p-Persistent MAC Protocol for WDM Ring Networks

Won-ho So*, Young-chon Kim** ***Regular Members***

ABSTRACT

In this paper, a WDM metro ring consisting of access nodes with FT-FR^n (Fixed Transmitter - *n* Fixed Receivers) is considered. A trade-off exists between node throughput and transmission fairness because the access nodes share wavelength channels. In order to eliminate the transmission unfairness and to increase throughput, the *p*-persistent medium access control (MAC) protocol is proposed: each node uses an empty optical slot to transmit a packet and make it available with the extraction of a transferred packet at the source access node, called source-stripping. The local empty slot can be used to transfer a head-of-line packet in the local buffer with probability *p* or it is used for the next downstream nodes with 1-*p*. The proposed MAC protocol provides better node throughput than the non-persistent protocol and exhibits better fairness index than the 1-persistent protocol in WDM ring networks. In addition, numerical analysis shows that the proposed MAC protocol maximizes the node throughput under uniform traffic conditions. For more detailed results, we use the network simulation under Poisson and self-similar traffic. Furthermore, unpredictable traffic constructed by the combination of the former and the latter is also considered. The reasonable probability of the *p*-persistent protocol for a given architecture can be determined through simulation.

Key Words : Medium Access Control, WDM networks, Fair transmission, Collision Avoidance.

Ⅰ. Introduction

The future Internet may be viewed as a three-level hierarchy consisting of backbone networks, metropolitan area networks, and local access networks. The backbone networks provide abundant bandwidth by employing wavelength division multiplexing (WDM) links. The local access networks carry the data between individual users by employing Gigabit Ethernet (GbE), broadband wired or wireless access networks. The existing metropolitan area networks, however, are limited by bandwidth bottleneck, which occurs in circuit-switched SONET/SDH metro networks. WDM-based solutions are therefore expected to be adopted in the metropolitan area as next generation access networks[1-3].

Although most of the research in WDM metro networks has focused on broadcast-and-select and wavelength routing mesh networks, there are a number of advantages associated with ring topologies: simple routing policy, simple control and management of network resources, simple hardware system, and simple protection. Several studies on the WDM ring have been performed, and one of notable WDM rings is HONET (Hybrid Opto-electronic Ring Network) with TT-FR (Tunable Transmitter - Fixed Receiver) node architecture. HONET uses the carrier sense multiple access with collision avoidance (CSMA/CA) MAC protocol based on sub-carrier multiplexing. In addition, another TT-FR model implements the synchronous round robin with the reservation (SR3) MAC protocol and adopts multi-metaring (MMR) to guarantee transmission fairness among the nodes in the network[4,5]. A

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* 순천대학교 컴퓨터교육과 컴퓨터네트워크 연구실 (whso@sunchon.ac.kr)
** 전북대학교 컴퓨터공학과 차세대통신망연구실 (yckim@chonbuk.ac.kr)

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WDM ring with FT-FRn (Fixed Transmitter - *n* Fixed Receivers) architecture was also proposed and evaluated through theoretic analysis and simulation. This WDM ring also uses CSMA/CA and contains a simple MAC protocol restriction to provide fairness transmission[6].

Bononi [7] analytically evaluated the performance of both FT-TR (Fixed Transmitter-Tunable Receiver) and TT-FR slotted architecture and concluded that they have similar theoretical networking performance. It is found through [6] that FT-FR^{n} as the FT-TR model is more accurate than the TT-FR model in terms of network scalability predictions. FT-FR^{n} architecture also provides very good results, as long as the overall traffic per wavelength does not reach a certain threshold value. In addition, the flexibility of the network is very high and attractive and easy physical deployment can be achieved.

In the FT-FR^{n} architecture, in order to support fairness transmission, each access node does not use a local empty slot, which is defined as an empty slot made by source node based on source-stripping. Thus the source node is able to use this for sending its head of line packet, otherwise, one of the downstream nodes may transmit a packet with this empty lot. The low bandwidth efficiency results from empty slot transmission until next node, which make network performance decrease. On the other hand, if each source node uses the local empty slot immediately, the unfairness problem occurs.

