,x}$ by q. The minimum value of $p_{i,x}$, denoted as p_{min}, is set to q^c using parameter c [9].

Control packets are received by each node via the star coupler. At first, node i stores control packets in latency buffer during $2(d_k-d_i)$ slots. After $2(d_k-d_i)$ slots, node i investigates whether a collision occurs or not. And node i refers to SA, DA and NPK fields of the contorol packet which does not collide with other ones. When the node corresponding to DA in the control packet is assigned λ_j, the value of NPK is added to GQ_j at the node i.

Fig. 4(a) illustrate example of transmission of control packets. In the figure, at time slot 0 and 1, node 3 transmits control packet A and B, which destine node 1 and 2 respectively. The value of a NPK field of them is equal to 5. Also, the receivers of node 1, 2, and 3 are tuned to λ_1, λ_2, and λ_3, respectively. At time slot 6 and 7, node 3 investigates a collision of control packet A and B, respectively. Now, they do not collide with other control packets. Also, in this example, the value of GQ_2 at time slot 6 is equal to 4, which indicates that other node is transmitting a message whose length is equal to 4. At time slot 6, since the value of GQ_1 is equal to zero, node 3 can transmit message A at time slot 7. And, node 3 adds the value of NPK to GQ_1.

Here, we consider a situation that a source conflict occurs. In the conventional protocol shown in Fig. 4(b), since the value of GQ_2 is equal to 3 at time slot 7, node 3 obtains the right to transmit message B from time slot 10 until time slot 14. And

