HOPSMAN: An Experimental Testbed System for a 10-Gb/s Optical Packet-Switched WDM Metro Ring Network

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ABSTRACT

For future WDM MANs, optical packet-switching has been considered to be a promising paradigm that efficiently supports a wide range of Internet-based applications having time-varying and high bandwidth demands and stringent delay requirements. This article presents the design of an experimental testbed system for a high-performance optical packet-switched WDM metro ring network, HOPSMAN. HOPSMAN boasts three crucial features. First, it has a scalable architecture in which the number of nodes is unconstrained by the number of wavelengths. Second, HOPSMAN nodes are equipped with high-speed photonic hardware components, including fast tunable receivers and optical slot erasers, capable of performing speedy optical packet-switching operations. Third, HOPSMAN incorporates a MAC scheme that embodies efficient and dynamic bandwidth allocation, resulting in exceptional delay-throughput performance. The article presents the key hardware components by highlighting the challenging issues we faced and the solutions we proposed for the testbed implementation. Finally, to demonstrate the feasibility of HOPSMAN, the article describes the experimental setup and presents the results obtained from running a commercially available remote media player application on the system.

INTRODUCTION

Over the last decade, advances in Internet technology brought about the proliferation of Internet-based multimedia applications, such as IPTV, remote terminal services, and online gaming. These applications virtually require meeting different time varying and high-bandwidth demands and stringent delay-throughput performance. While optical circuit switching (OCS) is successful in supporting bulky steady traffic over long-haul wavelength-division multiplexing (WDM) networks, optical packet switching (OPS) [1, 2] enables fine-grained on-demand channel allocation (i.e., statistical multiplexing) and has thus been considered to be a preeminent paradigm capable of supporting such applications over future optical WDM metropolitan area networks (MANs) [1, 3]. Note that the OPS technique studied here excludes the use of optical signal processing and optical buffers, a current technological limitation faced by OPS.

Numerous topologies and architectures [3–9] for OPS WDM MANs have been proposed in recent years. Of these proposals, the structure of slotted rings [4–9] has received the most attention. Comprehensive surveys of WDM metro slotted ring networks can be found in the literature [3]. While most of the work [8, 9] is simulation driven, only a handful [4–7] involve experimental prototypes. Because experimental prototyping has been one of our major tasks, we assessed two experimental testbed systems that are relevant to our work, focusing on three key challenges pertaining to OPS WDM slotted ring networks. They are the following: the scalable design of networks, particularly with respect to the number of wavelengths; the design and implementation of high-speed photonic hardware components (e.g., fast tunable receivers, optical slot erasers); and the design and implementation of medium access control (MAC) schemes [3] that achieve high statistical multiplexing gain, and satisfy diverse and stringent delay-throughput requirements under a wide range of traffic loads and burstiness.

First, the hybrid optoelectronic ring network (HORNET) [4] is a bidirectional WDM slotted ring network in which each node is equipped with a tunable transmitter and a fixed-tuned receiver (TT-FR). Note that although fast tunable transmitters [10] with a laser tuning time up to several nanoseconds have emerged, fast tunable receivers [11] operating on the order of nanoseconds remain virtually unavailable. HORNET uses a MAC protocol, called Distributed Queue Bidirectional Ring (DQBR), which is a modified version of the IEEE 802.16 Distributed

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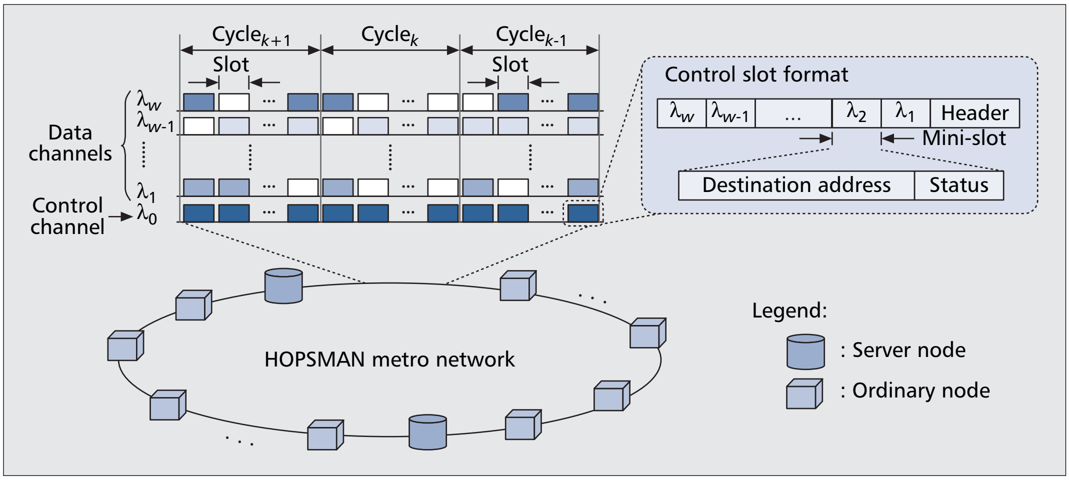


■ **Figure 1.** *General architecture of the HOPSMAN network testbed.*

HOPSMAN is a unidirectional WDM slotted-ring network with multiple WDM data channels and one control channel. Channels are further divided into synchronous time slots. Each data-channel slot contains a data packet in addition to some control fields to facilitate synchronization.

