A High-Performance Optical Access and Control System for Packet-Switched WDM Metro Ring Networks

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Abstract- In this paper, we present the access and control design of a High-Performance Optical Packet-Switched WDM Metro ring Network (HOPSMAN). HOPSMAN has been designed for networks and nodes to be unconstrained by the number of wavelengths. It includes a handful of nodes that are equipped with fast optical slot erasers making bandwidth reusable and achieving greater bandwidth efficiency. In essence, HOPSMAN incorporates a versatile Medium Access Control (MAC) scheme, which embodies efficient and fair bandwidth allocation in accordance with a quota being exerted probabilistically. The quota is analytically derived with the number of slot-eraser-nodes taken into account. The scheme also employs a new notion of credit to regulate flexible access of remaining bandwidth that is suitable for the metro environment with bursty traffic. With the MAC scheme, HOPSMAN is shown to achieve exceptional throughput, delay, and fairness performance under a wide range of traffic settings via simulation results.

1. Introduction

Optical Packet-Switching (OPS) [1,2,3] has been considered a promising paradigm to support a wide range of heterogeneous traffic with different time-varying and high bandwidth demand over future optical Metropolitan Area Networks (MANs) [1,4]. Pertaining to OPS-based WDM MANs, the structure of slotted rings [5-8] receives the most attention. Such network requires the use of a Medium Access Control (MAC) mechanism [9-12] to offer effective bandwidth allocation so as to assure fair and high-performance access under a wide range of traffic loads and burstiness.

While there have been numerous OPS WDM slotted-ring networks proposed in the literature [4], only a handful [5-6] undertook experimental prototypes. We hence examine two prototyping networks that are most relevant to our work. First, HORNET [5] is a bi-directional WDM slotted ring network, employing a MAC protocol, called Distributed Queue Bidirectional Ring (DQBR), which is a variant of IEEE 802.16 DQDB protocol [13]. DQBR requires each node to maintain a distributed queue by means of a pair of counters per each wavelength. HORNET achieves acceptable utilization and fairness at the expense of high control complexity for maintaining the same number of counter pairs as that of wavelengths. However, due to the use of fixed-tuned receiver, HORNET statically assigns each node a wavelength as its home channel for receiving packets. Such design does not take advantage of statistical multiplexing gain and thus results in deteriorating throughput.

Second, RINGO [6] is a unidirectional WDM slotted ring network connecting no more than *N* nodes, where *N* is equal to the number of wavelengths. Each node is equipped with an array of fixed-tuned transmitters and one fixed-tuned receiver operating on a given home wavelength that identifies the node. It employs a MAC protocol that governs periodical access based on token-controlled variable-length cycles [7]. RINGO was shown to achieve high utilization and fairness. However, it results in deteriorating access delay under heavier loads resulting from an increase in cycle length. In addition, the restriction in which the node number cannot exceed the number of wavelengths gives rise to the scalability problem.

The aim of our work has been the design and experiment of a High-Performance Optical Packet-Switched WDM Metro ring Network (HOPSMAN). In this paper, we focus on the design of Medium Access Control (MAC) for HOPSMAN. HOPSMAN has been designed for networks and nodes to be architecturally unconstrained by the number of wavelengths. It includes a handful of nodes that are equipped with fast optical slot erasers making bandwidth reusable and achieving greater bandwidth efficiency. Essentially, HOPSMAN incorporates an effective and versatile MAC scheme, called Probabilistic Quota plus Credit (PQOC). PQOC embodies efficient bandwidth allocation in accordance with a quota being exerted probabilistically. The quota is analytically derived with the number of slot-eraser-nodes taken into account. PQOC also employs a new notion of credit to regulate flexible access of remaining bandwidth. Simulation results show that with PQOC, HOPSMAN achieves exceptional throughput, delay, and fairness performance under a wide range of traffic settings.

The remainder of this paper is organized as follows. In Section 2, we present the architecture of HOPSMAN. In Section 3, we describe the PQOC scheme and give the analysis based on which the probabilistic quota is determined. Simulation results are shown in Section 4. Finally, concluding remarks are given in Section 5.

2. System Architecture

HOPSMAN is operated at a node in a unidirectional WDM slotted-ring network that carries multiple WDM data channels (λ_1-λ_W, 10-Gb/s) and one control channel (λ_0, 2.5-Gb/s). All data slots of *W* channels are fully aligned with their

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corresponding control slot. The network contains two types of nodes- Server-node (S-node), and Ordinary-node (O-node). An S-node is equipped with more than one pair of tunable transmitters and receivers. In addition, it includes an optical slot eraser that empties out the slots that have already been received. An O-node is a regular node with only one pair of tunable transmitter and receiver. As will be shown, the network achieves superior throughput with only a handful of S-nodes.