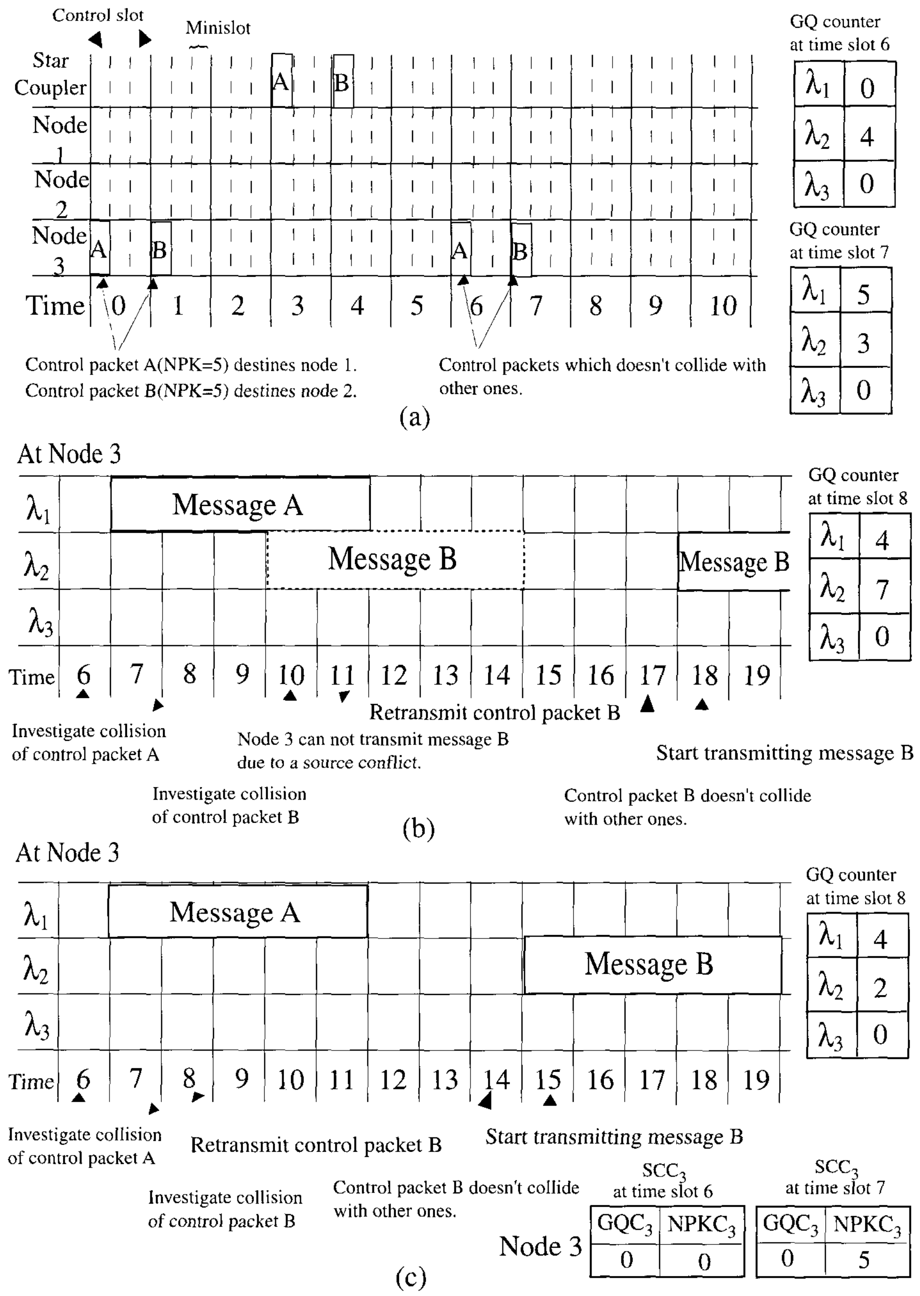

Fig. 4. An example of operation in the conventional and proposed protocols; (a) illustrates an example of transmission of control packets; (b) conventional protocol; (c) proposed protocol.

node 3 adds the value of NPK to GQ$_2$. However, at time slot 10, since node 3 is transmitting message A using λ_1, node 3 can not transmit message B at time slot 10. Thus, a source conflict occurs when a source node has the right to transmit more than or equal to two messages, which are transmitted using different wavelength, at the same time slot. Then, node 3 has to retransmit control packet B at time slot 11 in order to newly obtain the right to transmit message B using λ_2. Node 3 investigates a collision of the retransmitted control packet at time slot 17. And if it does not collide with other ones and the value of GQ$_2$ is equal to zero, a source node can start transmitting message B at time slot 18. Thus, it takes three slots for node 3 to detect a source conflict from the time that node 3 obtained the right to transmit message B using λ_2.

In the proposed protocol, each node has the source conflict counter(SCC$_i$) ($1 \leq i \leq N$) to detect a source conflict. Each SCC$_i$ consists of the counter for the GQ(GQC$_i$) and the counter for NPK(NPKC$_i$). The value of GQC$_i$ indicates a duration from the time that node i has obtained the right to transmit a message most lastly until the time that the message is transmitted by node i. The value of GQC$_i$ decreases one by one per time slot if its value is not equal to zero. Also, the value of NPKC$_i$ indicates the NPK of the message of which node i obtained the right to transmit most lastly, and decreases one by one per time slot if its value is not equal to zero and GQC$_i$=0. Now, we consider a situation that at a time slot t, a message transmitted by node i destines the node whose tunable receiver is tuned to λ_j. When a message arrives at node i, node i transmits a control packet, and investigates whether it collides with other ones or not. Then, for the control packet which does not collide with other ones, node i investigates the value of GQ_j and NPK in the control packet. If $\mathrm{GQ}_j \leq \mathrm{GQC}_i + \mathrm{NPKC}_i$ or $\mathrm{GQ}_j + \mathrm{NPK} \leq \mathrm{GQC}_i$, a source conflict does not occur. In these cases, node i obtains the right to transmit the message using λ_j, and updates the value of GQC_i and NPKC_i. Otherwise, a source conflict occurs, and node i retransmits a control packet in order to newly obtain the right to transmit the message using λ_j. Fig. 4(c) shows an operation of the proposed protocol. Control packet A and B are transmitted by node 3 as shown in Fig. 4(a). For the control packet B, node 3 investigates the SCC_3 at time slot 7. In this case, since $\mathrm{GQ}_2 \leq \mathrm{GQC}_3 + \mathrm{NPKC}_3$, node 3 can detect a source conflict at time slot 7. And node 3 retransmits control packet B at time slot 8 in order to newly obtain the right to transmit message B using λ_2. Node 3 investigates a collision of the retransmitted control packet at time slot 14. And, if it does not collide with other ones and the value of GQ_2 is equal to zero, a source node can start transmitting message B at time slot 15.

