Intelligent Highly-Functional Cross-Layer Optimized Interfaces for Future Access/Aggregation Networks

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ABSTRACT
Cross-layer communications allows future optical access/aggregation networks to meet stringent bandwidth and performance demands by facilitating the dynamic management and optimization of network routing based on performance monitoring measurements and other higher-layer attributes. Our work endeavours to design and demonstrate a test-bed of intelligent cross-layer optimized network interfaces that can seamlessly and transparently interconnect heterogeneous edge users. The proposed design will dynamically support high-bandwidth applications at low cost and with extremely high energy efficiency. The cross-layer nodes allow for quality-of-service aware packet routing and protection, and leverage real-time optical performance monitoring modules to enable physical-layer aware switching. In this paper, we will outline our vision for the cross-layer network architecture, describing the enhanced networking functionalities that have been developed in the optical packet switching test-bed, in addition to the experimental demonstrations of real-time performance monitoring. This work also involves parallel project goals of fast failure recovery, simulations of network routing algorithms, and a demonstration of physical-layer aware video transmission.
Keywords: Optical communication, cross-layer communications, optical performance monitoring, quality-of-service, optical packet switching.

1. INTRODUCTION

The design of the next-generation Internet infrastructure is driven directly by the need to address the massive growth in bandwidth demands and network traffic, in addition to the challenges arising from the unsustainable acceleration in energy consumption growth. The bottleneck in delivering efficient, low-cost, high bandwidths to a multitude of users and heterogeneous applications is the main driver for this work. In order to sufficiently address these stringent and challenging performance requirements, it is necessary for the future network infrastructure to incorporate emerging physical-layer technologies and to diverge from traditional network design paradigms, specifically supporting a cross-layer communications platform [1]-[3].

Leveraging innovative photonic devices allows the optical layer to realize ultrahigh bandwidths and a high-level of networking functionalities. Further, the deployment of optical-domain based switching results in a reduction in the number of costly optical/electronic/optical (O/E/O) conversions. However, the resulting system thus loses access to electronic regeneration and grooming techniques and functionalities, which are key to maintaining adequate signal integrity. High-capacity connectivity without excessive overprovisioning is likely to be achieved using a cross-layer design paradigm. The intelligent, cross-layer enabled optical networking platform will also facilitate meeting the requirements for broadband quality-of-service (QoS) guaranteed user connectivity. In this work, we first investigate the design of a cross-layer optimized network, to enable the dynamic management of optical switching based on performance monitoring measurements and other higher-layer attributes (i.e. QoS). Energy-aware routing schemes can also be supported, in addition to the increased awareness of the physical layer [4], [5].

Using an implemented networking test-bed, we present the design of an optical packet switching fabric with advanced switching functionalities. As an exemplary demonstration, an optical packet multicasting capability is discussed. The cross-layer platform is then outlined, showcasing its ability to incorporate performance monitoring modules and potential energy-saving techniques.

The overall goal is the design of an intelligent cross-layer optimized network interface/node (Fig. 1a) that can interconnect the core with heterogeneous edge nodes. The design can then support high-bandwidth user applications at low cost and with high energy efficiencies. The cross-layer nodes comprise a dynamic network element with distributed control plane management, featuring fast packet-rate optical switching capabilities and embedded physical-layer performance monitoring modules. The node realizes an intelligent traffic delivery system that can dynamically manipulate optical switching on a packet-granular scale. In order to truly optimize the performance of future networking infrastructures, a multi-layer control scheme must be conceived such that all network layers can be optimized in unison. By creating an intelligent, adaptable optical layer that is flexible and aware of both the optical signals and higher-layer requirements, more dynamic, energy-efficient links can be achieved.