The system architecture (see Figure 1) [3], consists of two building blocks- control-channel processing, and data-channel accessing. A fixed Optical Drop Filter (ODF) extracts the optical signal from the control channel on a slot-by-slot basis. The MAC Processor executes the PQOC scheme to determine the add/drop/erase operations for all W channels and the updates of the status in the control channel. Data-channel accessing corresponds to add/drop operations of data packets based on the *broadcast-and-select* configuration. Such design entails an unchanging architecture under different numbers of wavelengths.

After packets are passed through wideband optical splitters, a node receives a packet via an optical tunable receiver by means of the four-wave-mixing approach. Owing to the adoption of optical tunable receivers, HOPSMAN allows wavelengths to be flexibly accessed by nodes, rendering the network size unconstrained by the number of wavelengths. Likewise, a node tunes the tunable transmitter [14] to an available wavelength to transmit a packet. By using an array of W SOA on/off gates, the Slot Eraser reinserts new null signals on the wavelengths carrying unneeded packets.

3. Probabilistic Quota plus Credit (PQOC)

3.1. Basic Design

Notice that in one slot time, owing to single tunable transmitter/receiver, a node can make at most one packet transmission. Likewise, it is prohibited to have two packets destined for the same node but are carried by different wavelengths. We refer to this as the *vertical-access constraint*.

Basically, PQOC allows each node to transmit a maximum number of packets, called *quota*, within a cycle that is a pre-determined fixed number of slots. In essence, the quota is exerted in a probabilistic rather than deterministic fashion, in an attempt to prevent an unfairness problem under high network loads. This is because upstream nodes can access empty slots first, resulting in increasing tendency for downstream nodes to encounter available empty slots that are only located *vertically* around the rear of the cycle. This fact, together with the vertical-access constraint, gives rise to poorer throughput/delay performance for downstream nodes. The probabilistic quota is determined based on the analysis presented in the next subsection.

Furthermore, if a node cannot use up its quota within a cycle, the node yields the unused bandwidth (slots) to downstream nodes. In return, the node earns the same number of slots as credits. Such credits allow the node to transmit more packets beyond its original quota in upcoming cycles but within a limited number of cycles, called the *window*. The rationale behind such a design is to offer dynamic regulation of remaining bandwidth under the bursty traffic environment.

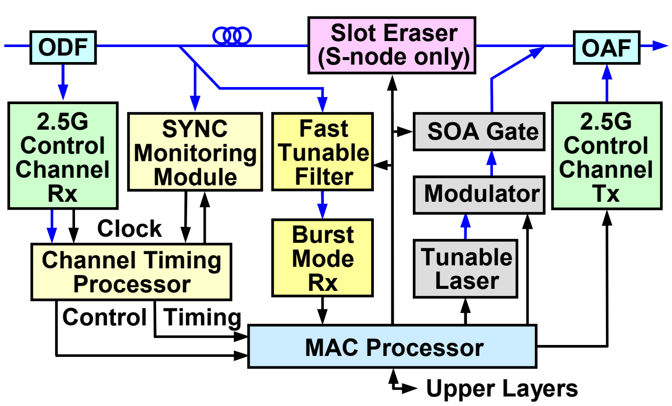

Figure 1. HOPSMAN- system architecture.

3.2. Probabilistic Quota Determination

Assume that there are S server-nodes (1 to S) in the network dividing itself into S sections (sections 1 to S). Each section contains more than one node including the server node. For the ease of illustration, the S-node for a section is placed in the most downstream location of that section. Namely, section 1 is preceded by S-node S in section S; and section k is preceded by S-node k-1 in section k-1, for k=2 to S. More specifically, for a network with N nodes, N is equal to the sum of N_k (k=1 to S), where N_k is the total number of nodes in section k.

A slot passed by an S-node is considered as either *Available Bandwidth* (*AB*) if the slot is empty or erased; or *Used Bandwidth* (*UB*) if the slot is non-empty and cannot be erased. Thus, the quota for a node can be computed as the mean value of *AB* observed by a section divided by the total number of nodes in the section. Consider an observed section (referred to as section b), we have $Q_b = \overline{AB_b} / N_b$, where Q_b denotes the quota to be allocated to any node in section b, $\overline{AB_b}$ the mean *AB* passed down by S-node b-1, and N_b the total number of nodes in section b. Notice that the value of $\overline{AB_b}$ is relevant to the traffic destination distribution; and S-nodes are possible to receive more traffic than O-nodes. Accordingly, we derive in the sequel a closed form for $\overline{AB_b}$ under two different destination distributions.