Thus, in the proposed protocol, by using the SCC the source node can detect a source conflict before a wavelength assignment. Therefore, the proposed protocol can reduce a delay of the message transmitted by the source node in which a source conflict is detected.

III. APPROXIMATE ANALYSIS

In this section, we analyze the throughput performance of the proposed protocol considering the effect of a source conflict. The state of a node for CS_x is "Idle" or "Active" when the node has no message, or when it can transmit a message, respectively. Only the nodes in "Idle" state generate a message according to geometric distribution with probability σ. An average of a message length is denoted by h. For simplicity, it is assumed that tuning latency of tunable transceivers and a duration to be required to process control packets are ignored [9].

In this paper, the throughput is defined as the mean number of data packets transmitted per one time slot per wavelength. We focus on an arbitrary control slot and analyze the throughput performance. Now, the number of "Active" nodes and the transmission probability of the control packet at a control slot are denoted as i and q^m, respectively. Then, an embedded Markov chain is obtained with the state (i, m) in the control slot. When the state in the control slot is (i, m), probability that k among i nodes transmit control packets, $Y(k|i, m)$, is expressed as

$$Y(k|i,m) = \binom{i}{k} q^{mk}(1-q^m)^{i-k}. \tag{1}$$

When i nodes are in the "Active" state at the previous control slot, the probability that j among $N - i$ nodes become in the "Active" state at the current control slot, $U(j|i)$, is expressed as

$$U(j|i) = \binom{N-i}{j} \sigma^j(1-\sigma)^{N-i-j}. \tag{2}$$

Also, $Z(x, y|k, L)$ is defined as the probability that x among k control packets don't collide with other ones and a collision occurs in y among L minislots[9]. And, $S(a|x)$ is defined as the probability that a among x control packets do not collide with other ones and are utilized for a wavelength assignment. That is, $x - a$ control packets will be retransmitted due to a source conflict. We describe $S(a|x)$ later. The state transition probabilities that the number of nodes in the state (i, m) in the previous control slot becomes equal to j when the collision rate of the control packets is smaller than Δ_L, larger than Δ_L or equal to Δ_U and larger than or equal to Δ_U, are denoted as $G_{i,j}^{low}(m)$, $G_{i,j}^{mid}(m)$ and $G_{i,j}^{high}(m)$, respectively. These are expressed as (3)–(5), where $\lceil a \rceil$ is denoted as the smallest integer larger than or equal to a.

$$\begin{aligned}
G_{i,j}^{low}(m) &= \sum_{a=0}^{k}\sum_{k=0}^{i}\sum_{x=\max(i-j,0)}^{\min(k,L)}\sum_{y=0}^{\lceil L\cdot\Delta_L\rceil-1} S(a|x) \\
&\quad \cdot Z(x,y|k,L)Y(k|i,m)U(j-i+x|i) \quad (3)\\
G_{i,j}^{mid}(m) &= \sum_{a=0}^{k}\sum_{k=0}^{i}\sum_{x=\max(i-j,0)}^{\min(k,L)}\sum_{y=\lceil L\cdot\Delta_L\rceil}^{\lceil L\cdot\Delta_U\rceil-1} S(a|x) \\
&\quad \cdot Z(x,y|k,L)Y(k|i,m)U(j-i+x|i) \quad (4)\\
G_{i,j}^{high}(m) &= \sum_{a=0}^{k}\sum_{k=0}^{i}\sum_{x=\max(i-j,0)}^{\min(k,L)}\sum_{y=\lceil L\cdot\Delta_U\rceil}^{\min(L-x,\lfloor\frac{k-x}{2}\rfloor)} S(a|x) \\
&\quad \cdot Z(x,y|k,L)Y(k|i,m)U(j-i+x|i) \quad (5)
\end{aligned}$$

