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Fully Distributed Work-Conserving MAC Protocols for Opportunistic Optical Hyperchannels

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Abstract—Light-trail is proposed as a candidate to carry IP traffic over wavelength division multiplexing (WDM) optical networks given its capability of accommodating multi-granularity traffic by time-division multiplexing (TDM). Light-trail's unidirectional shared-media multicast nature makes it hard to implement distributed access control and restricts that at most one packet transmission can take place at any time. Recently, opportunistic optical hyperchannel was proposed to improve light-trail by permitting easy distributed access control. In this paper, we propose a set of distributed access control protocols, namely, 1-persistent protocols, for opportunistic optical hyperchannels to maximize the throughput and provide fair service among contending nodes by taking their inherent advantage of adaptive space-division multiplexing (SDM). We also point out a possible generalization of opportunistic optical hyperchannels by removing the restriction of linear structure, and demonstrate possible applications of such a generalization.

Index Terms—Optical network, WDM, TDM, SDM, CSMA, MAC, light-trail, opportunistic optical hyperchannel.

I. INTRODUCTION

OPTICAL Wavelength Division Multiplexing (WDM) technology has been considered as the basis of the next generation wired Internet. In the past decades, great efforts have been made on elevating the wavelength utilization in WDM networks with off-the-shelf optical components. Wavelength utilization is limited in WDM networks due to the following two mismatches: (1) the mismatch between high bandwidth and relatively long delay of optical switch configuration; (2) the mismatch between high bandwidth per wavelength can provide and relatively low bandwidth requirement of a single connection. Correspondently, the work proposed to improve wavelength utilization mainly focus on either or both of the following two perspectives: (1) reducing the frequency of optical switch configuration; (2) multiplexing/grooming traffic into one optical path.

Optical packet switching (OPS) [1] and optical burst switching (OBS) [2] aim to resolve the second mismatch. However,

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Fig. 1. Opportunistic optical hyperchannel architecture.

such solutions require optical addressing and buffering, high-speed optical routing and switching, which are technologies still in nascent stages of development. Traffic grooming [3] on a virtual topology which consists of a set of lightpaths [4] aims to resolve both mismatches. Traffic grooming allows two connections to share the bandwidth of a lightpath according to time-division multiplexing (TDM) which can improve the inefficiency of lightpaths. However, in traffic grooming, two connections can share the bandwidth of a lightpath only when the start node and the end node of such lightpath are on the optical paths of both connections, which limits the flexibility of multiplexing. *Light-trail* [5] generalizes lightpath with improved scalability by allowing time-division multiplexing (TDM) bandwidth utilization between any two nodes within a light-trail. *Light-trail* is a multi-point to multi-point solution and can be viewed as a generalization of the sub-wavelength solutions proposed in the literature, e.g., super-lightpath [6] which provides point to multi-point communication and TWIN [7] which is applicable to multi-point to point communication.

In a light-trail, optical shutters at the start node and the end node are set to be in OFF state such that the start node can only send data to downstream nodes and the end node can only receive data from upstream nodes. The optical shutters at intermediate nodes are configured to be in ON state to allow the traffic from upstream nodes to be passed to downstream nodes. Once a light-trail is established, communications between pairs of nodes are accomplished in a time-multiplexing mode without optical switching. Therefore, only one packet can be transmitted at a time, which limits the system throughput.

With the recent development on ultra fast optical shutter [9], we proposed an improved light-trail architecture in [10], called *opportunistic optical hyperchannel* and a generalized WDM mesh network that supports opportunistic optical hyperchannels. Fig. 1 illustrates the architecture of a (unidirectional) opportunistic optical hyperchannel. In such an opportunistic optical hyperchannel, optical shutters at the start node and the end node are set to be in OFF state as in a light-

trail. The optical shutters at intermediate nodes can be set to ON or OFF state dynamically. Any intermediate node which is about to transmit data will set its optical shutter to be OFF, and “cut” the opportunistic optical hyperchannel into two segments. Therefore, the traffic from the upstream nodes will be intercepted at the current node and the current node is allowed to transmit its data without collision. If the packet intercepted from an upstream node already passed its destination, its transmission has finished and it will not consume the system bandwidth anymore. Thus, opportunistic hyperchannel can potentially improve the throughput given the fact that multiple simultaneous transmissions are possible as long as those connections are restricted to non-overlapped segments of the hyperchannel. We call this feature *adaptive space-division multiplexing* (adaptive SDM).

To maximize the throughput of an opportunistic optical hyperchannel, a medium access control (MAC) protocol is required to coordinate the access of the hyperchannel, which is the main focus of this paper. The goal of our investigation is to develop simple, easy-to-implement “aggressive” fully distributed MAC protocols that take the advantage of adaptive SDM to not only amplify the hyperchannel throughput with respect to the opportunistic optical hyperchannel bandwidth, but also achieve good fairness. The contributions of this paper are summarized as follows:

- We propose simple fully distributed and work-conserving dynamic scheduling protocols, namely *1-persistent* protocols, for opportunistic optical hyperchannels of a bus structure, which aim at achieving maximum amplified system throughput and providing good fairness.
- We analyze our protocols by deriving lower bound and upper bound for the throughput amplification of running 1-persistent protocols on an opportunistic optical hyperchannel in comparison with any work-conserving CSMA protocol running on a light-trail. We also provides an upper bound for the relative worst-case packet delay of our protocols compared with GRR. According to our analysis, though upstream nodes may experience longer delay than downstream nodes if 1-persistent protocols are used, no node will suffer from starvation. Upper bound of average buffer size at an intermediate node is also derived. We present simulation results, and show that our simulations validate our analysis.
- We extend the concept of opportunistic optical hyperchannel, which inherently has a linear (bus) topology, into opportunistic optical hyperchannels with non-linear topologies embedded in an optical mesh network. Due to the high bandwidth that one wavelength can provide, non-linear opportunistic hyperchannel is a solution to provide high bandwidth utilization. In particular, we show non-linear opportunistic optical hyperchannels of tree topologies, namely gathering tree and multicast-and-select tree. We present an implementation of 1-persistent protocols in a gathering tree opportunistic hyperchannel and applications of a pair of gathering tree and multicast-and-select trees.

The rest of the paper is organized as follows. The related work is summarized in Section II. In Section III, we review

the structure of an opportunistic optical hyperchannel. In Section IV, we describe the features of a class of 1-persistent MAC protocols. In Section V, we give the performance analysis of the proposed 1-persistent protocols. We present our simulation results in Section VI. In Section VII, we discuss non-linear opportunistic optical hyperchannels (a generalization of opportunistic optical hyperchannel), its associated 1-persistent protocols and its applications. Section VII concludes the paper.