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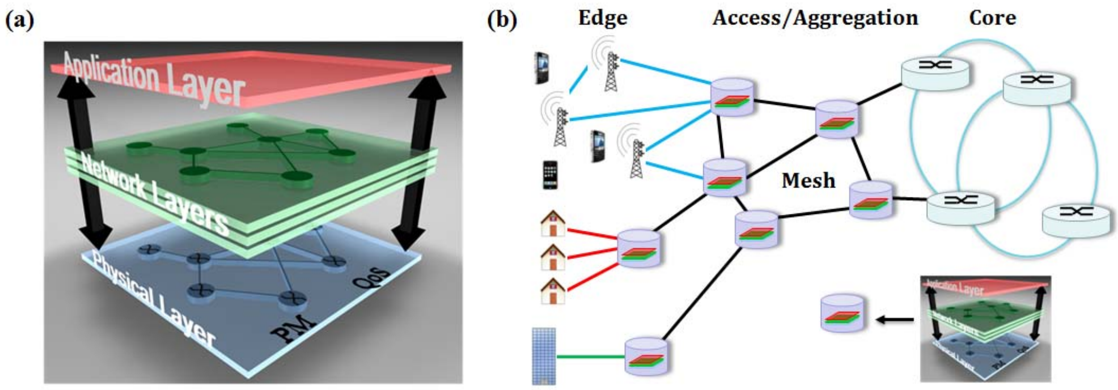

Figure 1: (a) Cross-layer optimized network protocol stack, with physical-layer awareness of the higher network layers; (b) Block diagram of the mesh-centred design to interconnect the cross-layer nodes.

2. NETWORK NODE ARCHITECTURE

We envision a cross-layer enabled network architecture composed of multiple network nodes arranged in a mesh topology (Fig. 1b) to be realized in the access/aggregation.

The ultimate goal of this work is to enable a fully-optimized intelligent cross-layer optical network node that incorporates packet-rate reconfiguration and optical switching capabilities, advanced physical-layer functionalities, dynamic performance measurement subsystems, a distributed cross-layer control plane, and cross-layer network routing protocols enabling dynamic resource allocation and multi-layer traffic engineering. Figure 2 depicts a detailed block schematic of the envisioned cross-layer enabled node. The development of an integrated cross-layer node will result in the enhanced routing techniques being able to actuate packet-level or flow-based rerouting, as well as the support for high-bandwidth applications (e.g. video transmission).

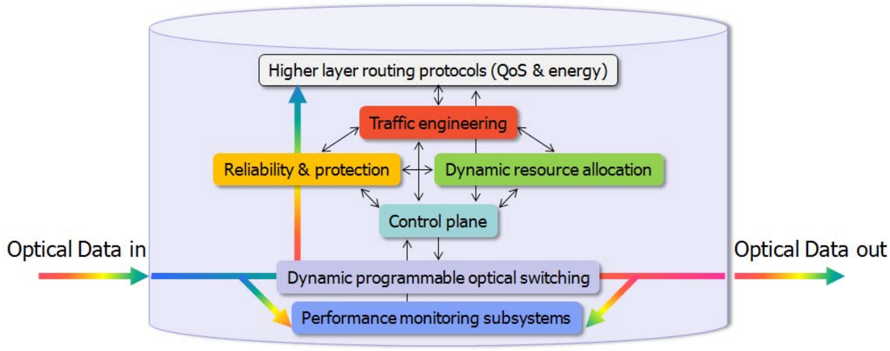

Figure 2. Detailed view of the cross-layer enabled node with various subcomponents.

Thus far, the current implementation is composed of the following components: a dynamic programmable optical switching fabric to enable fast all-optical switching of wavelength-striped optical messages, packet-level performance monitors to evaluate the optical data, and a field-programmable gate array (FPGA) based control plane to support packet-rate reconfiguration and feedback from the optical layer. The optical switching fabric below is realized, allowing the node to achieve advanced switching functionalities, including the support of packet- and circuit-switched data streams, quality-of-service based routing, etc. The fast packet-scale reconfiguration of the switching fabric has also been demonstrated using the FPGA-based control plane, as well as the transmission of circuit-switched video data through the switching fabric without distortion or frame loss using a 10-Gigabit Ethernet-based optical network interface card.