Queue Dual Bus (DQDB) protocol [12]. Specifically, DQBR requires each node to maintain a distributed queue via a pair of counters per wavelength. The counting system ensures that packets are sent in the order in which they arrive at the network. With DQBR, HORNET achieves acceptable utilization and fairness at the expense of high control complexity for maintaining the same number of counter pairs as wavelengths. However, due to the use of fixed-tuned receivers, HORNET statically assigns each node a wavelength as the home channel for receiving packets. Such static wavelength assignment results in poor statistical multiplexing gain, and as a result, throughput deteriorates.

Second, the ring optical network (RingO) [7] is a unidirectional WDM slotted ring network with 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. Such a design gives rise to a scalability problem. RingO employs a MAC protocol, called Synchronous Round-Robin with Reservations (SR^3) [8]. To achieve high utilization and fairness, SR^3 employs a combination of token-based access and slot reservation mechanisms. Unfortunately, under heavy loads RingO experiences deteriorating access delay as a result of an increase in cycle length.

In this article we present an experimental high-performance OPS WDM metro ring network (HOPSMAN) testbed system, particularly designed to meet the three challenges just mentioned. First, it has a scalable architecture in which the number of nodes is unconstrained by the number of wavelengths. Second, HOPSMAN nodes are equipped with two high-speed photonic hardware components, fast tunable receivers and optical slot erasers. These devices can perform speedy OPS operations, such as the drop-and-erase of data packets in nanoseconds. Third, HOPSMAN incorporates a versatile MAC scheme that embodies efficient and dynamic bandwidth allocation so that exceptional delay-throughput performance can be guaranteed. The article focuses on the key hardware components by highlighting challenging issues and our proposed designs for the testbed implementation. Finally, to demonstrate the feasibility of HOPSMAN, the article delineates the experimental setup and the results obtained from running a commercial remote-media-player application on the testbed.

The article is organized as follows: We first present the general network and node architectures of HOPSMAN. We follow this with a brief description of the MAC scheme. Mostly, we focus on the hardware implementation of the testbed and, finally, the demonstration of a potential application for HOPSMAN.

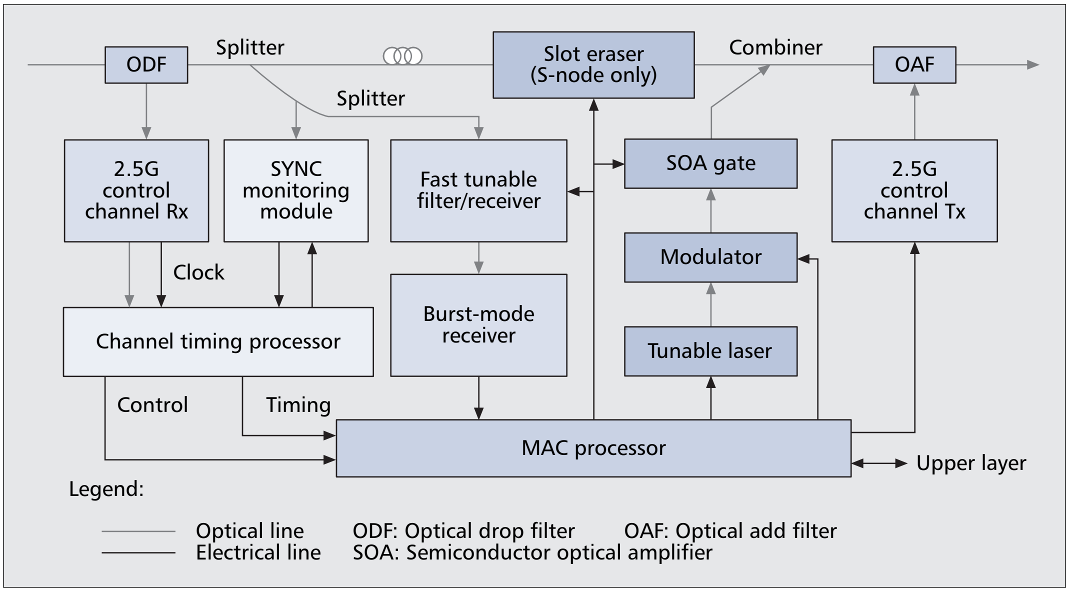
General Network and Node Architectures

HOPSMAN is a unidirectional WDM slotted-ring network with multiple WDM data channels (λ_1–λ_W, at 10 Gb/s) and one control channel (λ_0, at 2.5 Gb/s), as shown in Fig. 1. Channels are further divided into synchronous time slots. Each data-channel slot contains a data packet in addition to some control fields to facilitate synchronization. In the interest of clarity, "data slots" and "data packets" are used interchangeably in what follows.