In this paper, we evaluate the performance of two source-stripping protocols for the FT-FR^{n} architecture such as non-persistent MAC protocol and 1-persistent MAC protocol. In order to overcome the drawbacks of these two protocols, we propose the *p*-persistent MAC protocol. Through simulation, we find a reasonable probability *p* for a given network architecture and compare the performance of each protocol in terms of node throughput, fairness index, queuing delay, and packet loss probability.

This paper is organized as follows. In Section 2, we show the network architecture and the performance of previous protocols. The access protocol for considering the fairness transmission is proposed and described by numerical prediction in Section 3. In Section 4, we provide simulation results, such as node throughput, queuing delay, and so on. In addition, we find an acceptable probability for the given architecture. Finally, we draw conclusions and suggest future work in Section 5.

Ⅱ. Related Works and Comparisons

We consider a metropolitan area network as shown in Fig. 1. It is a simple multichannel WDM slotted-ring topology with fixed-size slots. It is unidirectional and basically consists of a number of access nodes (ANs) having add-and-drop capabilities to access the ring slots. Each node has three network ports. Firstly, a GbE port is used for connecting ANs to an access network, and the other two OC-like ports are used to access the WDM slotted-ring.

In the FT-FR^{n} architecture, each AN has a fixed transmitter and nfixed receivers, which allows them to transmit on a unique specific wavelength and receive all data on any wavelength. We assume the logical architecture of a node with source-stripping uses the information by carrier sensing and the MAC controller adjusts packet dropping, packet adding, and optical switching, which consists of On/Off SOAs (Semiconductor Optical Amplifiers).

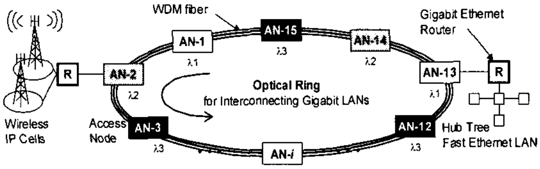
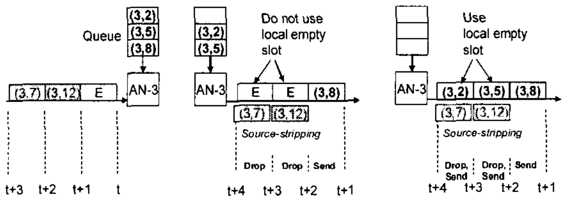


Fig. 1. WDM slotted-Ring Network

Fig. 2 shows examples about the different usage of local empty slots on previous MAC protocols such as the non-persistent MAC protocol and the 1-persistent MAC protocol. In Fig. 2a, there are three arrival slots, empty slot (E), slot

(3,12) set to (source address, destination address) and slot (3,7) at time *t*, *t*+1, and *t*+2, respectively. With the CSMA/CA protocol, when a node wishes to transmit data on its assigned wavelength, it simply inspects the activity of the channel via carrier sensing. If an empty slot is observed at *t*, a packet (3,8) in the local buffer (queue) can be transmitted in the slot data unit. If the slot is used, the transmission is simply delayed. In addition, each AN removes its packet once it is correctly received and makes the slot empty, which is now called local empty slot. In the case of the non-persistent protocol, AN-3 can not reuse the slot (Fig. 2b). This restriction introduces a simple fairness mechanism where nodes are forced to release local empty slots to their downstream neighbors transmitting packets on the same wavelength. On the other hand, as shown in Fig. 2c, the 1-persistent protocol uses local empty slots to transmit its packets, (3,5) and (3,2) without slot-time delay.

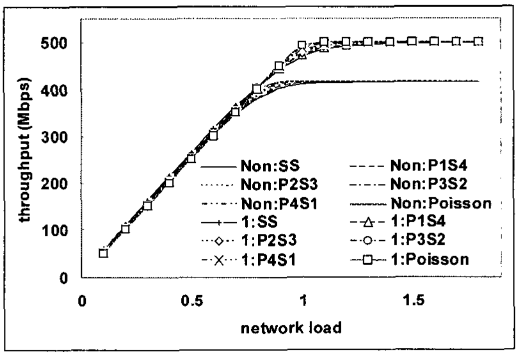
In order to evaluate the performance of the previous MAC protocols, we use network simulation. Firstly, under balanced traffic conditions, where we regard the traffic of each AN input from the GbE port as self-similar traffic and its destination address is decided uniformly, we evaluated the two protocols and present the results in [8,9]. Indeed, however, is not reasonable to assume that each AN has the same input traffic type. Thus, we consider Poisson and self-similar traffic and some combinations of the former and the latter as described in detail in Section 4.