II. RELATED WORK

As pointed out in [10], the capability of “intercepting” packets from upstream nodes in an opportunistic optical hyperchannel makes it possible to design a family of distributed MAC protocols. In [10], we proposed a distributed QoS-assuring MAC protocol, called *minSrcRR* protocol. In *minSrcRR* protocol, each node selects one of its upstream nodes as the reference node and adjust its accumulated quota by observing the traffic coming from its reference upstream node. When it has enough quota, it will set its optical shutter to be in OFF state and start the local transmission. Thus, QoS is assured. Since some nodes may hold their transmission until they have enough quota, opportunistic optical hyperchannel may not achieve its capacity of high throughput in *minSrcRR* protocol. In this paper, our focus is to design distributed protocols to maximize the throughput of an opportunistic optical hyperchannel and provide good fairness. Besides comparing the protocol proposed in this paper with *minSrcRR* protocol, we are also interested in comparing our protocol with other MAC protocols in the generic family of opportunistic optical hyperchannel, unidirectional optical bus in terms of throughput and fairness.

Basically, there are three kinds of architectures for optical buses: folded, dual, and unidirectional. A dual bus consists of two unidirectional buses with signals propagating in opposite directions. All-to-all communications are supported in both folded and dual optical bus, while only upstream nodes can transmit packets to downstream nodes in a unidirectional optical bus. Without incorporating a “feedback” mechanism, upstream nodes has no knowledge of what is happening on the downstream segment of a unidirectional bus. Thus, most of the previous studies were focused on the architecture of either folded or dual optical bus and were carrier sense multiple access (CSMA) protocols. These protocols use collision detection to avoid packet transmission collisions. Representative CSMA protocols for optical folded and dual buses can be found in [11]–[16].

CSMA protocols for unidirectional optical buses [17]–[22] can be classified into two categories: CSMA protocols maximizing system throughput and CSMA protocols providing fairness among contending nodes. A representative CSMA protocol maximizing system throughput in optical buses is called *priority based CSMA* protocol [17]. In a priority based CSMA protocol, whenever the downstream nodes sense data from the upstream nodes, the downstream nodes will interrupt their transmissions and free the bus for the transmissions from the upstream nodes. Priority based CSMA protocol can obviously achieve high throughput at the cost of severe unfairness to the downstream nodes. A representative CSMA protocol providing fairness in a unidirectional optical bus is

p_i -persistent CSMA protocol [18]–[21]. Node N_i in a system running the p_i -persistent CSMA operates as: (1) If the channel is sensed idle, it transmits the packet with probability p_i ; (2) If the channel is sensed busy, it waits until the channel goes idle (i.e. persisting on transmitting) and then transmits the packet with probability p_i . Slotted p_i -persistent CSMA protocols were analyzed in [18]–[20]. It was shown that, by deriving the steady-state probabilities of all nodes using queuing theory, a set of p_i s can be computed to enforce fairness. In [21], an unslotted p_i -persistent CSMA protocol was introduced.

Theoretical analysis and simulation results of [18]–[21] show that theoretically a unidirectional optical bus can provide fair service using p_i -persistent CSMA protocols, assuming that p_i s, which are the parameters used to control packet transmissions, match the traffic pattern and service requirement. However, p_i -persistent CSMA protocols also have drawbacks: (1) Obviously, any p_i -persistent CSMA protocol is not work-conserving; i.e. the channel may be idle with waiting packets. (2) In addition, packets transmitting collision cannot be completely avoided, which wastes channel bandwidth. (3) The responsiveness of p_i -persistent CSMA protocols is slow. To achieve desired performance, p_i s have to be computed beforehand for specific traffic pattern and/or service requirement. Even for a small traffic change in one node, p_i s have to be recalculated and nodes have to be notified of new p_i s. For dynamic traffic and/or service requirements, this process is not only wasting channel bandwidth, but also slow in response to changes of network conditions.

The work proposed in [22] can provide fairness in a unidirectional optical bus where each destination receives information in a fixed wavelength and each source has a tunable transmitter. Each node maintains a Virtual Output Queue (VOQ) for each wavelength and determines to which wavelength it should tune such that collision will be reduced and fairness can be provided. When there is only one wavelength in a unidirectional optical bus, the proposed work is equivalent to priority-based CSMA protocol.

III. SYSTEM MODEL

In this section, we review the architecture of opportunistic optical hyperchannel proposed in [10]. In an $(n + 1)$ -node opportunistic optical hyperchannel, the nodes are labeled $N_0, N_1, \dots, N_n$, with N_0 and N_n as the *start node* and *end node*, respectively, as shown in Fig. 1. Each intermediate node can receive packets from upstream nodes and likewise transmit packets to downstream nodes, whereas the start node and end node can only transmit and receive packets, respectively. The architecture of an opportunistic hyperchannel is different from the architecture of a light-trail in the following two aspects:

- *Controllable Optical Shutter*. In an opportunistic optical hyperchannel, each intermediate node can control its optical shutter through the control component according to its traffic dynamically. When a node's optical shutter is set to be in ON state, it allows the traffic from its upstream nodes to continue. It can also set its optical shutter to be in OFF state and thus send its own traffic.
- *Electronic Buffer*. When the optical shutter of an intermediate node is in OFF state, packets transmitted from

Fig. 2. CA switch in an opportunistic hyperchannel.

upstream nodes are electronically buffered, which may be forwarded later if the destinations are the downstream nodes. Since each node in any optical bus is capable of transmitting and receiving, such Optical-Electro-Optical (OEO) conversion does not incur any extra hardware cost. A packet may be intercepted before reaching its destination only when a downstream node has traffic to send at the same time slot. In such cases, the process of receiving packets from the upstream nodes takes place with the process of transmitting a packet generated by the downstream node simultaneously. In other words, at least one packet from the downstream node will reach its destination. Thus, OEO conversion will not affect bandwidth utilization. In terms of the capacity requirement of electronic buffer, as we will show shortly, the proposed 1-persistent protocol will not require too large electronic buffer when the total traffic load of all connections in an opportunistic optical hyperchannel is less than the wavelength capacity.

Since each intermediate node N_k in an opportunistic hyperchannel can dynamically control its optical shutter to be in ON or OFF states, it is equivalent to that each intermediate node N_k controls a 2×1 optical switch S_k , referred to as a *continue-add (CA) switch*. Each CA switch consists of an optical shutter, a combiner, and a transmitter as shown in Fig. 2. S_k operates in two states: *drop-and-continue state (DC state)*, in which the optical shutter is in ON state, and *drop-and-add state (DA state)*, in which the optical shutter is in OFF state. When S_k is set to be in DC state, the signal from the upstream nodes can drop a copy at node N_k and pass S_k simultaneously. When S_k is set to be in DA state, it intercepts the signal from the upstream nodes for later processing and transmits packets from local buffers of N_k without collision.

IV. 1-PERSISTENT MAC PROTOCOLS

In this section, we define 1-persistent MAC protocols for an $(n + 1)$ -node opportunistic hyperchannel, and propose two simple such protocols, and discuss related implementation issues.