The state transition probability from (i, m) to (j, n), $P_{(i,m)(j,n)}$, is expressed as

$$P_{(i,m)(j,n)} = \begin{cases} I_{m\neq 0}G_{i,j}^{low}(m), & \text{if } n = m-1 \\ G_{i,j}^{mid}(m) + I_{m=0}G_{i,j}^{low}(m) & \\ \quad + I_{m=c}G_{i,j}^{high}(m), & \text{if } n = m \\ I_{m\neq c}G_{i,j}^{high}(m), & \text{if } n = m+1 \\ 0, & \text{otherwise,} \end{cases} \tag{6}$$

where c is the parameter that satisfies $p_{min} = q^c$, and the value of I_A is 1 if the statement A is true, otherwise it is 0.

The stationary probability of the state (i, m), $\pi_{(i,m)}$, is given by (7) and satisfies (8).

$$\pi_{(i,m)} = \sum_{j=0}^{N}\sum_{n=0}^{c} \pi_{(j,n)}P_{(j,n)(i,m)} \tag{7}$$

$$\sum_{j=0}^{N}\sum_{n=0}^{c} \pi_{(i,m)} = 1 \tag{8}$$

Also, the probability that j control packets don't collide with other ones in the state (i, m), $X(j|i, m)$, is expressed as

$$X(j|i,m) = \sum_{k=j}^{i}\sum_{y=0}^{\min(L-j,\lfloor\frac{k-j}{2}\rfloor)} Z(j,y|k,L)Y(k|i,m). \tag{9}$$

Now, we introduce $S(a|x)$. ψ' is defined as the expected value of the number of control packets which don't collide with other ones per slot, and is expressed as

$$\psi' = \sum_{k=j}^{i} \sum_{j=1}^{\min(i,L)} jX(j|i,m)\pi_{(i,m)}. \tag{10}$$

ψ' at each control slot is assumed to be independent. We describe the value of queues for each wavelength. In the long term, each queue lengths can be almost identical if traffic distribution is uniform. However, it depends on L, M and h in the term of one time slot. In this paper, for simplicity of an analysis, the length of queue for each wavelength, or the value of each GQ counter, is assumed to be identical at the end of every control slot. Now, the source node i, whose control packet doesn't collide with other ones, and in which a source conflict doesn't occur, utilizes wavelength λ_j to transmit a message. We consider a situation that another control packet transmitted by node i does not collide with other ones within h time slots. When a wavelength except λ_j is assigned to a data channel in which the source node utilizes, a source conflict occurs at node i. Therefore, probability that a source conflict occurs per slot, P_{conf}, is given by

$$P_{conf} = \sum_{k=1}^{h-1}\left(1 - \frac{\psi'}{N}\right)^{k-1}\frac{\psi'}{N}\left(1 - \frac{1}{M}\right). \tag{11}$$

Then,

$$S(a|x) = \binom{x}{a} P_{conf}^{x-a}(1 - P_{conf})^{a}. \tag{12}$$

The number of successful control packets per slot, ψ, is expressed as

$$\psi = \sum_{i=0}^{N}\sum_{m=0}^{c}\sum_{j=1}^{\min(i,L)}\sum_{a=1}^{j} aS(a|j)X(j|i,m)\pi_{(i,m)}. \tag{13}$$