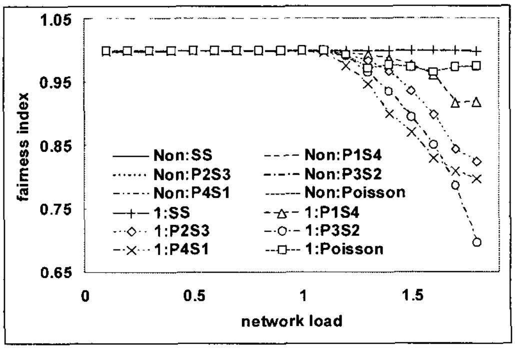
(a) Packet arrival (b) Non-persistent (c) 1-persistent

Fig. 2. Local empty slot usage according to protocols

Figure 3 shows the results of non- and 1-persistent protocols under the above assumptions. The node throughput of the 1-persistent case is high in Figure 3a, but its fairness index defined in the following Section 4 is equal to or less than non-persistent one, but it drastically decreases after a load of 1.0 in Figure 3b. Notice that the decrease in fairnessof the 1-persistent protocol means that the difference of the node throughput among ANs sharing same wavelength channel increases. Especially, the fairness index is very low in the case of P4S1 (P*x*S*y* means that a group sharing same wavelength consists of *x* Poisson input traffic based ANs and *y* Self-similar traffic based ones) combination, wherein four ANs have Poisson input and one AN receives self-similar traffic when located along the unidirectional link. This is because the fifth AN can not send packets when its four upstream ANs use optical empty slots depending on Poisson characteristics. Thus, there



(a) Node throughput of non- and 1-persistent protocols



(b) Fairness index of non- and 1-persistent protocols

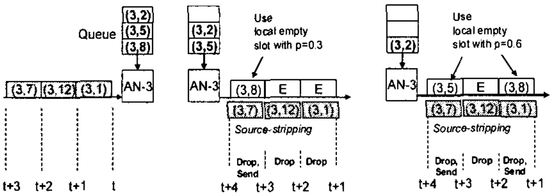
Fig. 3. Performance comparison of conventional protocols

are a lot of packets waiting in the queue of fifth AN and node throughput decreases.

In summary, ANs release local empty slots for downstream nodes using the non-persistent protocol. This leads to the degradation of node throughput. On the other hand, in the case of the 1-persistent protocol, ANs use local empty slots immediately when its local queue is full or input load is high. Thus, in the worst case, the source AN never concedes the next ANs local empty slots, and consequently the unfairness problem occurs.

Ⅲ. Probabilistic MAC Protocol

As described in the previous section, the sender can decide whether it can use a local empty slot when the slot is available by dropping the packet of a rotated-slot by the node. We propose *p*-persistent based CSMA/CA MAC protocol for WDM ring network. The sender can use a local empty slot with probability *p*, or not use it with probability 1-*p*. This means that the proposed protocol has an access node not only to send more packets than the non-persistent protocol, but provides more transmission chances to downstream nodes than the 1-persistent MAC protocol. One example is shown in Figure 4. The local queue of AN-3 has three packets (3,2), (3,5), and (3,8) and three optical slots (3,1), (3,12), and (3,7) arrive at time *t*, *t*+1, and *t*+2 respectively as shown in Fig. 4a. The arrived packets are to be removed by AN-3 because the slots are rotated-slots sent from the node. The Figure 4b shows the example of the operation with $p = 0.3$.



(a)Packet arrival (b) p=0.3 (c) p=0.6

Fig. 4. Probabilistic usage of empty slot of p-persistent protocol

Among three local empty slots, the first two slots are transferred without packets and the third slot (3,8) is transferred with packet. On the other hand, AN-3 can use two local empty slots to transmit packets in the case of $p = 0.6$, as depicted in Figure 4c. In summary, if the probability is low, the upstream node gives the downstream node more chances to use the local empty slot. Thus, if the downstream node has a waited packet for transmission, it will use this empty slot with high probability. If it is high, AN can use the empty slot for the transmission of its local packet with high probability. This means that the throughput of a node can be increased even though the fairness among nodes gets worse.