A generic 1-persistent protocol work as follows. Each intermediate node N_k , $0 < k < n$, maintains two queues q_k^0 and q_k^k . The packets from the upstream nodes of N_k are always dropped at node N_k , some of which will be added to q_k^0 depending on the state of S_k . The locally generated packets are stored in q_k^k . If there is no locally generated packet in q_k^k , S_k remains in DC state. The packet in q_k^0 or q_k^k of N_k will trigger S_k to be changed from DC state to DA state. We define that a 1-persistent protocol for an opportunistic hyperchannel is a

fully distributed protocol such that any N_k , which is not the end node, transmits a packet whenever its $q_k^0 \neq \emptyset$ or $q_k^k \neq \emptyset$. Note that in this definition persistent packet transmission is the key condition, where the usage of the two queues, q_k^0 and q_k^k , is not essential. A node running a particular 1-persistent protocol may have one queue (merging q_k^0 and q_k^k into one), or even have more than two queues. Using a 1-persistent protocol, parallel packet transmissions without collision can be achieved by dynamically setting S_k to DA or DC state.

In the rest of this paper, we assume that packets have a fixed length, and their transmissions are slotted. Suppose that it takes t_g time to switch from one state to the other at a 2×1 optical switch. Let the transmission delay of a packet be T . With the advance of the switching technology, t_g can be expected to be much smaller than T . The timing of state change of a CA switch is controlled as follows. At each node, a t_g time latency, referred to as “guard time”, is inserted between the transmission of two consecutive packets. Thus, the period of each time slot will be $T + t_g$. Time slot i is the time interval $((i-1) \cdot (T + t_g), i \cdot (T + t_g)]$ for $i > 1$. Suppose that in a time slot i a local packet p is generated at N_k so that q_k^k is changed from empty state to non-empty state. Then S_k will be switched from DC state to the DA state during the time $((i-1) \cdot (T + t_g) + T, i \cdot (T + t_g)]$. In other words, By introducing the guard time t_g , an intermediate node is able to pass one packet from an upstream node and also change its state in one time slot.

Suppose in a time slot i a packet from either q_k^0 or q_k^k is transmitted, then the transmission must have been finished by the time of $(i-1) \cdot (T + t_g) + T$. If no more packets in either queue, at the time period of $((i-1) \cdot (T + t_g) + T, i \cdot (T + t_g)]$, S_k is switched from DA state to DC state. Clearly, node is able to transmit a packet and also change its state in one time slot. This approach divides each time slot into two portions, one portion for packet transmission and one portion for the potential state change. During the time portion of the state change, no data transmission is ongoing, thus incomplete packet transmission is avoided. This approach is very efficient when $t_g \ll T$, which is highly feasible nowadays for optical shutter [9].

To implement such a 1-persistent protocol, the following technical issue has to be addressed:

- Since each packet from the upstream nodes will be dropped at N_k , N_k needs to determine which packets should go to q_k^0 to be relayed to downstream nodes.
- When S_k is in DA state, which packet from either q_k^0 or from q_k^k should be relayed to downstream nodes to assure fairness.

In the rest of this section, we present a procedure for each node to determine whether a packet from the upstream nodes should be buffered or not, followed by introducing the implementation of two particular 1-persistent protocols at each node. At the end of this section, we summarize the properties of the proposed protocols.

A. Queuing Decisions for Received Packets

The packets dropped at N_k include: (i) packets from N_k 's upstream nodes that have passed S_k when S_k is in DC state.

The destinations of these packets can be the upstream nodes of N_k , N_k itself, or the downstream nodes of N_k . (ii) packets from N_k 's upstream nodes that are stored in N_k when S_k is in DA state. For these packets, some of them should be discarded, some of them should enter queue q_k^0 for later transmission, and some of them should be taken (locally “consumed”) if the destination of the packets is N_k .

With respect to a received packet p , at the end of a time slot, N_k will process p according to the following procedure:

- Case 1: if S_k is in DC state and the destination of p is a downstream node, then discard p ; otherwise,
- Case 2: if the destination of p is an upstream node of N_k , then discard p ; otherwise,
- Case 3: if the destination of p is N_k , then take p ; otherwise,
- Case 4: put p at the end of q_k^0 .

B. Simple 1-Persistent Protocols

According to the definition of 1-persistent protocols, many 1-persistent protocols can be designed. Our goal is to design fair 1-persistent protocols that are easy to implement.

We assume that all nodes share the same system clock and each packet is associated with two attributes, timestamp $t_{stamp}(p)$ and source $s(p)$, which are respectively the system time at which p is originally generated and the node index that packet p is originally generated, in addition to the destination of p . Let $p_{i,k}$ be the packet originally generated at N_k at time slot i . Define that packet $p_{i',k'} < p_{i,k}$ if and only if $i' < i$ or $i' = i$ and $k' > k$. We say that packet $p_{i',k'}$'s timestamp is smaller than the timestamp of $p_{i,k}$ if $p_{i',k'} < p_{i,k}$. Clearly, there is a total order on the timestamps of all packets. Our 1-persistent protocol makes a decision for the next time slot after the first T time interval of the current slot as follows:

- When both q_k^0 and q_k^k are empty, S_k is set in DC state.
- When there are packets in either q_k^0 or q_k^k , S_k is changed to DA state. Among the head packets of q_k^0 and q_k^k , the one with the smaller t_{stamp} will be transmitted in the next time slot.

Implementing q_k^k as a First-In-First-Out (FIFO) queue, the packets in q_k^k are inherently sorted according to increasing time stamp order. However, if q_k^0 is a FIFO queue its packets might not be in sorted order. To see this, consider the following situation. All packets are destined for the end node N_n . Before time slot i , all nodes N_0 , N_1 , N_2 and N_3 do not have any packet. During slot i , N_0 generates a packet $p_{i,0}$, N_1 generates $p_{i,1}$ and N_3 generates $p_{i,3}$. During slot $i+1$, N_2 generates a packet $p_{i+1,2}$, N_3 generates $p_{i+1,3}$. In the following slots, none of N_0 through N_3 generates a packet. Let us observe q_3^0 . In slot $i+1$, $p_{i,3}$ is transmitted to N_n , $p_{i,1}$ is intercepted by N_3 and buffered in q_3^0 , and $p_{i,0}$ is intercepted by N_1 . In slot $i+2$, $p_{i,1}$ in q_3^0 is transmitted to N_n , $p_{i+1,2}$ is intercepted by N_3 and buffered in q_3^0 , and $p_{i,0}$ is intercepted by N_2 . In slot $i+3$, $p_{i+1,3}$ in q_3^0 is transmitted to N_n , $p_{i,0}$ is intercepted by N_3 and buffered in q_3^0 . Clearly, $p_{i+1,2}$ entered q_3^0 before $p_{i,0}$. Thus, packets in q_3^0 are out of order.

Given the above property, in order to achieve better fairness, we need to sort the packets in q_k^0 for $1 \leq k \leq n$ in the non-decreasing timestamp order. With the sorted packets in

q_k^0 , node N_k only needs to compare the timestamp of the two packets at the heads of q_k^0 and q_k^k and transmits the packet with the smaller timestamp in each time slot. The packet transmitted at N_k in each time slot must have the smallest timestamp among all packets available in N_k 's q_k^0 and q_k^k . A priority queue implemented with a min-heap for q_k^0 and a first-in-first-out (FIFO) queue for q_k^k can well achieve the fairness. If a software min-heap queue is used to implement q_k^0 , the time complexity for maintaining q_k^0 is $O(\log m_k)$ where m_k is the number of packets in q_k^0 . The 1-persistent protocol using the min-heap queue for q_k^0 ($1 \leq k \leq n$) is referred to as 1PER/1 in this paper.