Within each slot time, all data slots of *W* channels are fully aligned with the corresponding control slot. Each control slot is then subdivided into *W* mini-slots to carry the status of *W* data slots, respectively. Moreover, there are two types of nodes in HOPSMAN: ordinary-node (O-node) and server-node (S-node). An S-node differs from an O-node by having an additional optical slot eraser that makes bandwidth reusable and achieves greater bandwidth efficiency for the network. It is important to note that the network attains much better bandwidth efficiency by using only a few S-nodes. Each node of both types has a fixed transmitter and receiver pair for accessing the control channel, and a tunable transmitter and receiver pair for accessing data channels.

In general, with respect to accessing data channels, the node architecture [13] falls into one of two categories: switch-based and broadcast-and-select-based. Basically, the switch-based

While switch-based nodes provide high channel capacity through the simultaneous access of multiple wavelengths, it becomes costly for some nodes that demand less capacity than provided. In contrast, the broadcast-and-select structure enables an incremental and cost-effective upgrade of the channel capacity. Accordingly, our HOPSMAN testbed system adopts the broadcast-and-select architecture.



■ **Figure 2.** *General node architecture of HOPSMAN.*

architecture includes the use of a demultiplexer and a space-switch matrix to direct all desired channels to the optical receivers. Opposed to this, the broadcast-and-select architecture uses an optical coupler to tap off a portion of the optical signal power from the ring to make all data channels available ("broadcast") to the node. The desired data channel is then "selected" via a tunable or band-pass filter. While switch-based nodes provide high channel capacity through the simultaneous access of multiple wavelengths, it becomes costly for some nodes that demand less capacity than provided. In contrast, the broadcast-and-select structure enables an incremental and cost-effective upgrade of the channel capacity. Accordingly, our HOPSMAN testbed system adopts the broadcast-and-select architecture. As a result, while each O-node has only one optical transmitter and receiver pair, an S-node can easily be upgraded to multiple pairs of tunable transmitters and receivers.

The architecture of a node in HOPSMAN is shown in Fig. 2. It is best described as consisting of two building blocks for control channel processing and data channel access. For control channel processing, a fixed optical drop filter (ODF) at the input port first extracts the optical signal from the control channel slot by slot. The control information is electrically received by a fixed-tuned receiver, and processed by the MAC processor. While the control information is extracted and processed, data packets remain transported optically in a fixed-length fiber delay line. The channel timing processor, in coordination with the SYNC monitoring module, is responsible for extracting the slot boundary timing and subsequently providing the activation timing for other modules. Having obtained the control information (the status of W data channels), the MAC processor then executes the MAC scheme (described later) to determine the add/drop/erase operations for all W channels and the status updates of the corresponding mini-slots in the control channel. Finally, a fixed-tuned transmitter inserts the newly updated control signal back in the fiber, which is, in turn, combined with the data channels' signal via the optical add filter (OAF).

Data channel access corresponds to add and drop operations of data packets based on the broadcast-and-select configuration described above. Specifically, packets of all wavelengths are first tapped off through wideband optical splitters. They are in turn received via a four-wave-mixing (FWM)-based optical tunable filter/receiver (described later). To transmit a packet onto a particular wavelength, the node simply tunes the tunable transmitter [10] to the wavelength. Finally, to discontinue unneeded data packets on any wavelengths, the slot eraser (in S-node only) employs a mux/demux pair and an array of W SOA on/off gates to reinsert new null signals on the wavelengths.

The MAC Scheme

Since each node has only one tunable receiver, receiver contention [3] occurs when there are more than one packet destined for the same receiver in one slot time. Thus, two packets destined for the same node are not allowed to be carried by different wavelengths in a single slot time. Likewise, because there is only one tunable transmitter, any one node can make at most one packet transmission in a single slot time. Such a limitation is referred to as the *vertical access constraint*. Note that by vertical we mean the access of different wavelengths within the same slot time.

HOPSMAN employs a MAC scheme called Probabilistic Quota plus Credit (PQOC). First, a cycle (Fig. 1) is composed of a predetermined fixed number of slots. In general, PQOC allows each node to transmit a maximum number of packets (slots), or *quota*, within a cycle. Most important, even though the total bandwidth is equally allocated to every node via the quota, unfairness surprisingly appears when the network load is high. This is because upstream nodes can access empty slots first, resulting in an increasing tendency for downstream nodes to encounter empty slots that are located *vertically* around the back of the cycle. This issue, as well as the vertical access constraint, gives rise to poorer delay-throughput performance for downstream nodes. To resolve the unfairness problem, the quota is exerted in a probabilistic rather than deterministic fashion, as "probabilistic quota" implies. In other words, rather than transmitting packets immediately, each node makes the transmission decision according to a probability (e.g., the quota divided by the cycle length). Note that using the probability, a node may end up making fewer packet transmissions than its quota. The problem can be resolved simply by enforcing a packet transmission in a subsequent slot time with an idle slot. Such an approach evenly distributes idle slots within the entire cycle at all times and eliminates unfairness against downstream nodes.