The diagram of the proposed MAC protocol is depicted in Fig. 5. As described above, AN uses the CSMA/CA protocol for sending a packet in an empty slot. The local empty slot usage of each AN depends on whether the Send_Flag is zero or one, which is determined by *p*. If *p* is zero or one, the protocol used is either the non-persistent protocol or the 1-persistent protocol described in the previous section. In our protocol, the **Send_Flag** is 1 when a random value *x* from 1 to 100 based on a uniform distribution is satisfied with $x < (100 \times p)$. This means that the 100×p% of local empty slots is used for sending packets at this AN.

In the previous sections, we introduced the proposed MAC protocol. In this section we demonstrate the suitability through numerical analysis. Because the topology considered is a unidirectional ring and a packet is delivered by an optical slot and removed at source AN, the network throughput depends mainly on the optical slot reuse. The slot-reuse factor defined in [6] is used to derive the bandwidth efficiency of the FT-FR^n architecture. We also define N as being the number of nodes that share wavelength for transmission, $N = N_T / N_W$, where N_T and N_W are the number of access nodes and number of wavelengths per fiber in the ring network, respectively.

Figure 6 shows graphical representations of the three MAC protocols. If a complete ring rotation is defined as being a normalized distance $d = 1$, then ***slot-reuse factor*** f_r is defined as the normalized distance it takes for a slot, once filled, to be made available. Furthermore, the ***bandwidth efficiency*** η is simply defined as the maximum number of packets that can be transported by any slot during full rotation around the ring. It should also be remembered that the packet size is supposed to be equal to the slot size. In that case, the bandwidth efficiency is simply equal to $1 / f_r$.

For example, in the 1-persistent case, it is true that the slot-reuse factor $f_r = 1$, i.e., a complete rotation is needed for the slot to be made reusable. Thus, for the bandwidth efficiency, $\eta_1 = 1$. However, in the non-persistent case, assuming that nodes are equally spaced around the ring (i.e., the normalized distance between any two nodes sharing a common wavelength for transmission is equal to $1/N$), $f_r = 1+1/N$ and $\eta_0 = N/(N+1)$. In the case of the p-persistent MAC protocol, the slot-reuse factor depends on p. When a slot is emptied and used at the source node with p, the slot-reuse factor is $1 \times p$. On the other hand, it is $(1+1/N)\times(1-p)$. Thus the expected value of the slot-reuse factor of this case is $1\times p+(1+1/N)(1-p)$, and it is finally $1+(1-p)/N$. In addition, we also obtain the bandwidth efficiency, given by

$$\eta_p = \frac{1}{1+(1-p)/N} = \frac{N}{N+(1-p)}. \tag{1}$$

Finally, in order to calculate the maximum throughput per node, T_{MAX}, we assume that all nodes transmit at the same rate. Thus, T_{MAX} is simply derived from the bandwidth efficiency as being R_W/N, where R_W is the transmission rate of the wavelength. The maximum throughput per node can therefore be derived for 1-persistent (T^1_{Max}), non-persistent (T^0_{Max}), and p-persistent (T^p_{Max}) cases, as equal to

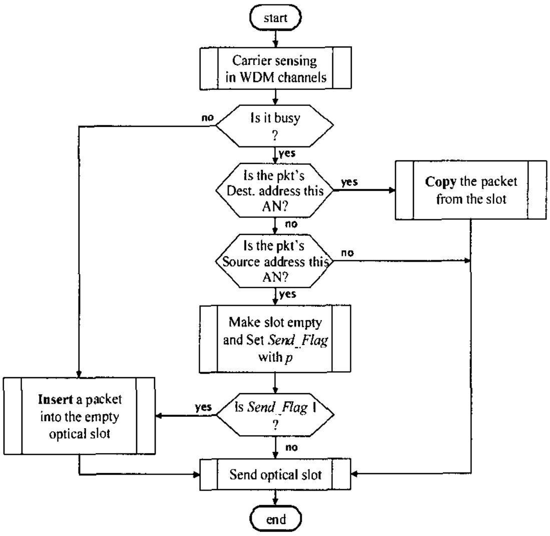
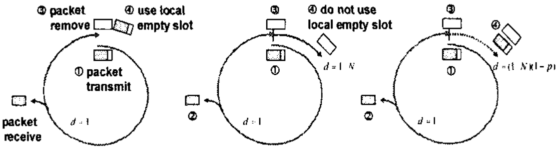