For 1PER/1, maintaining the min-heap queue and comparing the timestamp of two head packets in q_k^0 and q_k^k must be accomplished within t_g . However, if the queue size is too large, it might not be feasible to maintain the min-heap queue within t_g . There are three options for solving this problem: (a) A hardware priority queue of $O(1)$ -time insertion and delete-min operations introduced in [23] can be used. (b) We may apply pipeline principle to implement insertion/delete-min operations in one slot time T in the following way: during the T interval of slot i , packets stored before the start of slot i are considered for transmission in slot $i+1$. Thus, min-heap maintenance time can be extended to $T+t_g$. This method may result in one more time slot delay for the newly arrived packet without affecting the overall performance of the opportunistic optical hyperchannel. (c) Combination of (a) and (b).

We also propose an alternative protocol in which both q_k^0 and q_k^k are FIFO queues. This protocol is referred to as 1PER/2. In 1PER/2, operations on q_k^0 and q_k^k have $O(1)$ time complexity. Through the simulation, we can see that fairness that 1PER/2 can achieve is almost the same as that of 1PER/1. This experimental result has important practical implication: using FIFOs for both of q_k^0 and q_k^k at intermediate nodes can remove priority queue insertion/delete-min operations.

C. Properties of 1-Persistent Protocols

Our generic 1-persistent MAC protocol exhibits the following properties:

- **Work-Conserving and Fully Distributed.** Each intermediate node N_k , $0 < k < n$, persistently transmits a packet to its downstream nodes whenever either $q_k^0 \neq \emptyset$ or $q_k^k \neq \emptyset$. The decisions of when to transmit and what to transmit are made completely locally.
- **Collision Free.** Suppose that two nodes N_k and N_j transmit a packet simultaneously at time slot i and $k < j$. Then both N_k and N_j must be in DA state. The packet transmitted by N_k cannot pass S_k at time slot i ; thus, the packet transmitted by N_k will never collide with the packet transmitted by N_j . We would like to note that packet collision is avoided without carrier sensing.
- **Fair.** If each intermediate node N_k selects a packet with the smallest timestamp for transmission when it is in DA state, fairness is enforced among nodes.
- **High Efficiency.** Once a packet is transmitted by a node N_k , the packet is transmitted in optical domain as far as possible until it encounters a downstream node N_l whose switch S_l is in DA state and has packets to transmit.

Compared with any carrier sense multiple access protocol running on an optical bus, 1-persistent protocol running on an opportunistic hyperchannel does not require collision detection hardware, which is hard to implement for optical media. Instead, high speed shutters are needed. OE and EO converters, receivers and transmitters used in opportunistic hyperchannel do not incur extra cost in comparison with any optical bus because they can not be avoided.

V. PERFORMANCE ANALYSIS

In this section, we analyze the performance of 1PER/1 by calculating a lower and upper bound for the amplification ratio of the throughput, deriving a relative worst-case upper bound for packet delays in comparison with an ideal fair packet scheduler, and estimating average buffer size at any intermediate node.

A. Throughput Amplification

We compare 1-persistent protocols running on an opportunistic hyperchannel and work-conserving protocols running on a light-trail in terms of their throughput. To focus on throughput, we assume that each node has unlimited amount of buffer space. We define the *throughput* TP of a communication channel, which is either a light-trail (optical bus) or an opportunistic hyperchannel in our context, as the rate of packets successfully delivered to their destinations.

Let TP_{LT} and TP_{OH} be the throughput (packet delivering rate) of a light-trail running an work-conserving protocol and the throughput of an opportunistic hyperchannel running a 1-persistent protocol, respectively. We define the *throughput amplification factor* $F_{TA} = \frac{TP_{OH}}{TP_{LT}}$. Clearly, $F_{TA} \geq 1$. If the channel load is less than 100% of the channel bandwidth, the throughput of a light-trail and an opportunistic hyperchannel running work-conserving protocols are the same, which is 100% of the channel bandwidth. When the channel load is larger than channel bandwidth, opportunistic hyperchannel exhibits an amplification of throughput compared with a light-trail, because the opportunistic channel can be partitioned into multiple segments, and multiple packets can reach their destinations in one time slot.

We present a lower bound and an upper bound for the throughput amplification factor F_{TA} of 1-persistent protocols running on an opportunistic hyperchannel with respect to any work-conserving protocol running on the corresponding light-trail.

In an $(n+1)$ -node opportunistic hyperchannel with nodes $N_0, N_1, \dots, N_n$, suppose that traffic arrival process at each node follows Poisson distribution with arrival rate of λ_i for $0 \leq i \leq n-1$.

1) *Lower Bound:* Among those concurrent transmissions in an opportunistic hyperchannel during one time slot, some of them may have reached their destinations in the same time slot. If we only consider such transmissions when we calculate system throughput, we can achieve the lower bound of the system throughput.

In an $(n+1)$ -node opportunistic hyperchannel with nodes $N_0, N_1, \dots, N_n$, $m \in \{1, 2, \dots, n\}$ packets may be transmitted and reach their destinations simultaneously in a time

slot. For the case of $m = 1$, the probability that one packet is transmitted in the system is $prob_1 = \lambda \cdot e^{-\lambda}$ since the system can be regarded as having one Poisson arrival process with parameter $\lambda = \sum_{j=0}^{n-1} \lambda_j$.

For the cases that $m \geq 2$, let Com_m be the set of all possible non-overlapping segments of an opportunistic hyperchannel that results in m packets reaching their destinations. Without loss of generality, let $\{(s_i^1, d_i^1), (s_i^2, d_i^2), \dots, (s_i^m, d_i^m)\}$ be i -th element in Com_m , where (s_i^l, d_i^l) is the source-destination pair of its l -th segment in the opportunistic hyperchannel. Let $prob_m^i$ be the probability of the i -th element in Com_m . Suppose that the destinations of all packets at each node are uniformly distributed among all downstream nodes of N_j . Thus, $\lambda_{j,k} = \frac{\lambda_j}{n-j}$ is the arrival traffic parameter generated at node N_j and destined for a downstream node N_k . In a Poisson distribution, the probability that there are exactly s occurrences (s being a non-negative integer, $s = 0, 1, 2, \dots$) is equal to $\frac{\lambda^s e^{-\lambda}}{s!}$. Therefore, the probability that one packet is generated at node N_j for destination node N_k is $\lambda_{j,k} \cdot e^{-\lambda_{j,k}}$. Thus, $prob_m^i$ can be calculated as follows:

$$prob_m^i = \prod_{l=1}^m \lambda_{s_i^l, d_i^l} \cdot e^{-\lambda_{s_i^l, d_i^l}}, \text{ for } m \geq 2 \quad (1)$$

In Equation (1), $prob_2^i$ includes the concurrencies of $m > 2$ cases; $prob_3^i$ includes the concurrencies of $m > 3$ cases; and so on. Therefore, in the throughput calculation, we count 2 packets in $prob_2^i$ and 1 packet in $prob_m^i$ when $m > 2$. Thus, we get a lower bound F_{TA}^- of the throughput amplification factor as the following equation:

$$F_{TA}^- = \frac{1 \cdot prob_1 + \sum_{i=1}^{|Com_m|} 2 \cdot prob_2^i + \sum_{m=3}^n \sum_{i=1}^{|Com_m|} prob_m^i}{\min\{1, \sum_{j=0}^{n-1} \lambda_j\}} \quad (2)$$

The numerator of Equation (2) is the packet delivering rate of an $(n+1)$ -node opportunistic hyperchannel, whereas the denominator is the packet delivering rate of a corresponding light-trail.