Furthermore, if a node cannot finish its entire quota in a cycle (i.e., it has fewer packets than its quota), the node yields the unused bandwidth (slots) to downstream nodes. By doing so, the node earns the same number of slots as credits. These credits allow the node to transmit more packets beyond its original quota in a limited number of upcoming cycles, called the *window*. That is, the credits are only valid when the number of elapsed cycles does not exceed the window. The rationale behind this design is to regulate fair use of unused remaining bandwidth particularly in the metro environment with traffic that is bursty in nature. Notice that there are system trade-offs in PQOC involving cycle length and window size. For example, the smaller the cycle length, the better the bandwidth sharing; the larger the window size, the better the bursty-traffic adaptation, both at the cost of more frequent computation. The cycle length and window size can be dynamically adjusted in accordance with the monitored traffic load and burstiness via network management protocols, which are beyond the scope of this article.

Testbed Implementation and Experimental Results

We built an experimental ring testbed to demonstrate the feasibility and performance of HOPSMAN. The testbed consists of three nodes: one S-node and two O-nodes (O_1-node and O_2-node). The hardware implementation of an S-node is illustrated by the functional diagrams in Fig. 3. Note that the implementation for an O-node is the same as that of an S-node except with the slot eraser removed. The ring testbed is 38.3 km long, with 10 cycles per ring, 50 slots per cycle, and each slot 320 ns long, yielding a total of 500 time slots, or 160 ms in one ring length. The testbed uses a control channel wavelength of 1540.56 nm, and four data channels at wavelengths of 1551.72 nm, 1553.33 nm, 1554.94 nm, and 1556.55 nm. The input and output power per channel is kept at –10 dBm and 0 dBm, respectively, by using attenuators and amplifiers on the ring. The control channel employs continuous mode transmission at a rate of 2.5 Gb/s, and is processed at each node through opto-electro-optical (O-E-O) conversion. On the other hand, data channels adopt burst mode transmissio at a target rate of 10 Gb/s. Due to the technological immaturity of high-speed optical burst-mode receivers (BMRs), we have deliberately downgraded the data channels' bit rate to 1.25 Gb/s so that commercially available BMRs could be used. It is important to note that the HOPSMAN testbed has been designed so that the rates of the data and control channels are independent of each other. Because of the extensive use of BMRs in passive optical networks, we expect that 10 Gb/s BMRs will be commercially available soon.

Besides a fast tunable transmitter, as shown in Fig. 3a, a node (S-node) contains three major components: an FPGA-based central processor, a fast tunable filter/receiver, and an optical slot eraser. These components are described in detail in the following sections.

The FPGA-based central processor consists of a control-channel board and a data-channel board. The processor is responsible for performing four major functions: channel synchronization, medium access control, optical device control, and data packet framing.

Channel Synchronization and Medium Access Control

The field programmable gate array (FPGA)-based central processor consists of a control channel board and a data channel board, as shown in Fig. 3c. The processor is responsible for performing four major functions: channel synchronization, MAC, optical device control, and data packet framing. Before describing these functions, we address a number of key design features for channel synchronization on HOPSMAN. For WDM slotted ring networks, the timing synchronization between the data and control channels must be perfectly maintained at all times. In the HOPSMAN testbed the channel timing synchronization is ensured via two levels of alignment, coarse-grained and fine-grained, as well as guard-time-based dispersion compensation.

First-level coarse-grained synchronization is achieved by inserting a fixed short fiber delay line (5 m in our case) in the optical data channel path to accommodate the basic control computation latency. Second-level fine-grained synchronization is accomplished by matching a fixed-pattern preamble field (i.e., the SYNC field) at the beginning of each control slot, as shown in Fig. 4a. Moreover, as a result of the fiber's inherent chromatic dispersion, after long fiber transmissions the pre-aligned data channels undergo different propagation delays and are no longer synchronized with the control channel. For HOPSMAN's ring length of less than 50 km, simply adding a guard-time field at the beginning and/or end of each data slot can solve the problem. In the HOPSMAN testbed the data can be correctly recovered without any error with a guard time of 40 ns. HOPSMAN's data and control slots were found to be perfectly synchronized, as shown in Fig. 4b. Note that longer rings require an in-line dispersion compensation module to tolerate the propagation-delay difference.

The control channel board contains a Xilinx VertexII FPGA chip and a 2.5 Gb/s continuous-mode optical transceiver. It is responsible for the first three functions (i.e., synchronization, access, and device control) of the central processor. Ini-