Fig. 5. Diagram of the proposed MAC protocol



(a) 1-persistent (b) non-persistent (c) *p*-persistent

Fig. 6. Slot-reuse factor and bandwidth efficiency

$$T^{\delta}_{Max} = \frac{\eta_\delta \times R_W}{N} = \frac{R_W}{N+(1-\delta)}, \tag{2}$$

where is 1, 0, and p, $0 < p < 1$.

Ⅳ. Simulation Results

The traffic received by each node from its GbE access link is generated according to a self-similar process and simulation environment, as referred to in [10]. The normalized network load L_N is defined as the ratio of the sum of all node transmission rates to the total network transmission capacity R_N. We consider node throughput, fairness index, queuing delay, and packet loss probability in the simulation. In particular, if node throughput results of m ANs are x_1, x_2, $\cdots$, x_m, respectively, then the fairness index is computed by equation (3)

$$\text{fairness index} = \frac{\left(\sum_{i=1}^{m} x_i\right)^2}{m\sum_{i=1}^{m} x_i^2}\ . \qquad (3)$$

Where, if all node throughput results are the same, the fairness index is 1. Otherwise, the fairness index decreases. Finally, we consider Poisson, self-similar, and combinations of former and latter traffic types. Thus, a combination traffic of PxSy means x upstream ANs depends on Poisson distributed input traffic and y folloing ANs use self-similar input traffic.

Firstly, from the numerical analysis, Fig. 7 shows the bandwidth efficiency of source-stripping based MAC protocols, depending on probability p. While the bandwidth efficiency of 1-persistent case is 1 constantly, the other cases show gradual increase of it regarding N, the number of access nodes sharing a common wavelength channel. Specially, when the probability is on $0 < p < 1$, p-persistent case is very dependent on N and p bandwidth efficiency. We assume N is 5 in this paper.

Fig. 8 shows the average node throughput of the three different MAC protocols. From (2), we can compute the maximum node throughput such as T^1_{Max} = 500 Mbps (p = 1.0), T^0_{Max} = 416.6 (p = 0). In the case of the p-persistent protocol, 446.4 and 490.2 Mbps for p = 0.4 and 0.9, respectively. The simulation results reach their numerical prediction. This means that the downstream AN can useempty slots with p if the upstream AN does not use the local empty slot, with probability 1-p. In addition, when we use the proposed protocol with probability above 0.9, the node throughput is similar to the 1-persistent case after the network load increases to 1.0.