2) *Upper Bound*: An intermediate node N_j contributes to throughput amplification if its CA switch S_j is in DA state, and N_j receives a packet p' whose destination is not a downstream node of N_j . Though the destination of p' can be any upstream node of N_j , we only consider the case that the destination of p' is N_j to avoid duplicated calculation. This is because the packets destined for N_{j-1} are already counted at node N_{j-1} .

The average number of packets arrived from upstream nodes and destined for node N_j is $\sum_{k=0}^{j-1} \frac{\lambda_k}{(n-k)}$. So the maximum average number of packets contributed by node N_j to the throughput amplification is no larger than $\min\{\lambda_j, \sum_{k=0}^{j-1} \frac{\lambda_k}{(n-k)}\}$.

Thus, we can use the following formula to calculate an upper bound F_{TA}^+ of the throughput amplification factor:

$$F_{TA}^+ = \frac{\sum_{j=1}^{n-1} \min\{\lambda_j, \sum_{k=0}^{j-1} \frac{\lambda_k}{(n-k)}\} + \min\{1, \sum_{j=0}^{n-1} \lambda_j\}}{\min\{1, \sum_{j=0}^{n-1} \lambda_j\}} \quad (3)$$

B. Relative Maximum Packet Delay

To find an upper bound for the relative maximum packet delay, we assume that the destinations of all packets are the same, the end node. We compare our 1-persistent protocols with an ideal protocol, *General Round Robin* (GRR), which enforces packet $p_{i',k'}$ reaching the end node before packet $p_{i,k}$ if and only if $p_{i',k'} < p_{i,k}$. Conceptually, GRR transmits packets to the end node in rounds, with each round consisting of packets generated at the same time, in the increasing order of packet generating times, and transmits packets in the same round in the decreasing order of node indices. Clearly, GRR is a fair algorithm which cannot be implemented distributively without knowing the arriving order of packets. We analyze the performance of 1PER/1 by comparing them with algorithm GRR.

Let $t_{GRR}(p)$, $t_{1PER/1}(p)$ be the time at which packet p reaches the end node in an $(n+1)$ -node opportunistic hyperchannel according to the GRR algorithm and the 1PER/1 protocol respectively. Define the delay of packet p using 1PER/1 with respect to GRR as $D_n^1(p) = t_{1PER/1}(p) - t_{GRR}(p)$. Note that $D_n^1(p)$ can be negative, when p reaches the end node using 1PER/1 earlier than the time it reaches the end node using GRR. Define

$$D_n^{1*} = \max_{\text{all packets } p} \{D_n^1(p)\},$$

which is the worst-case delay upper bound for the 1PER/1 protocol compared with the GRR algorithm.

Theorem 1: For 1PER/1, $D_n^{1*} \leq (n-1) \cdot (T + t_g)$.

Proof: Consider a packet $p_{i,k}$ where $1 \leq k \leq n$. Let $A_{i,k}$ be the set of packets that are in the system when $p_{i,k}$ is generated with $p' < p_{i,k}$ for $p' \in A_{i,k}$. Given the work-conserving property of the 1PER protocol, there must also be $|A_{i,k}|$ packets in the system when $p_{i,k}$ is generated no matter which scheduling algorithm is applied. Clearly, in the GRR algorithm, packet $p_{i,k}$ will have a delay of $|A_{i,k}| \cdot (T + t_g)$.

Suppose that packet $p_{i,k}$ reaches the destination at time slot t under 1-persistent 1PER/1. Because the system will keep busy as long as there are packets in the system, there will be one packet reaching destination at any time period i' for $i' = i+1, \dots, t$. Among the packets arrived at the destination during the period from time slot $i+1$ to time slot $t-1$, if there is a packet $p_{i',k'}$ with larger timestamp than $p_{i,k}$, then we say $p_{i,k}$ has an extra delay caused by $p_{i',k'}$.

Now we claim that the total extra delay incurred to $p_{i,k}$ cannot be more than $n-k$; i.e. using 1-persistent protocol, $p_{i,k}$ will not have delay that is $(n-k) \cdot (T + t_g)$ longer than it has using GRR.

Since the only packets which may cause extra delay to $p_{i,k}$ are the packets from N_k 's downstream nodes, if we can prove that at most one packet with the smaller timestamp can be inserted in front of $p_{i,k}$ at each downstream node of N_k during the time period from time slot $i+1$ to time slot $t-1$, our claims hold. Consider a node N_j with $j \geq k$, which is a downstream node of N_k .

- Case 1. Suppose node N_j is in DA state at time slot i . Then node N_j cannot be switched to DC state before $p_{i,k}$ passes node N_j because q_j^0 will not be $\emptyset$ as long as there are packets in the queues of N_j 's upstream nodes. In

such a case, any packet $p_{i',j}$ with $i' \geq i$, i.e., with lower priority than $p_{i,k}$, will be first inserted into the local queue at node N_j . Consequently, $p_{i',j}$ cannot be sent out from node N_j until $p_{i,k}$ passes node N_j . In other words, $p_{i',j}$ will not cause any extra delay to $p_{i,k}$.

- Case 2. Suppose that node N_j is in DC state at time slot i . Then it keeps in DC state and does not block any packet until a packet $p_{i',j}$ is generated at time $i' \geq i$.
 - Case 2.1. If $p_{i',j}$ is generated after $p_{i,k}$ passes node N_j , then $p_{i',j}$ will not cause any extra delay to $p_{i,k}$.
 - Case 2.2. If $p_{i',j}$ is generated before $p_{i,k}$ passes node N_j , then $p_{i',j}$ causes node N_j to be switched from DC state to DA state, and may reach destination earlier than $p_{i,k}$. In such a case, $p_{i',j}$ causes one extra delay to $p_{j,k}$. After this, node N_j cannot be switched to DC state before $p_{i,k}$ passes node j , an analysis similar to Case 1 as we have conducted.