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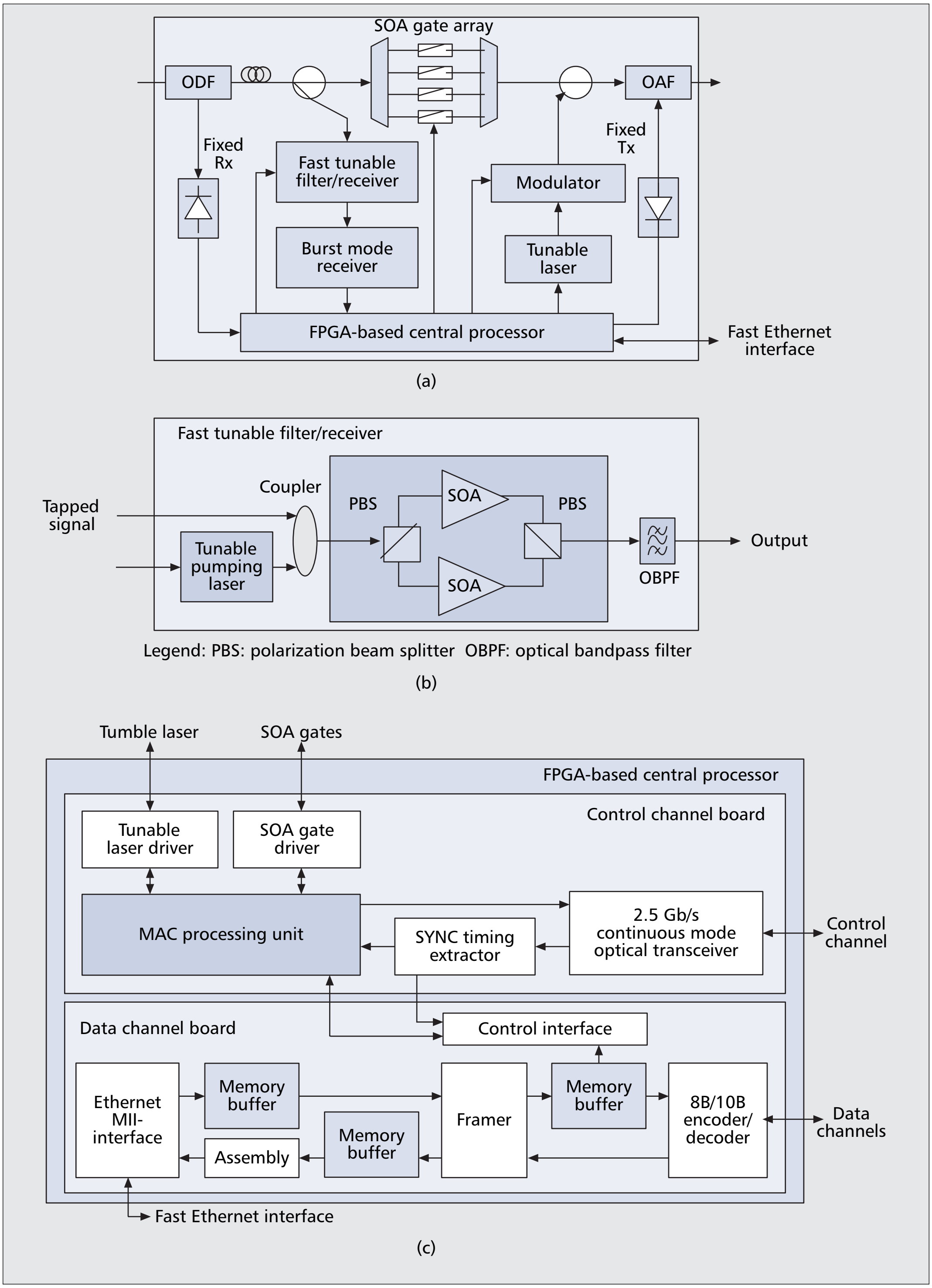
tially, the optical transceiver strips off the control slot from the ring. Each control slot (Fig. 4a) contains one 16-bit SYNC field, one 16-bit header, and four 16-bit mini-slots, respectively, carrying the states of four data channels. The SYNC timing extractor (STE) mainly detects the SYNC field in the control slot. Upon having matched the SYNC field, the STE passes the precise timing trigger to the data channel board via the control interface to bring the output data slot into full alignment with the control slot.

Followed by the STE, in accordance with the status of each data channel, the MAC processing unit (MPU) performs the MAC scheme, PQOC, which includes the five operations described next. Each data slot has four distinct states-BUSY, BUSY/READ (BREAD), IDLE, and IDLE/MRKD (IMRKD):

- To transmit a packet from the memory buffer into an IDLE slot on a wavelength, the MPU signals the tunable laser driver to perform the wavelength tuning, and updates



■ **Figure 3.** *Hardware implementation of the HOPSMAN testbed system: a) experimental node setup (S-node); b) four-wave-mixing-based fast tunable filter/receiver; c) FPGA-based central processor.*

the state from IDLE to BUSY in the corresponding mini-slot.
- To receive a packet from a wavelength, the MPU directs the same wavelength-tuning operation, but updates the slot state from BUSY to BREAD.
- To erase a BREAD slot, the MPU of an S-node informs the slot eraser module via the SOA gate driver in the control channel board.
- As a result of having no packet in the memory buffer but with positive quota, the MPU yields an IDLE slot to downstream nodes (and earns a credit) by changing the state from IDLE to IMRKD.
- Thus, with a credit, the MPU transmits a packet from the memory buffer into an IMRKD slot by changing the state from IMRKD to BUSY. Finally, the updated control slot is sent back to the ring through the optical transceiver.