3. ADVANCED OPTICAL SWITCHING FUNCTIONALITIES

Optical packet switching is a potential technology for realizing the required high-performing switching fabric within routers and the cross-layer node, achieving high bandwidths through wavelength-division multiplexing. The implemented test-bed is based on a 4×4 optical fabric, composed of 2×2 wideband non-blocking photonic switching elements. The test-bed supports multiwavelength optical packets using a wavelength-striped format [6]. Each 2×2 element transparently switches the supported optical messages using four fast semiconductor optical amplifier (SOA) gates, arranged in a gate-matrix structure. The SOA-based switching decision uses distributed reprogrammable control logic based on the extracted control header bits. The experimental switching fabric acts as a fundamental vehicle on which to test our networking hypotheses; several high-level switching capabilities have been demonstrated using the test-bed.

3.1 Packet Multicasting Overview

Optical packet multicasting is a high-bandwidth application that enables greater functionality and programmable flexibility for future switching fabrics. Currently, multicasting is an inherent function of the IP layer that allows a single source to simultaneously transmit packets to multiple destinations. By migrating this functionality lower in the network stack to the optical layer, broadband packet-based applications can be envisioned to be supported directly on the underlying optical network, with lower effective cost.

We focus on realizing packet multicasting, wherein wavelength-striped optical messages can be transmitted from a single source to a subset of the destination ports. We take advantage of the optical switching fabric architecture's distributed electronic routing logic control to seamlessly support the multiwavelength packet multicast operation in an optical test-bed. The design discussed here is a packet-splitter-and-delivery (PSaD) architecture. The input wavelength-striped packet can be split multiple ways to enable multicasting. The proposed design leverages an optical switching fabric that is internally composed of *M* parallel optical packet switches interconnecting *N* network terminals. Figures 3(a) and 3(b) show the wavelength-striped optical packet structure, in addition to photographs of the multicast-capable switching fabric test-bed implemented here. Two parallel optical packet switches are realized to connect four distinct fabric ports. The PSaD architecture creates *M* distinct and independent paths between each source and destination, in a non-blocking fashion. Each path (i.e. optical switch) supports the multiwavelength optical packet format. One clear advantage of this design is that the optical switching fabric can either handle a unicast using a single switch, or multicast using combinations of several of the switches.

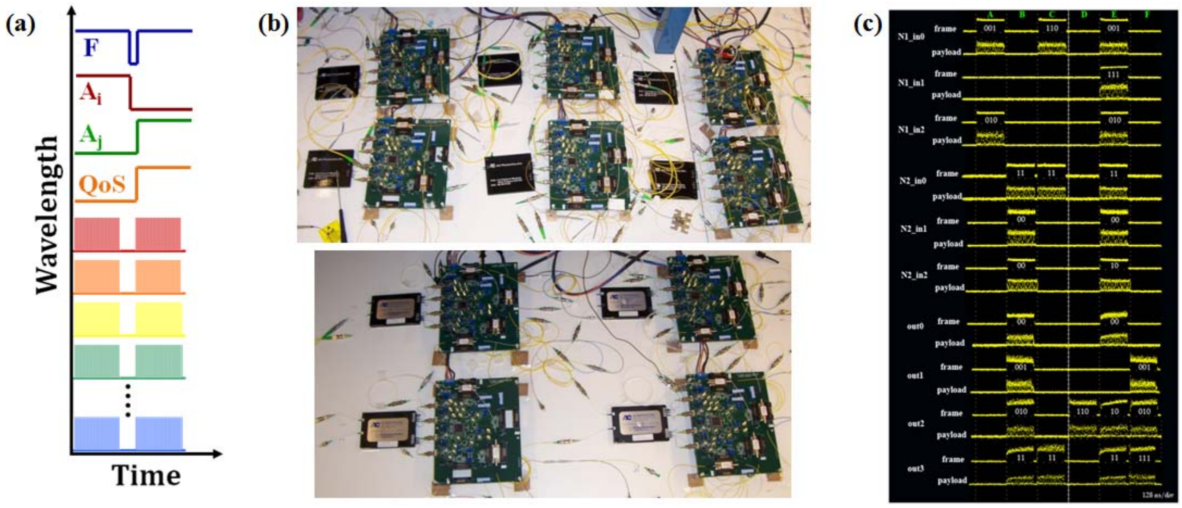

Figure 3: (a) Wavelength-striped packet format; (b) Photograph of multicast-capable switching fabric test-bed; (c) Experimental waveform traces of the input and output optical traffic, with labels referring to the address information encoded in the optical packets.