Summarizing the above cases, we know that at most one extra delay will be caused to $p_{i,k}$ at any node N_j for $j \geq k$. Thus, any packet generated at N_k will experience at most $(n - k) \cdot (T + t_g)$ more delay in the 1PER/1 protocol than in GRR algorithm. The packets generated at N_1 may experience $(n - 1) \cdot (T + t_g)$ more delay in 1-persistent 1PER/1 protocol than in GRR algorithm. This completes the proof of Theorem 1. ■

C. Average Buffer Size

As mentioned in Section IV-A, every intermediate node N_k would buffer and forward packets which were intercepted in DA state and destinate to downstream nodes of it. Using the same assumptions as Section V-A1, the Poisson arrival rate for the traffic destinated to downstream nodes of node N_k is $\lambda_{\bar{k}} = \sum_{i=0}^{k-1} \sum_{j=i+1}^n \lambda_{i,j}$. However, some of such traffic may pass node N_k when S_k is in DC state, which does not need to be buffered. Let $prob_{DA,k}$ be the probability that S_k is in DA state. Then $prob_{DA,k} \cdot \lambda_{\bar{k}}$ is the traffic that need to be buffered. Adding the traffic generated locally at node N_k , the total arrival traffic would be

$$\lambda_{total,k} = prob_{DA,k} \cdot \lambda_{\bar{k}} + \lambda_k \leq \lambda_{\bar{k}} + \lambda_k.$$

Analyzing the queuing behavior at node N_k , it is a typical M/D/1 model with Poisson arrival rate $\lambda_{total,k}$ and deterministic departure rate $\mu_k = 1.0$, $\sigma_k^2 = 0.0$. Then, the average buffer size of node N_k is

$$B_k = \frac{1}{2} \cdot \frac{\rho_k^2}{1 - \rho_k}, \text{ where } \rho_k = \frac{\lambda_{total,k}}{\mu_k} \in [0, 1).$$

Clearly, B_k is a monotone increasing function of ρ_k . Thus, we have

$$B_k \leq \frac{1}{2} \frac{(\lambda_{\bar{k}} + \lambda_k)^2}{1 - \lambda_{\bar{k}} - \lambda_k} \quad (4)$$

VI. SIMULATION

As mentioned earlier, the design principle of 1-persistent protocols for opportunistic optical hyperchannels is to design work-conserving protocols with fairness. In this section, we conducted simulations to compare the performance of 1-persistent protocols running on an opportunistic hyperchannel

Fig. 3. Throughput vs. system load.

with the performance of *minSrcRR* protocol running on an opportunistic optical hyperchannel, p_i -persistent CSMA protocol and priority-based CSMA protocol running on a light-trail. We compare these protocols in terms of the following performance metrics: (1) throughput, (2) average delay at each node, (3) worst delay at each node. A higher throughput indicates that the system is more work-conserving. Both the average delay at each node and the worst delay at each node can be used as the measurements of fairness. We also conducted simulation to compare performance of our proposed 1-persistent protocols with the theoretical bounds we derived in Section V in terms of the relative maximum delay compared with an ideal fair protocol GRR, throughput amplification ratio, and buffer size.

The unidirectional opportunistic optical hyperchannel we simulated has 11 nodes. The data rate in this opportunistic optical hyperchannel is set to 2.5Gbps, packet size is 1500 bytes, and the guard time t_g is 10^9 seconds. The destinations of all packets are uniformly distributed among all its downstream nodes. For example, the destinations of packets generated at node N_j are uniformly distributed in $[j + 1, n]$. The packet arrival process (i.e. packet generating process) at node N_j is assumed to follow Poisson distribution with parameter λ_j , and system load is uniformly distributed among all nodes, which means $\lambda_j = \lambda_k$, $0 \leq j, k < n$. Then, system load can be identified by $\lambda = \sum_{j=0}^{n-1} \lambda_j$.

A. Throughput

In an opportunistic optical hyperchannel, a packet will be dropped at the first downstream node which is in DA state after it passes its destination instead of occupying the whole optical bus. Thus, multiple non-overlapping segments can be used to transmit packets simultaneously without conflict. Therefore, a larger throughput can be achieved in an opportunistic optical hyperchannel compared with the corresponding light-trail. Fig. 3 verifies this property. Since both 1-persistent protocols and *minSrcRR* protocol are designed for opportunistic optical hyperchannel, both exhibits the throughput amplification feature and can achieve throughput higher than 2.5Gbps when system load is higher than 100%. Figs. 3 also shows that the

Fig. 4. (a) average delay vs. node index when system load=29.28% ; (b) average delay vs. node index when system load=77.08%.

curves of 1PER/1 and 1PER/2 protocols almost completely overlap. This indicates that for practical purpose 1PER/2 is a better choice than 1PER/1 because of its $O(1)$ time complexity. From Fig. 3, we can see that protocols specifically designed for opportunistic optical hyperchannels can achieve much higher throughput than priority-based CSMA protocol and p_i -persistent CSMA protocol under different system loads.

B. Average Packet Delay

For priority-based CSMA protocol, the packets originated from upstream nodes have smaller average packet delay than the packets originated from downstream nodes simply because of the fixed node priority. This is verified by Fig. 4.

For p_i -persistent CSMA protocol, the difference between average delays of different nodes is small, given that p_i s are correctly calculated (i.e. the real traffic demand matches the estimated traffic demand). As shown in Fig. 4(a), when p_i s are calculated according to a low system load, the curve of the average delay for p_i -persistent CSMA protocol is quite flat. However, when the system load is high, as shown in Fig. 4(b), the differences of average delays among nodes can be dramatic, which means that the fairness of p_i -persistent protocol is hard to achieve if the real traffic demand does not match the estimated traffic demand.

For *minSrcRR* protocol, the first node has no reference node, thus, its average delay will be less than others. From Fig. 4(a), we can see that the average delay at all nodes except the first node is quite close. When system load is high as shown in Fig. 4(b), *minSrcRR* protocol can still provide good fairness assurance while p_i -persistent protocol fails to do so.

For 1-persistent protocols, packets generated at downstream nodes tend to have lower average delays since their transmissions may be enabled when their originated nodes' switches are changed from DC state to DA state, blocking packets from upstream nodes. Thus, the average delay curves of 1-persistent protocols are decreasing curves. However, the slope of such decreasing curve is very small, which means that 1-persistent protocols can still provide good fairness. Moreover, as we can see from Fig. 4(a) and (b), the average delay of packets generated at each node of an opportunistic hyperchannel running a 1-persistent protocol is much smaller than that of other protocols.

C. Worst Packet Delay

Though 1-persistent protocol may allow the downstream nodes to block the packets from the upstream nodes and

Fig. 5. (a) worst delay vs. node index when system load=29.28% ; (b) worst delay vs. node index when system load=77.08% .

transmit their locally generated packets each time when they switch from DC state to DA state, the fair schedule is enforced once the CA switch at a node is in DA state. As proved in Theorem 1, at most one packet with larger timestamp can be inserted before a packet with lower timestamp at any downstream node. Thus, each node will experience similar worst delay. Fig. 5 shows that the curves of worst delay under 1-persistent protocols and *minSrcRR* protocol are quite flat especially when the system load is heavy. The difference of the worst delays among different nodes under both p_i -persistent CSMA protocol and priority-based CSMA protocol are quite large. Fig. 5 shows that 1-persistent protocols can provide similar fairness as *minSrcRR* protocol in terms of the worst delay at each node.