The data channel board contains a Xilinx Spartn3A FPGA chip. It is responsible for the last function of the central controller: data packet framing between Fast Ethernet and the HOPSMAN ring. Note that the testbed can support any type of local area network and interface; we use Fast Ethernet only because of its wide availability. Specifically, for the outbound flow, the framer module first segments incoming Ethernet packets into smaller 350-bit-long HOPSMAN slots. Before being sent to the ring, data packets are encoded via the 8B/10B encoder, which enables reliable transmission and easier burst mode reception. In the inbound flow the framer performs the reverse function by assembling a number of data slots back to an original Ethernet frame.

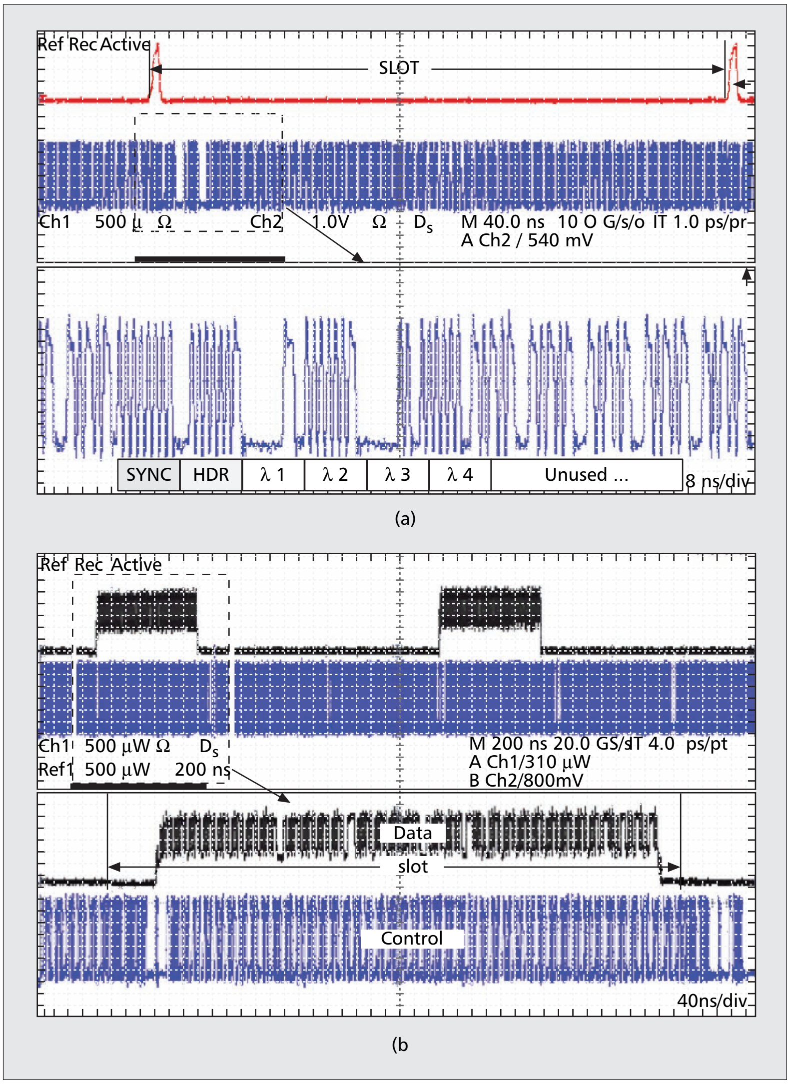


Figure 4. *Synchronization of control and data channels: a) control channel slot; b) synchronized data and control slots.*

Fast Tunable Filter/Receiver and Optical Slot Eraser

Tunable filters made from mechanically moving elements usually require millisecond tuning times, which is not feasible for OPS networks. New devices that achieve tuning times on the order of 1 µs have been proposed. Among them, the electro-optic tunable filter (EOTF) [14] can achieve sub-microsecond tuning speed, but requires a high tuning voltage. The acousto-optic tunable filter (AOTF) [15] reaches microsecond speeds but only during the selection of channels. The fiber Fabry-Perot-based tunable filter [16] also efficiently provides a response time of up to a few microseconds. In principle the microsecond-level tuning time is still unacceptable for an OPS network that adopts a slot as small as 320 ns, as HOPSMAN does.

In the HOPSMAN testbed system we adopted a polarization-insensitive four-wave-mixing (FWM)-based optical tunable filter/receiver, as shown in Fig. 3b. Based on the FWM method, by using a sampled grating distributed Bragg-reflector (SGDBR) tunable pumping laser and an SOA, the wavelength of the tapped-off data signal can be converted to the target wavelength, which is the wavelength of the fixed filter provided. The inherent polarization tracking problem of this FWM-based system is solved using polarization diversity [17], as illustrated in Fig. 3b. The approach attains a conversion efficiency of 18 dB. Since the system tuning time depends on the tuning speed of the pumping laser, our FWM-based tunable filter/receiver achieves a tuning time of less than 25 ns. The experimental result in Fig. 5a displays the optical spectrum and eye diagram of the received signal.