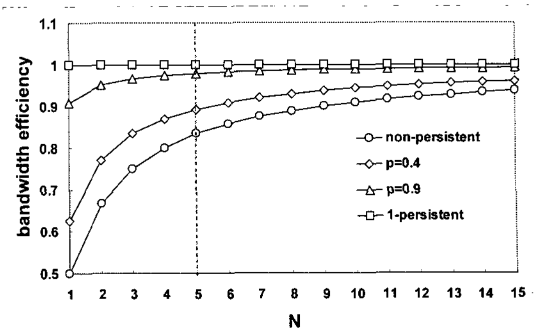


Fig. 7. Bandwidth efficiency of MAC protocols

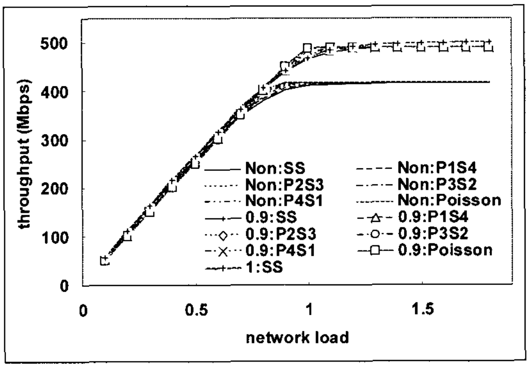


Fig. 8. Average node throughput

The fairness index is depicted in Fig. 9. Because this parameter is not analyzed by numerical prediction we use network simulation. From network load 0.6, the difference among different protocols increases, but this trend is not shown. In the case of combination traffic with the 1-persistent protocol, the fairness index increases after load 1.0. This is because upstream ANs using an empty slot have more chances than downstream ANs, when the capacity of the wavelength is fully utilized. For the non-persistent case, each AN should restrict the packet transmission on local empty slots. Thus, the fairness index is almost 1. In the case of the p-persistent protocol, however, the fairness problem is not critical, although p approaches 1. Although an upstream AN uses an available slot, it is not able to use that slot again after source-stripping, due to the law of probability. The fairness index of the p persistent protocol is within 1 percent of the fairness index of the non-persistent protocol. Fig. 10 shows the node throughput of all ANs in the simulated ring network under network load, L_N = 1.0 and 1.5. When p = 0.9 and each AN uses the proposed protocol, in an ideal case, all ANs have the similar node throughput and the average node throughput increases. In cases of p = 0 and p = 1.0, there are problems where thelow average node throughput or unfairness increases.

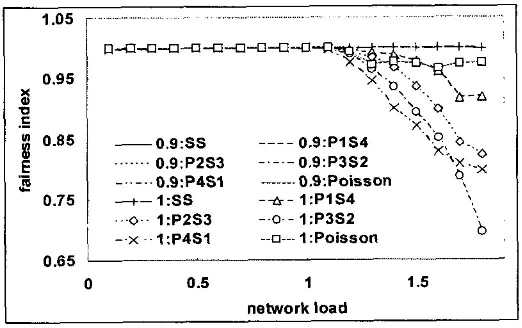


Fig. 9. Fairness index

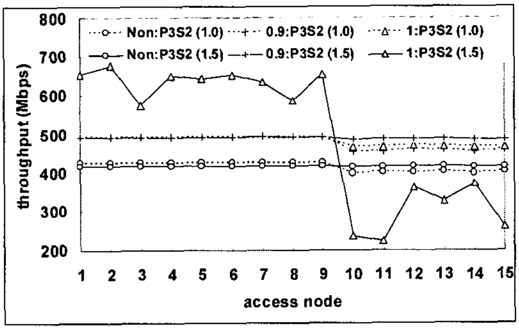
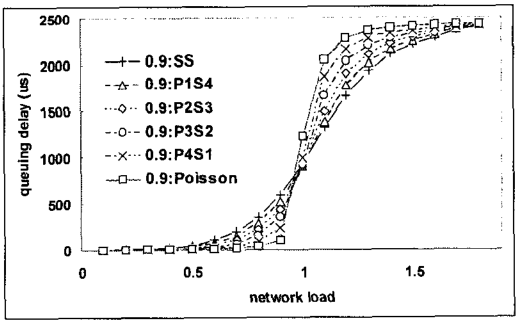
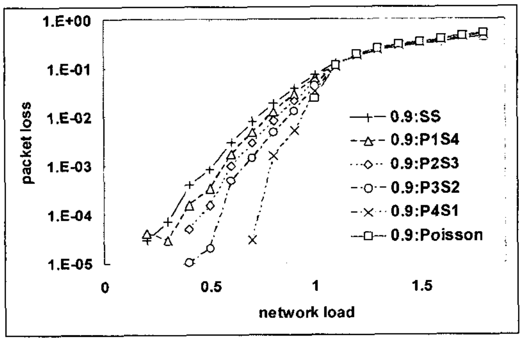