Though the performance in terms of throughput and fairness of 1-persistent protocols and *minSrcRR* protocol is quite close in the simulation, these two protocols can not replace each other due to the following reasons: (1) 1-persistent protocols can provide good fairness, however, it can not assure QoS, i.e., nodes can not transmit according to their weight. Thus, 1-persistent protocols can not replace *minSrcRR* protocol if differentiated QoS metric is important; (2) In an opportunistic optical hyperchannel, if throughput is more important than providing QoS, 1-persistent protocols outperform *minSrcRR* protocol due to its higher throughput and simpler implementation.

D. Throughput Amplification Factor

In the previous section, we have derived the theoretical upper bound and lower bound of throughput amplification ratio. In this section, we conduct simulation to see how close that the real throughput amplification ratio is to our derived bounds. Fig. 6 compares the throughput amplification factor F_{TA} of 1-persistent protocol running on an opportunistic hyperchannel with the lower bound F_{TA}^- and upper bound F_{TA}^+ of throughput amplification factor calculated according to Equation (2) and Equation (3) under heavy system load. From Fig. 6, we can see that the actual throughput amplification ratio is quite close to the upper bound.

E. Relative Maximum Packet Delay

We also conduct simulations to compare the packet delay in an opportunistic hyperchannel implementing 1-persistent protocol with an ideal fair protocol, called GRR protocol. To be comparable, we assume that the destination of all traffic is the last node. Fig. 7 shows that the maximum delay difference between 1PER/1 and GRR is bounded by

Fig. 6. The throughput amplification factor of the theoretical lower bound, simulation results of 1-persistent protocol, and the theoretical upper bound under different system loads.

Fig. 7. The relative maximum packet delay of the theoretical upper bound and simulation results of 1-persistent protocol compared with GRR protocol.

9 ($n - 1 = 10 - 1 = 9$) time intervals where each time interval is $4.801\mu s$ in our simulation, which verifies the proof of Theorem 1.

F. Buffer Size

Fig. 8 compares the theoretical average buffer size with the simulation results, where the former is an upper bound of the later. Maximum buffer size at each node under different system loads is shown in Fig. 9. As analyzed in Section V-C, more buffers are needed at intermediate nodes with larger λ_k which is demonstrated in Fig. 9. From Fig. 9, we can see that an opportunistic optical hyperchannel will not require too large electronic buffer capacity at each node when system load is not significant heavier than the wavelength capacity. This is reasonable since an opportunistic optical hyperchannel is setup such that the total traffic load in an opportunistic optical hyperchannel is less than the wavelength capacity. Otherwise, a more appropriate opportunistic optical hyperchannel shall be setup.

Fig. 8. (a) average buffer size vs. node index when system load=74.46% ; (b) average buffer size vs. node index when system load=99.85% .

Fig. 9. Maximum buffer size vs. node index under different system loads.

VII. GENERALIZATION OF OPPORTUNISTIC HYPERCHANNEL

We call the opportunistic hyperchannel discussed so far a *linear opportunistic hyperchannel*, simply because the nodes in such a hyperchannel are ordered as a linear array. We denote a linear opportunistic hyperchannel as an ordered node sequence $(N_0, N_1, \dots, N_n)$ according to the positions of the nodes in the hyperchannel. In some applications, linear opportunistic hyperchannel are not efficient, as shown in the following example.

Example 1: Consider the tree optical network topology shown in Fig. 10(a). We use $N_i \rightarrow N_j$ to represent a connection request for sending packets from node N_i to node N_j . Let $R = \{N_0 \rightarrow N_1, N_1 \rightarrow N_3, N_5 \rightarrow N_1, N_5 \rightarrow N_2, N_1 \rightarrow N_3, N_4 \rightarrow N_3, N_2 \rightarrow N_3\}$ be a set of connection requests. In order to accommodate such requests, three linear opportunistic hyperchannels may be established, as shown in Fig. 10(a), with one distinct wavelength for each channel. These linear opportunistic hyperchannels are: $L_1 = (N_0, N_1, N_2, N_3)$, $L_2 = (N_4, N_2, N_3)$, and $L_3 = (N_5, N_1, N_2, N_3)$. Assume Poisson arrival process, with arrival parameter $\lambda_{i,j}$, for packets generated at each node N_i and destined for node N_j . If $\sum_{i=0}^5 \sum_{N_i \rightarrow N_j \in R} \lambda_{i,j} < 1$, this opportunistic hyperchannel solution is inefficient because one wavelength can support all these connections.

A. Non-Linear Opportunistic Hyperchannels

We generalize the opportunistic hyperchannel architecture to one that removes the linear topology limitation, thereby improving the system utilization for the case as shown in Example 1. Such a generalization is useful for constructing special purpose networks. We call the generalized opportunistic hyperchannel the *non-linear opportunistic hyperchannel*. In general, a non-linear opportunistic hyperchannel is informally

Fig. 10. (a) three opportunistic hyperchannels; (b) a gathering tree; (c) the states of a BCA switch in a T_M node.

defined as a subnetwork G of a mesh network M that satisfies the following conditions:

- G is a structure obtained by superimposing a set of linear opportunistic hyperchannels in M ;
- optical connections in M can be shared by different component linear opportunistic hyperchannels, and the transmissions on shared connections must have the same direction;
- G uses a single wavelength; and
- in any switch setting, no optical cycle exhibits in G .

Based on this definition and assuming appropriate node architectures with adequate dynamic optical switching and electronic buffering capabilities, one can construct many different types of non-linear opportunistic hyperchannels. We restrict our discussions to implementations of non-linear opportunistic hyperchannels whose underlying topologies are trees.

B. Gathering Tree

A *gathering tree* T_M is a directed tree with leaf nodes being the start nodes of some component linear opportunistic hyperchannels, the root node being the end node of some component linear opportunistic hyperchannel. The packet transmissions are in the direction toward the root. Each intermediate node in a gathering tree has only one optical output, but may have multiple optical inputs; one input can be connected to the output through a switch at any time.

Assuming that for a gathering tree T_M , each node has a constant in-degree, i.e. a fixed number of optical inputs. We show how T_M can be constructed in mesh network M

by considering Example 1. The gathering tree T_M can be constructed to accommodate all requests using one wavelength as shown in Fig. 10(b).

The node architecture for T_M is shown in Fig. 10(c), where an Integrated Logic Controller (ILC) controls two optical shutters simultaneously. Integrating the control of two optical shutters, it is equivalent to that each internal node of T_M tree is associated with a 3×1 bi-continue-add (BCA) switch S_k . There are three buffers in each T_M node: $BUFA$ is used to save the packets intercepted from input A ; $BUFB$ is used to save the packets from input B ; and $BUFC$ is used to save the packets generated locally. The optical signals from both input A and input B will drop a copy at the electronic buffer, and at the same time go to its corresponding optical shutter. Depending on the state of the BCA switch, the signal may go to the downstream (parent) node directly or need to be re-transmitted from the local buffers. The local buffers are responsible for receiving and re-transmitting the packets intercepted from input A and B , and transmitting the packets generated locally. A 3×1 BCA switch S_k can be in one of the following three states as shown in Fig. 10(c):

- *Drop-Add (DA)* state. The optical shutters associated with input A and input B are in OFF state. In this state, the packets from the buffers of the node are transmitted.
- *Drop-Continue from A (DCA)* state. The optical shutter associated with input A is in ON state and the optical shutter associated with input B is in OFF state. In this state, the optical signals from A can pass through S_k and the signals from B , if any, are saved in $BUFB$.
- *Drop-Continue from B (DCB)* state. The optical shutter associated with A is in OFF state and the optical shutter associated with B is in ON state. In this state, the optical signals from A , if any, are saved in $BUFA$ and the signals from B can pass through S_k .