The optical slot eraser was built with a mux/demux pair and an array of SOA gates, which can be turned on/off in 5 ns and achieve an on/off extinction ratio greater than 30 dB. Figure 5b displays the two distinctive waveforms of a data channel before and after the erasing operation. The SOA gates also provide a 10 dB gain to cover the nodal loss contributed by the control-channel add/drop filter and mux/demux filters.

Demonstration of a Commercial Real-Time Application

We conducted a feasibility test by running commercially available remote media player applications over a three-node HOPSMAN testbed, as shown in Fig. 6. There are three nodes in the testbed, S-node, O_1-node, and O_2-node, and the

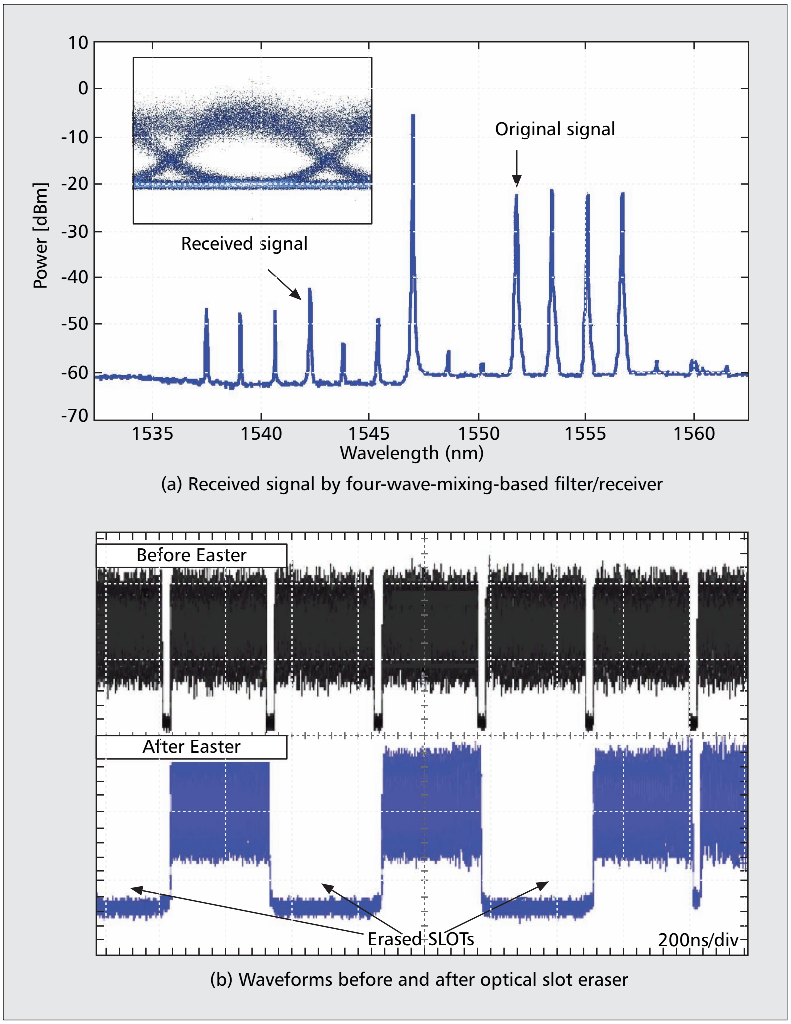


Figure 5. *Experimental results with fast optical devices: a) received signal by FWM-based filter/receiver; b) experimental results with fast optical devices.*

S-node and O_1-node are connected to PC_S and PC_1, respectively, via a Fast Ethernet interface. At PC_1, a video playback application, *Windows Media Player 10*, requests a 30-min-long 5.2 Mb/s MPEG-4-encoded video stream to be sent from PC_S, which runs a video server application, *Windows Media Services 9*. The third node of the testbed, O_2-node, serves as a mass traffic generator, continuously sending dummy traffic to both O_1-node and S-node. The total amount of traffic to be generated is determined according to the following guidelines: the normalized per-wavelength load is set as high as 0.9, and the real-time video-stream traffic occupies only one-forth percent of the total load ($0.9 \times 4 = 3.6$). In other words, the video-stream traffic is only provided with one-forth percent of quota out of the entire bandwidth. Based on our simulation results, the maximum normalized throughput of the network with only one single server is 0.667. Accordingly, the maximum achievable throughput for the 8B/10B-encoded video stream traffic is equal to 1.25 Gb/s/wavelength $\times$ (8/10) $\times 4 \times 0.9 \times 0.667 \times$ (0.01/4) = 6 Mb/s. Such a setting makes HOPSMAN a potential bottleneck for the video-stream traffic as a result of poor bandwidth allocation. With the PQOC scheme under such a heavy load, the testbed has been shown to achieve delay- and jitter-free video playback at PC_1 in the O_1-node. With experiments of this sort, we concluded that HOPSMAN is particularly advantageous for bandwidth-hungry and delay/jitter-sensitive applications. Medical imaging, online interactive gaming, distance learning, and remote terminal services are among potential applications for HOPSMAN.