Case 1

In this case, traffic is uniformly distributed to all nodes. Moreover, for simplicity we consider a prevailing case in which S-nodes are evenly located in the network, namely $N_k = N/S$, where k=1 to S. Accordingly, each node is given the same $\overline{AB}$ and quota Q, where $Q = \overline{AB} / (N / S)$, for all nodes in the network.

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The value of $\overline{AB}$ can be computed as the mean total bandwidth (total number of slots in a cycle) minus $\overline{UB}$. Thus, in the sequel we analyze the $\overline{UB}$ value passed through S-node b-1. The analysis is given in two parts: one is to consider the transmissions from a section to itself (called intra-section traffic), and the other is to consider the transmissions from the section to all other sections (called inter-section traffic). For intra-section traffic, since the total amount of traffic (slots) generated from any section is $Q\cdot(N/S)$, thus the intra-section traffic amount is $Q\cdot(N/S)/S$. Within this amount of traffic, the proportion $Q\cdot(N/S)/2S$ will be erased by the most downstream node (S-node) of the section. Notice that erasable traffic corresponds to the traffic sent from upstream to downstream nodes within this section. Therefore, the remaining traffic, $Q\cdot(N/S)/2S$, which is sent from downstream to upstream nodes within this section, will be passed through the entire ring and seen by the section as UB.

For inter-section traffic, take section b+2 as an example. The traffic that is sent from section b+2 and passed through the entire ring and seen by S-node b-1 and section b as UB is the sum of the traffic destined to sections b and b+1. Thus, the UB is equal to $2\cdot Q\cdot(N/S)/S$. Finally, with all sections taken into account by summing all UB which passes through S-node b-1, and given that the total bandwidth in a cycle is $C\cdot W$, where C is the total number of slots in a cycle and W the number of wavelength channels, we obtain $\overline{AB}$ as the following equation

$$\overline{AB} = C\cdot W - \sum_{k=1}^{S}\left\{Q\cdot\frac{N}{S}\left(\frac{1}{2S}+\frac{k-1}{S}\right)\right\}, \quad (1)$$

With the equation, $Q = \overline{AB}/(N/S)$, we can attain the closed form solution for Q, as

$$Q = \frac{C\cdot W}{N}\left(\frac{2S}{S+2}\right). \quad (2)$$

Case 2

In this case, S-nodes are to receive additional traffic amount than O-nodes. In the sequel, we derive a closed form for $\overline{AB_b}$ under an assumption that a p_A probability of destination traffic is uniformly distributed to all nodes (including the S-nodes), while the remaining $1-p_A$ ($=p_S$) probability of traffic is additionally and evenly destined to all S-nodes. Notice that, the p_A value can easily be obtained through periodic traffic monitoring in network management which is beyond the scope of the paper.

Similar to case 1, to compute the value of $\overline{AB_b}$, we analyze the $\overline{UB}$ value passed through S-node b-1. Likewise, we consider both intra-section and inter-section traffic. For intra-section traffic, since the total amount of traffic (slots) generated from any section, take section k as an example, is $Q_k\cdot N_k$, thus the traffic amount from section k to section k itself is $(Q_k\cdot N_k\cdot p_S/S)+(Q_k\cdot N_k\cdot p_A\cdot N_k/N)$. Within this traffic amount, the proportion $(Q_k\cdot N_k\cdot p_S/S)+(Q_k\cdot N_k\cdot p_A\cdot N_k/2N)$, will be erased by section k's most downstream node, i.e., S-node k. Notice that the second term corresponds to the traffic sent from upstream to downstream nodes within section k. Therefore, the remaining traffic, $Q_k\cdot N_k\cdot p_A\cdot N_k/2N$, which is sent from downstream to upstream nodes within section k, will be passed through the entire ring and seen by section b as UB.

For inter-section traffic, take section b+2 as an example. The traffic that is sent from section b+2 and passed through the entire ring and seen by S-node b-1 and section b as UB is the sum of the traffic destined to sections b and b+1. Thus, the UB is $Q_{b+2}\cdot N_{b+2}\cdot((p_s/S)+(p_A\cdot N_b/N))+ Q_{b+2}\cdot N_{b+2}\cdot((p_s/S)+(p_A\cdot N_{b+1}/N))$. Finally, with all sections taken into account by summing all UB which passes through S-node b-1, and given that the total bandwidth in a cycle is $C\cdot W$, where C is the total number of slots in a cycle and W the number of data channels, we obtain $\overline{AB_b}$ as the following equation

$$\overline{AB_b} = C\cdot W - \sum_{k=1}^{S}\left\{Q_k N_k\left(\frac{p_A N_k}{2N}+U_k\right)\right\}, \text{ where}$$

$$U_k = \begin{cases} \sum_{m=b}^{k-1}\left(\frac{p_S}{S}+\frac{p_A N_m}{N}\right) & ,\text{if } b\le k\le S \\ \sum_{m=b}^{S}\left(\frac{p_S}{S}+\frac{p_A N_m}{N}\right)+\sum_{n=1}^{k-1}\left(\frac{p_S}{S}+\frac{p_A N_n}{N}\right), & \text{if } 1\le k< b \end{cases}. \quad (3)$$