IV. NUMERICAL RESULTS

In this section, we show results of the throughput performance by the approximate analysis and computer simulations. Also, we compare the proposed protocol with the conventional one with regard to mean message delay performance by computer simulation. In the approximate analysis, we assume the length of queue for each wavelength, or the value of each GQ counter, is identical at the end of every control slot. In all simulations, behavior of the proposed protocol and the conventional one, which does not include the approximations introduced in the analytical model, are simulated. The number of nodes $N = 30$, the parameters used to update the transmission probability of a control packet $q = 0.8$ and $c = 12$, and the parameters used as a threshold to increase or decrease the transmission probability of control packets $\Delta_L = 0.3$ and $\Delta_U = 0.6$ are selected. And we treat with uniform traffic, where destination address of a message is selected randomly with probability $1/N$. A message length is general distribution, and a mean and variance of message length are denoted as h and g. Furthermore, since the maximum capacity of the system is M[packets/slot], we normalize the number of packets transmitted by all nodes per slot by M. In this paper, we define the ratio of the total number of packets transmitted by all nodes and the maximum capacity M as the offered load ρ. That is, ρ can be calculated as $(\sigma \cdot h \cdot N)/M$.

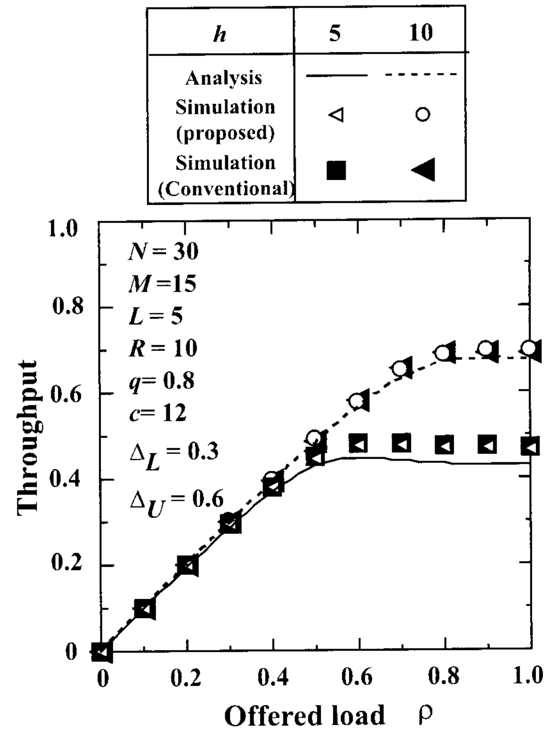

Fig. 5. Throughput versus the offered load for an average of message length ($N = 30$, $M = 15$, $L = 5$, $R = 10$, $q = 0.8$, $c = 12$, $\Delta_L = 0.3$, $\Delta_U = 0.6$).

Fig. 5 shows throughput versus offered load for an average of message length. A solid line and a plot indicate results of an approximate analysis and computer simulations, respectively, where $M = 15$ and $L = 5$ are set. In this figure, these results nearly are close, whereas the analytical results don't coincide with the computer simulated results as ρ is large. This is because we assume that the length of the queue for each wavelength is equal to be identical. Therefore, as offered load increases and the values of queues are larger, the difference between these results is larger. Also, the throughput of the proposed protocol coincides with the conventional one. This is because the throughput is related to the number of control packets which does not collide with other ones, and the source conflict counter used in the proposed model does not give any effects for the throughput performance. From the figure, it is observed that throughputs are saturated as ρ increases. When $\rho = 1$, the value of throughputs for $h = 5$ and 10 are 0.428 and 0.672, respectively.