Conclusions

In this article we have presented the architectural design and hardware implementation of HOPSMAN, an optical packet switched metro WDM slotted ring network testbed system. It uses FWM-based fast tunable filters/receivers and optical slot erasers that enable nanosecond-order OPS operations. In essence, HOPSMAN employs a versatile MAC scheme that provides quota-based guaranteed bandwidth and the credit-based dynamic allocation of the remaining bandwidth. With flexible optical devices and an efficient MAC scheme, HOPSMAN was shown, by means of a feasibility test, to be capable of achieving guaranteed delay-throughput performance particularly for bandwidth-hungry and delay/jitter-sensitive applications.

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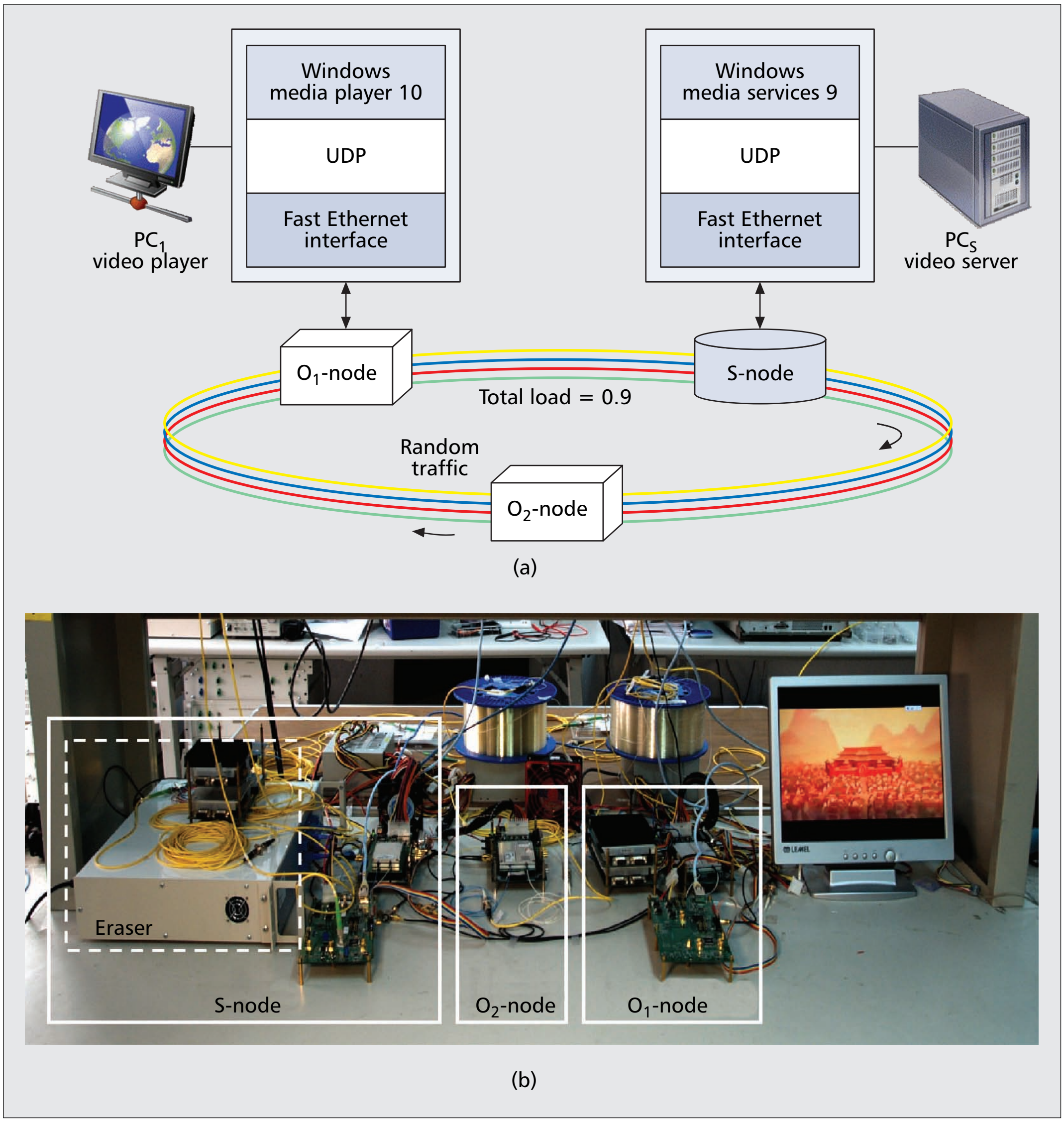

■ **Figure 6.** *Feasibility test and demonstration of HOPSMAN testbed: a) experimental setup; b) snapshot of the system.*

With flexible optical devices and an efficient MAC scheme, HOPSMAN was shown, by means of a feasibility test, to be capable of achieving guaranteed delay-throughput performance particularly for bandwidth-hungry and delay/jitter-sensitive applications.

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BIOGRAPHIES

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