Furthermore, consider that the S-nodes are evenly located in the network, namely $N_k = N/S$, where k=1 to S, we can attain the closed form solution for Q, as

$$Q = \frac{C\cdot W}{N}\left(\frac{2S}{S-p_S+2}\right). \quad (4)$$

With the quota determined as given in Equations (2) and (4), we are now at the stage of determining the probabilistic quota, denoted as P_Q. Given the total number of packets currently in the queue as np_{queue}, P_Q can simply be expressed as

$$P_Q = \min\left(\frac{Q}{C}, \frac{np_{queue}}{C}\right). \quad (5)$$

4. Simulation Results

We carried out simulation to demonstrate the performance of PQOC-operated HOPSMAN, in terms of throughput, delay, and fairness. In the simulation, node 1 is an S-node. Each cycle consists of 100 400-byte-long slots, or 8 μs long under a data rate of 10 Gb/s. The credit window size is set to be 10. Traffic is generated following either Poisson distribution or two-state (H and L) Markov Modulated Poisson Process (MMPP) for modeling smooth and bursty traffic, respectively. Simulation is terminated after reaching a 95% confidence interval. Notice that, due to multiple S-nodes and bandwidth reuse, the *traffic intensity* (*TI*) to be generated per slot per wavelength is unequal to the normalized load (*L*) per slot per wavelength. They can be related, according to Equation (4), as

$$TI = L \cdot \frac{Q}{C \cdot W / N} = L \cdot \left(\frac{2S}{S - p_S + 2} \right). \quad (6)$$

Therefore, given S S-nodes in the network, the maximum value of *TI*, defined as the *maximum throughput* (T^S_{max}), occurs at the normalized load L being equal to one. That is,

$$T^S_{max} = \frac{2S}{S - p_S + 2}. \quad (7)$$

We first depict the throughput performance of HOPSMAN under different S-node numbers and traffic destination probabilities (p_S). In the simulation, there are 60 nodes in the network. In Figure 2, we present analytic results of T^S_{max} from Equation (7). We have clearly observed that doubling the S-node number (between 1 and 16) results in noticeable improvement in throughput. However, the improvement rate declines as the S-node number increases, namely the throughput improves most effectively between the S-node numbers changing from one to two. The result explains the economy and efficiency of HOPSMAN behind the scarce use of S-nodes.

Focusing on HOPSMAN with one S-node, we examine the delay performance under a high load (0.9). In the simulation, there are 20 nodes in the network in which 19 nodes were O-nodes. Simulation results are plotted in Figure 3. As shown in the figure, HOPSMAN guarantees low delay and superior delay fairness under all traffic burstiness settings. As expected, delay increases with traffic burstiness. We further study the impact of credit window size on mean access delay under various burstiness settings. Simulation results are plotted in Figure 4. We observe from the figure that the mean delay declines with increasing window size under all burstiness. The results can serve as a guideline on the determination of an appropriate and small window size satisfying an acceptable grade of delay.

Recall that the use of credit to access slots beyond the quota in PQOC is to exert fair access control of unused remaining bandwidth on all nodes. This feature is demonstrated by the

T^S_{max} \ S / p_S	1	2	4	8	16
0	0.667	1.000	1.333	1.600	1.778
0.2	0.714	1.053	1.379	1.633	1.798
0.4	0.769	1.111	1.429	1.667	1.818
0.8	0.909	1.250	1.538	1.739	1.860

S = The number of S-nodes;
T^S_{max} = Max throughput under S S-nodes;
p_S = The probability of traffic additionally destined to all S-nodes;

Figure 2. Throughput under different S-node numbers.