Fig. 10. Node throughput of access nodes

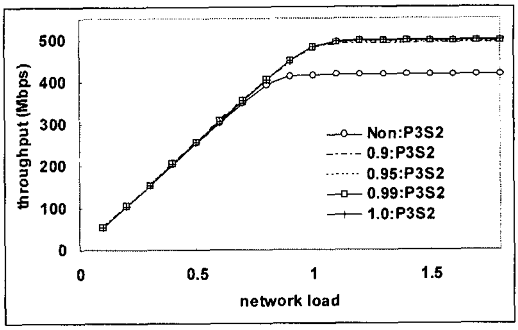


(a) Average queuing delay

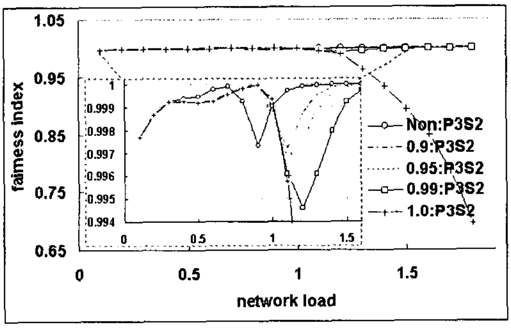


(b) Packet loss rate

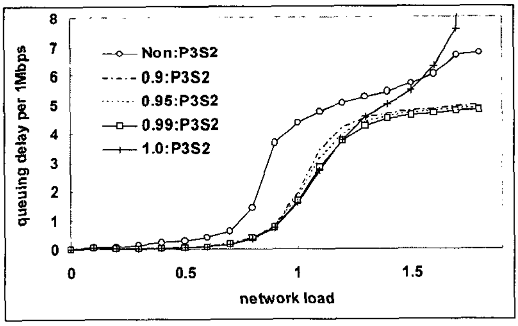
Fig. 11. Comparison of p-persistent protocol under varying input traffic



(a) Average node throughput



(b) Fairness index



(c) Required queuing delay for sending 1 Mbps data traffic

Fig. 12. Comparison of p-persistent protocol for finding reasonable probability

The average delay experienced by packets in the AN buffer and packet loss due to buffer overflow for p = 0.9 is considered in Fig. 11. Note that the average delay is very sensitive to both the characteristics of traffic combination and network load. When the network load is below 1, delay performance under Poisson-like traffic is improved. However, the opposite is true as network load increases (Fig. 11a). In the case of Fig. 11b, we also notice that the packet loss rate is better under Poisson traffic, when network load is below 1.

In the remaining sections, we consider a reasonable probability for the p-persistent MAC protocol to support both high node throughput and fair transmission. Fig. 12 shows the comparison of average node throughput, fairness index, and another queuing delay when pis 0.9, 0.95, and 0.99, respectively. In the case of throughput, there is little difference among them (Fig. 12a). When the 0.99-persistent MAC is used, the node throughput is closest to that of the 1-persistent case due to the high bandwidth efficiency resulting from equation (1). Fig. 12b of fairness, however, depicts that all cases of probabilities show that the degradation of fairness index is very low. Among them, the case of 0.9 is least, but all results converge to 1. Finally, we assess queuing delay per 1Mbps node throughput, through this parameter, we notice that the case of 0.99 needs a lower queuing delay for sending 1 Mbps data traffic, than the cases of 0.9 and 0.95 (Fig. 12c). In summary, it is very difficult to select a reasonable probability for the proposed MAC protocol. However, we can recommend the 0.99-persistent protocol in order to increase node throughput as much as possible.

V. Conclusions

In this paper, we consider a WDM metro ring network that consists of unidirectional optical link and access nodes sharing wavelengths. Usually, there is a tradeoff between transmission fairness and node throughput. We propose the p-persistent MAC protocol to guarantee these two performance parameters simultaneously. In order to obtain the objective, the proposed MAC protocol is based on CSMA/CA and use access probability to reduce the greedy usage of local empty slot at the upstream node. We evaluate the performance by not only numerical analysis but also simulation. Through network simulation, we find that our protocol resolves the fairness problem happened in the 1-persistent protocol while the node throughput increases more than in the case of the non-persistent protocol. In addition, we can recommend that the reasonable probability of the p-persistent protocol for source-stripping based FT-FR^n architecture is above $p = 0.9$. A variety of traffic conditions such as Poisson, self-similar, and both combinations were adopted for simulation.

In future study, we will not only consider the proposed protocol under the hot-spot traffic but also include an approach related to the MAC protocol to support QoS or service differentiation under various traffic scenarios. In addition, detailed analysis is needed to find the relationship between the probability p and transmission fairness.

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소원호 (Won-ho So) 정회원
한국통신학회 논문지 제25권 1A호 참조
현 재 순천대학교 컴퓨터교육과 조교수
<관심분야> WDM 망과 무선망 통신 프로토콜, QoS 제어 및 트래픽 엔지니어링, 네트워크 성능 분석 및 시뮬레이션

김영천 (Young-chon Kim) 정회원
한국통신학회 논문지 제19권 제2호 참조
현 재 전북대학교 컴퓨터공학과 교수