End-to-End Layer-3 (IP) Packet Throughput and Latency Performance Measurements in an All-Optical Label Switched Network with Dynamic Forwarding

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Abstract: We experimentally demonstrate dynamic IP-packet forwarding through an All-Optical Label-Swapped network and for the first time report true end-to-end Layer-3 IP throughput and latency performance measurements. No observable core throughput penalty and a 0.79 µsecs latency increase was measured for 40 to 1500 byte packets at OC-48 rates.

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1. Introduction

Optical packet switching has advanced to the point where it is now possible to forward packets all-optically with potential benefits in power, footprint and scalability of packet forwarding rate [1]. To date there have been optical packet switching systems demonstrations that involve the manipulation of ISO layers 1 and 2 [2-7] where the quality is measured by analyzing the bit errors in the packet and routing fields called the packet bit-error rate (PBER). However, until now there has been no measurement or demonstration of IP packet layer-3 performance through an optical packet switched network. The experimental results reported here involve a first time implementation of an optical packet forwarding system that incorporates (1) mapping of IP forwarding information with optical packet network forwarding information, (2) adaptation of ISO Layer 2 transport protocols between an electronic routed network and an optical packet network, and (3) analysis using industry-standard measures including throughput and latency. This was accomplished by first implementing a complete optical packet switching system, interposing it within a real-world IP routed network, and then injecting IP traffic which traversed the IP network and then the all-optical packet switched network before being injected back into the IP network. Also, a new packet idler concept is introduced that addresses many system issues in getting layer-3 operation to work. Measurements were based on analysis of the IP traffic injected into this system. The optical packet switched network is an edge-core all-optical label-swapped (AOLS) network with per packet edge node adaptation, lookup and core node forwarding using wavelength conversion. True End-To-End layer-3(IP) performance of an optical label switched network with one ingress, one core, and two egress nodes showing negligible core throughput penalty and a 0.79usec core latency increase, indicating a low delay optical network with a high degree of transport efficiency is demonstrated.

2. Optical Packet Structure and AOLS Network Architecture

AOLS has become an important technique for separating the optical packet forwarding and routing planes [8]. Individual IP packets are encapsulated with an optical label (OL) as they enter the optical edge ingress node. Once in the core network, only the optical label is used in making forwarding decisions. Labels are kept small compared to the original IP headers to maximize transport efficiency and reduce lookup latency. As a consequence, it is necessary to erase and rewrite labels at each switch node to maintain a large overall address space.

Fig. 1(a) shows the AOLS network demonstrated in this paper. At the ingress edge node OC-48 Packet-Over-SONET (POS) framing is decapsulated to extract the raw IP packet only. Various schemes for mapping external network paths or routes to the optical domain routes can be implemented (e.g. Overlay or Peer-Peer). In this work, mapping of IP destination address to Optical Label was conducted assuming pre-computed path and label associations (generally the function of a routing protocol). Routing information contained in the IP header is used to look up an ingress wavelength ($\lambda_{\text{ingress}}$) and an optical label. IP packet header information is used to update Optical Time-To-Live (TTL) and priority fields in the optical header at the ingress node. Each IP packet and the computed Optical Header is encapsulated in a 2.5 Gbps asynchronous optical container as shown in the inset in Fig. 1(a) and written optically on $\lambda_{\text{ingress}}$ [9]. Upon exiting the All-Optical domain at the egress edge node, the IP packet TTL and Priority fields are updated and the IP packet encapsulated within a framing format commensurate with the IP network it is entering (e.g. POS or Gigabit Ethernet).
At the core node, the payload of the optical packet frame is maintained within the optical forwarding plane while the optical packet header is detected and processed electronically to conduct lookup, control forwarding and update TTL. Asynchronous optical packet framing is used to generate control signals for header and frame erasure, wavelength switching and interpacket idler signaling control. We report for the first time in this paper the use of optical idlers. Idlers are interpacket fills used primarily to maintain optical power between packets required to avoid EDFA transients and at the burst mode receiver for packet detection. Idlers are generated between packets at every ingress router and used to fill inter-packet gaps at each output port of the switched packet streams of each core node. The recovered optical label is used to determine the outgoing core wavelength ($\lambda_{\text{core}}$) and a new outgoing optical header on a per-packet basis. The wavelength conversion to $\lambda_{\text{core}}$ is used to implement space switching of the optical packets framed with the new optical header, by selecting an output port at the core node.

3. Experimental Setup

The experimental setup is shown in Fig. 2. The incoming packet stream is kept in the optical forwarding plane and is passively delayed to match the processing time of the core controller and subsequently fed to a two-stage wavelength converter [10] The first WC stage removes the optical framing and the second stage performs wavelength switching. An electro-optic modulator at the output of the two-stage wavelength converter imprints new framing onto CW light surrounding the converted optical packet payload, which is amplified and forwarded to separate space ports using an Arrayed Wave Guide Router (AWGR). Optical packet headers and packet frame delimiters are identified in the electronic core control plane by detecting and processing the incoming optical packet stream. The control signals for framing removal, wavelength switching, framing rewrite and idler insertion are all derived from the core FPGA controller board which identifies individual optical packets, extracts all-optical processing plane.

Fig. 1. (a) AOLS network architecture demonstrated. GB: Guard Band, OPH/T: Optical Packet Header/Trailer (b) End-to-End IP test setup

Fig. 2. Core Node Experimental Setup
4. Measurements and Results

Figs. 3(a) and (b) show measured layer-3 packet throughput and average latency (as defined in [11]) variation versus packet size. The POS throughput and latency of the electronic router (ER), a GSR 12000, were measured through path 1-5-6 as shown in Fig 1(b). A theoretical computation of the achievable throughput (% of available POS payload bandwidth) accounts for the optical packet header and framing overheads and Ingress-Egress back-to-back (IE B2B) throughput measurement shows that the edge node adaptation closely matches the theoretical throughput for different packet sizes. Throughput for Core Dynamic forwarding with or without Rewrite (CDR/CDNR) shows that no significant throughput penalty is incurred both due to either wavelength switching and conversion or label swapping. The 4% penalty measured without label swapping is attributed to imperfect optimization of the two stage wavelength converter for sufficient extinction ratio at the output. Variation in packet latency with packet size is linear as expected due to the nature of the simple lookup at the core node. The bulk of the latency seen in the system results from the ER and the Ingress-Egress Adaptation and a comparison between latency measured for the fully switching network system versus Ingress-Egress and Electronic Router (IE-ER) path shows that only a minimal latency increase (max 0.79usec) is introduced by the core node.

5. Summary

We experimentally demonstrate a complete dynamic layer-3 (IP) forwarding AOLS network and present the first true end-to-end layer-3 performance measurements. The agreement between the measured throughput and the theoretically predicted is excellent and only show a penalty for small packet sizes, which is ascribed to the electronic processing in the SONET layer outside the AOLS network. The latency added is constant due to the fixed optical path through the core node and measured to 0.79usec. It is negligible compared to electronic switching and adaptation.

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7. References