Fig. 6 shows throughput versus offered load for the number of minislots by an approximate analysis, where $M = 15$ and $h = 10$ are set. In this figure, as L becomes large, the values of throughput are larger. This is because the collision probability of control packets is small as L is large. Also, it is shown that the increase of throughput between $L = 3$ and $L = 5$ is larger than that between $L = 5$ and $L = 7$. When $\rho = 1$, the value of

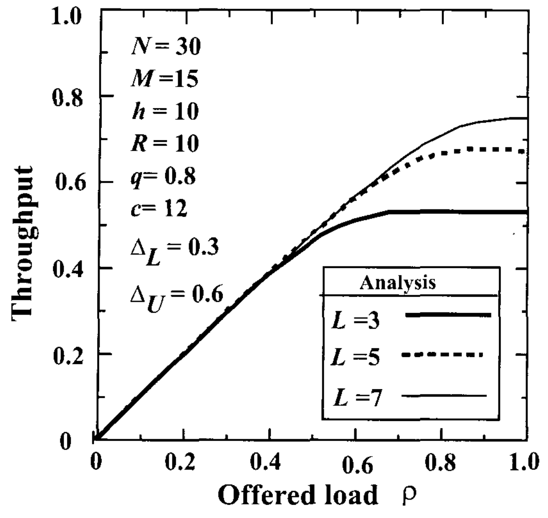

Fig. 6. Throughput versus the offered load for the number of minislots ($N = 30$, $M = 15$, $h = 10$, $R = 10$, $q = 0.8$, $c = 12$, $\Delta_L = 0.3$, $\Delta_U = 0.6$).

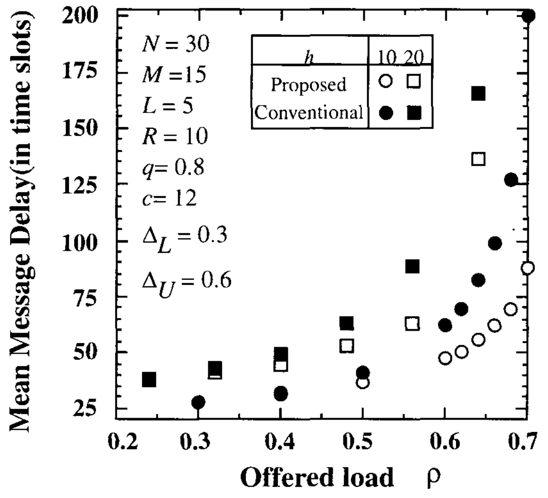

Fig. 7. Mean message delay versus the offered load for message length ($N = 30$, $M = 15$, $L = 5$, $R = 10$, $q = 0.8$, $c = 12$, $\Delta_L = 0.3$, $\Delta_U = 0.6$).

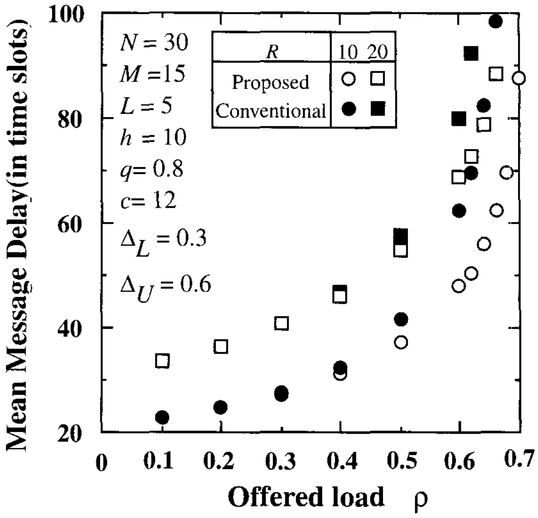

Fig. 8. Mean message delay versus the offered load for the maximum round-trip propagation delay ($N = 30$, $M = 15$, $L = 5$, $h = 10$, $g = 90$, $q = 0.8$, $c = 12$, $\Delta_L = 0.3$, $\Delta_U = 0.6$).

throughputs for $L = 3$ and 7 are 0.528 and 0.749, respectively.