By choosing the setting scheme of S_k , a class of packet scheduling protocols can be designed for a gathering tree T_M . In what follows, we introduce the implementation of 1-persistent protocols in a gathering tree.

In the 1-persistent protocols for a linear opportunistic hyperchannel, a CA switch is set to be in DC state when the local buffers are empty. To implement the 1-persistent idea in a gathering tree T_M , a little modification should be made for the T_M nodes due to three states of a BCA switch.

There are two DC states for a BCA switch: DCA and DCB. Assuming Poisson arrival process at each node, let $w_{(i,A)}$ (resp. $w_{(i,B)}$) be the arrival process parameter of the traffic from node N_i 's input A (resp. B) destined for downstream nodes of N_i . Let $Prob_{(i,DCA)}$ and $Prob_{(i,DCB)}$ be the probabilities of a BCA switch S_i in DCA state and DCB state, respectively. $Prob_{(i,DCA)}$ and $Prob_{(i,DCB)}$ can be computed from equations $\frac{Prob_{(i,DCA)}}{Prob_{(i,DCB)}} = \frac{w_{(i,A)}}{w_{(i,B)}}$ and $Prob_{(i,DCA)} + Prob_{(i,DCB)} = 1$.

When all local buffers at a T_M node N_i are empty, the output of BCA switch S_i connects to input A and B alternatively, with fractions $Prob_{(i,DCA)}$ and $Prob_{(i,DCB)}$ of time in DCA and DCB state, respectively. Each T_M node N_i maintains two variables: $num_{i,A}$ and $num_{i,B}$. Initially, $num_{i,A} = num_{i,B} = 0$. $num_{i,A}$ (resp. $num_{i,B}$) is increased

by 1 at each time slot when S_i is in DCA (resp. DCB) state. We compare $num_{i,A} \cdot Prob_{(i,DCB)}$ with $num_{i,B} \cdot Prob_{(i,DCA)}$ to decide the state of S_i for the next slot when local buffers are empty:

- If $num_{i,A} \cdot Prob_{(i,DCB)} > num_{i,B} \cdot Prob_{(i,DCA)}$, set S_i to be in DCB state;
- if $num_{i,A} \cdot Prob_{(i,DCB)} < num_{i,B} \cdot Prob_{(i,DCA)}$, set S_i to be in DCA state;
- otherwise, the state of S_i does not change.

When S_i is in DCA state, it is possible that a packet arrives from input B . If such a case happens, the packet is buffered in BUF_B , and S_i switches to DA state in the next time slot. Then, packets in BUF_B can be transmitted. This, which may violate the assigned $\frac{Prob_{(i,DCA)}}{Prob_{(i,DCB)}}$ ratio, is called *slot stealing*. Slot stealing is allowed by increasing $num_{i,B}$ with 1 for this case.

1-persistent protocols for T_M can be summarized as follows:

- Any node with at most one optical input works using the same rules as in a linear opportunistic hyperchannel.
- Any node with multiple (in our case, 2) optical inputs, sets its BCA switch to DA state when at least one of its local buffers are non-empty. In this state, the packet with the smallest timestamp will be scheduled to be transmitted persistently from local buffers.
- For any node N_i with more than one optical input, if its all local buffers are empty, it sets its BCA switch S_i to be in either DCA or DCB state with probability $Prob_{(i,DCA)}$ or $Prob_{(i,DCB)}$, respectively.

C. Multicast-and-Select Tree

We introduce another non-linear opportunistic hyperchannel called *multicast-and-select tree* in a mesh network M . A broadcast-and-select tree T_{MS} is a directed tree in M with the root being a unique node, which is the start node of every component linear opportunistic hyperchannel, and with leaf nodes being the end nodes of some component linear opportunistic hyperchannels. The packet transmissions are from the root to leaves. Each intermediate node has only one optical input, but may have multiple optical outputs; the input is connected to all outputs through a multicast splitter (no switching element and electronic buffers are not needed). The root node transmits packets to all nodes in the tree, and each non-leaf node decides if it keeps the broadcast packets.

D. Applications of Nonlinear Opportunistic Hyperchannels

A pair of gathering tree T_M and multicast-and-select tree T_{MS} of the same underlying tree topology are suitable for implementing a client-server network. Non-root nodes are client nodes sharing the same root node, which is a server node. All or a subset of the remaining nodes are client nodes. Client nodes send upstream traffic/requests to the server node using a fully distributed, work-conserving, 1-persistent protocol such as the one described in the last subsection. The server node broadcasts downstream traffic to clients according to the computed schedule, and each client only keeps the result destined for itself. One example of such "client-server"

network is a storage-area network, in which the server is a memory shared by many client nodes, which may be processors.

A pair of gathering tree T_M and multicast-and-select tree T_{MS} can also be used to implement an access network with the root connected to the core network and leaves as users. Tree T_M is used to carry upstream traffic and T_{MS} is used to carry downstream traffic.

Compared with an access network implemented by a TDM-PON that determines the schedule for upstream traffic either through fixed TDM or centralized DBA protocols, our proposed non-linear opportunistic hyperchannel can implement distributed MAC protocol to share bandwidth for upstream traffic. Compared with WDM-PON which requires one wavelength per user for upstream traffic, a T_M opportunistic hyperchannel requires only one wavelength as long as its bandwidth can accommodate all upstream traffic.

VIII. CONCLUSION

As an improvement of light-trail, opportunistic optical hyperchannels inherently provide the capability of designing fully distributed and work-conserving media access control. To demonstrate this capability, we proposed simple 1-persistent protocols and studied their performance. Our analysis and simulations show that 1-persistent protocols have bounded worst-case delay and reasonable fairness. The price paid for this advantage is the additional cost for optical switches and electronic buffers. This cost overhead associated with high-speed optical shutters is further offset by throughput amplification achieved using space-division multiplexing (SDM) through self-adjusted multiple concurrent packet transmissions on non-overlapping segments. As a generalization of opportunistic hyperchannel, non-linear opportunistic hyperchannels are introduced in the context of mesh networks or access networks. Optical hyperchannels also have applications in constructing high-performance storage-area networks and interconnection subsystems for processor clusters. We believe that the unique feature of opportunistic hyperchannels that combines wavelength-division multiplexing, time-division multiplexing and space-division multiplexing deserves further investigations for the design and implementation of high-performance optical/electrical hybrid communication networks.

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