3.2 Experimental Demonstration and Results

In order to verify the architecture's ability to support the packet multicasting, a pattern of 8×10-Gb/s wavelength-striped optical messages are generated and injected in the fabric. The packets are correctly routed through both parallel switches and are multicasted to two different destinations (if desired) by unicasting on each switch. Figure 3(c) provides the waveform traces associated with the optical packet traffic sequence in this experiment, as well as the resulting packets egressing from the switching fabric.

The 8×10-Gb/s multiwavelength optical messages are correctly routed through the complete switching fabric, and accurately emerge at the destinations that are encoded in the control address headers. The multicasting operation is clearly validated, with all the packets successfully routed from one input port to multiple output ports. The switching fabric seamlessly supports both unicasting using a single switch entity and multicasting with both switches. Bit-error-rate (BER) measurements confirm that all packets are received error-free, achieving BERs less than 10^{-12} on all eight payload wavelengths. The experimental demonstration is more fully described in [6]. A second multicast-capable architecture has also been explored [7].

4. PERFORMANCE MONITORING

Within the scope of our proposed cross-layer platform, the network routing algorithms possess an enhanced awareness of the optical signals' properties as the packets propagate on the physical layer. This awareness is realized by embedding fast packet-scale performance monitoring within the optical network layer. Optical performance monitoring allows future networks and systems to monitor and isolate physical-layer impairments, and to perform a fast evaluation of the quality of the transmitted data signals. These metrics can then provide a means of feedback to higher network layers or a control plane to optimize routing. We envision performance monitoring within OPS fabrics to help enable an agile network that can independently and holistically isolate degradations and reroute optical messages accounting for impairments.

In the cross-layer optimized network, we have shown the packet-level monitoring of the optical packet's optical-signal-to-noise ratio (OSNR). The OSNR monitor is based on a ¼-bit Mach-Zehnder delay-line interferometer, which may support multiple modulation formats and is insensitive to the effects of other impairments (such as chromatic dispersion and polarization mode dispersion). Using power monitors and a high-speed FPGA, the OSNR has been shown to be evaluated on a message timescale. The packet-level OSNR monitor can then trigger the rerouting of degraded high-priority packets. This is discussed in [8].

Real-time burst sampling within the 4×4 cross-layer enabled switching fabric has also been shown using the TiSER oscilloscope [9]. TiSER captures a burst of samples in real-time and reconstructs the corresponding eye diagrams in equivalent-time mode. It enables the capture of fast non-repetitive dynamics at the modulation rate, comprising a real-time monitoring solution for high-data-rate optical links. The system shows the potential of rapidly and dynamically extrapolating the messages' BER, which can then be used an indication of the physical-layer performance in the cross-layer optimized infrastructure. The BER estimation will be performed using advanced signal processing, to rapidly determine the quality factor from the captured eye diagrams. [10] addresses this work more thoroughly.

5. CONCLUSIONS

This work has been motivated by the requirement to support extremely agile, highly-functional, and reliable optical connectivity without excessive overprovisioning in future networks. In order to enable these intelligent optical networking functionalities at low cost and with extreme energy efficiency, we envision an advanced cross-layer infrastructure that allows optical switching to be executed at a packet-timescale incorporating inputs and performance metrics from all layers of the network stack. The goal is to create seamless, more transparent paths across an intelligent network that incorporate emerging physical-layer technologies. We propose a cross-layer enabled network architecture and present experimental demonstrations of an optical switching fabric with advanced networking functionalities. The cross-layer platform is outlined, incorporating enhanced awareness of the physical optical channels, as well as the ability to react to the physical-layer awareness on a packet-timescale and the support of cross-layer reaction. To achieve advanced multi-layer control algorithms, the network node requires an intelligent co-optimization across all the layers. Complementary work involves the demonstration of fast failure recovery [11], and the demonstration of physical-layer aware video transmission.

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