Fig. 7 shows mean message delay versus offered load for the message length h by computer simulations. The maximum round-trip propagation delay $R = 10$, and $L = 5$ are set. When $h = 10$ and 20, $g = 90$ and 380 are selected, respectively. In this paper, the message delay is defined as a period from the time that a source node generates a message until the time that the source node completes transmitting the message. In this figure, the proposed protocol can reduce mean message delay dramatically compared to the conventional one as ρ increases. This is because in the proposed protocol, each node can detect a source conflict using the source conflict counter. So, the proposed protocol can start the procedure to newly obtain the right to transmit the message, which cannot be transmitted due to a source conflict, earlier than in the conventional one. Also, as h increases, the difference of delay performance between these results is larger. This reason is as follows. As h increases, the value of the counter GQ becomes larger since the value of the message length is added to the counter GQ. In the conventional protocol, a source node which obtains the right to transmit a message using a wavelength must wait during a period which is equal to the value of the counter GQ for the wavelength. After that, a source node cannot transmit the message if a source conflict occurs, and has to newly obtain the right to transmit the message using the wavelength. On the other hand, in the proposed protocol, by using a source conflict counter a source node can detect a source conflict before a wavelength assignment is performed, without waiting for a period which is equal to the value of the counter GQ. Therefore, as the value of the counter GQs is large, the difference between results of the proposed protocol and conventional protocol is larger.

Fig. 8 shows mean message delay versus offered load for maximum round-trip propagation delay R by computer simulations, where $M = 15$, $L = 5$, $h = 10$, and $g = 90$ are set. In this figure, the proposed protocol can reduce the message delay dramatically compared to the conventional one as ρ increases. This reason is the same as that of Fig.7. Also, mean message delay is large as R is large. This is because as R is large, a period from the time that a source node transmits a control packet until the time that a collision of control packets is investigated by each node becomes large.

Fig. 9 shows mean message delay versus the number of wavelengths M by computer simulations, where $R = 10$, $h = 10$, $L = 5$, and $g = 90$ are set. In this figure, as M is small, the proposed protocol can reduce the message delay largely compared to the conventional one. This is because the value of GQ counters is large as M is small.

V. CONCLUSIONS

In this paper, we have proposed a new channel reservation protocol using a counter for a detection of a source conflict in a WDM single-hop network with non-equivalent propagation delay. We approximately analyze the throughput performance

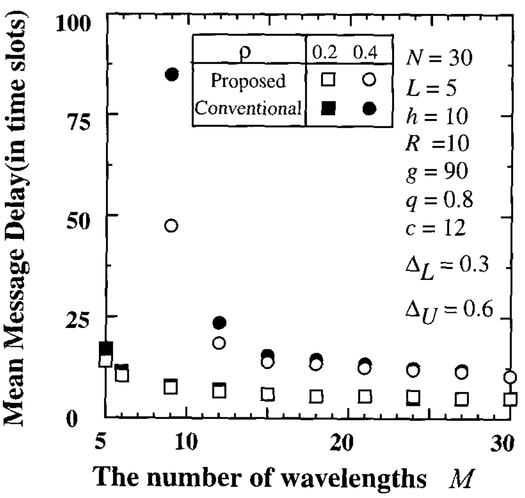

Fig. 9. Mean message delay versus the number of wavelengths ($N = 30$, $L = 5$, $h = 10$, $g = 90$, $R = 10$, $q = 0.8$, $c = 12$, $\Delta_L = 0.3$, $\Delta_U = 0.6$).

considering the effect of a source conflict, and show the result of approximate analysis is close to that of the computer simulation. Also, we show by computer simulations that our proposed protocol can reduce mean message delay dramatically without degrading throughput performance as the offered load becomes large.

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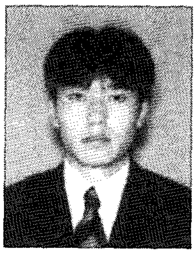

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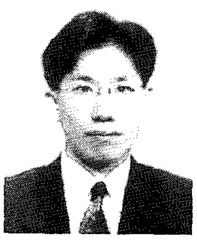

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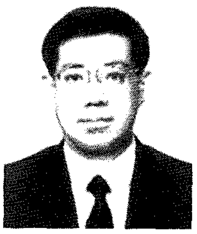

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