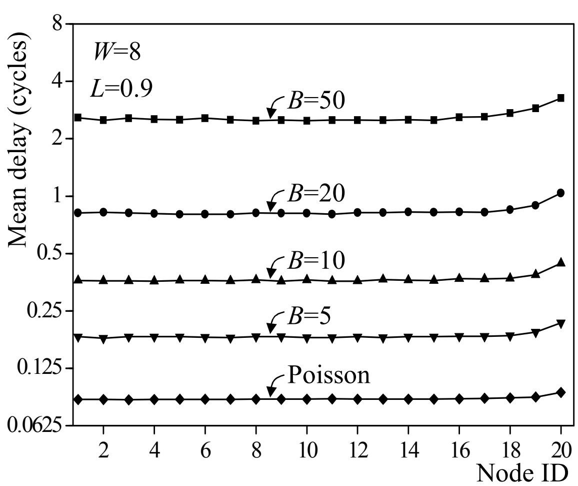

Figure 3. Delay performance under various burstiness.

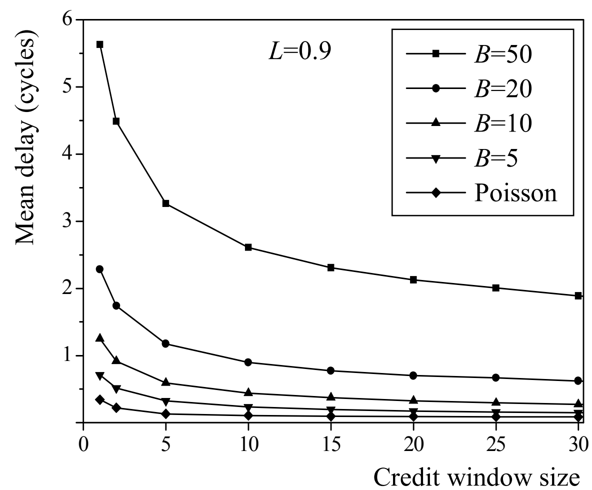

Figure 4. Credit window size impact on mean delay.

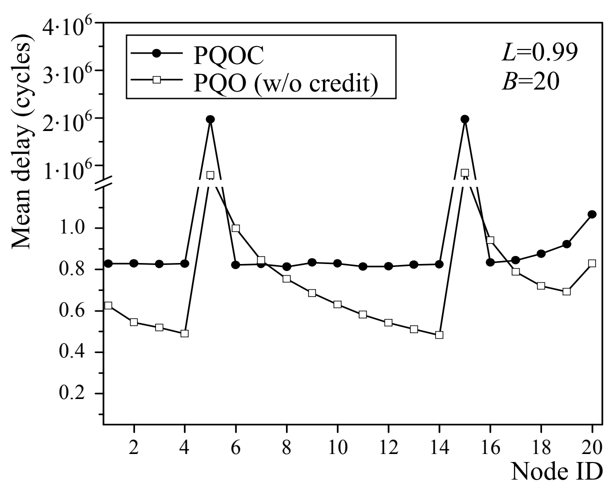

Figure 5. Effectiveness of credit.

simulation of HOPSMAN with malicious nodes. In the simulation, nodes 5 and 15 are considered malicious nodes each of which generated an excessive loads of 0.09, whereas each of the rest of the nodes generated a load of 0.045, rendering the network saturated, namely with a total load of 0.99. Simulation results are shown in Figure 5. In the figure, we draw a comparison of delay between the PQOC scheme and PQO (without the credit) under high burstiness of traffic (B=20). Notice that in PQO, due to the lack of the credit-based constraint, the remaining bandwidth is used on a first-come-first-serve basis. We observe from the figure that PQOC makes the two malicious nodes suffer severe delay while leaving other normal nodes completely unaffected, except for several downstream nodes due to network saturation. On the contrary, the PQO scheme without the credit gives rise to delay deterioration (and thus unfairness) to the neighboring nodes of the two malicious nodes. The PQOC scheme is thus justified robust and fair even when the network is under attack by malevolent nodes.

5. Conclusions

In this paper, we have presented the architectural and access control (PQOC), of our experimental optical packet-switched metro WDM ring network, HOPSMAN. HOPSMAN encompasses a few server nodes (S-nodes) that are equipped with optical slot erasers, resulting in a drastic increase in system throughput. Essentially, the PQOC scheme employs a probabilistic-quota-based method to achieve fair and efficient bandwidth allocation. Given the number of S-nodes and destination-traffic distribution, we derived a closed-form formula for the determination of the probabilistic quota. PQOC also uses a window-constrained credit-based approach to facilitate versatile allocation of the remaining bandwidth under highly-bursty and fluctuating traffic environments. Simulation results delineated that HOPSMAN achieves 100% throughput when there are only two S-nodes in the network. Furthermore, HOPSMAN with PQOC was shown to achieve exceedingly efficient and fair bandwidth allocation under various traffic loads and burstiness. Finally, HOPSMAN was justified robust and fair when under attack by malevolent nodes.

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