Creating a Future Internet Network Architecture
with a Programmable Optical Layer

Abstract: The collective transformational research agenda pursued under the FIND program on clean-slate architectural design of the future Internet is progressing in parallel with revolutionary advances in networking technologies that span a broad and heterogeneous space. As the FIND program transitions to Phase II the challenge of coupling the architectural effort in a manner that drives and exploits the emerging heterogeneous physical network will be imperative to the ultimate success and realization of the FIND vision. The central goal of this proposed exploratory research is to bridge the gap between the FIND architectural efforts and advances in the underlying heterogeneous substrate by creating an integrative cross-layer environment that enables deeper access to the physical layer in a context consistent with the diverse capabilities and limitations of the emerging technologies.

Our focus will be on design exploration of a networking architecture for the future Internet that encompasses the capabilities of a fully programmable optical layer. In the proposed program we will develop an integrated cross-layer environment that enables bi-directional interaction and programmability of the optical layer. The effort will include the design and experimental validation of an integrated cross-layer communications platform that comprises: an interface plane with user programmable access to the optical node, mechanisms for information exchange with the optical layer, and diverse traffic routing capabilities. This experimental environment will be used to perform architectural explorations of networking across varied applications and traffic scenarios envisioned for the future Internet from real time streaming video, to latency sensitive packetized data computation, that are executed simultaneously. For the initial experimental efforts these will be run over current protocols such as IP, however the platform will enable experimentation with emerging protocols and signaling that explicitly exploit photonic layer programmability and cross-layer communications. The core intellectual merit of the proposed program lies in the creation of a unifying architectural platform that brings cross-layer information exchange and programmability directly to the optical layer. In its broader impact, this architectural approach will enable users and applications at the upper layers of the network to directly drive and exploit emerging heterogeneous technologies. The cross-layer platform will therefore provide a framework for seamlessly evolving the network architecture to take advantage of the optical layer’s functionalities in an integrated fashion with the needs and requirements of future Internet applications. We will coordinate and work closely with the FIND research community to develop this platform in a manner that facilitates the realization of the broader architectural research goals.

1.0 Research Rationale

Today’s era of explosive information growth, driven by the computation/communications convergence across the networking infrastructure, will clearly accelerate and drive the future Internet. Advanced optical networking systems designed primarily as high-capacity static transport pipes are increasingly challenged by the need to process these emerging diverse data centric traffic [1]. It is broadly accepted that emerging optical technologies addressing these challenges that manipulate optical traffic at the packet granularity and can accommodate a diverse set of formats will play an increasingly central role in future Internet network architectures. However very limited coupling currently exists between the optical and networking architecture research communities. As the FIND initiative drives forward clean slate future Internet architectures [2], it become imperative that heterogeneous technological advances at the physical layer can be exploited in a manner consistent with the research vision.

The rationale for this exploratory research proposal is to bridge the gap between the FIND architectural efforts and advances in the underlying heterogeneous substrate by creating an integrative cross-layer environment that enables deeper access to the physical layer in a context consistent with the diverse capabilities and limitations of the emerging technologies. The enabling cross-layer platform we propose constitutes exploratory research that would not be independently pursued in either community.
2.0 Overview

The original Internet architecture was build around a rigid notion of network layering. Each layer is designed to provide bare-bones functionality that can be used by the layers above it. For instance, the network layer provides “best-effort” routing, making no guarantee on delivery time, or, for that matter, delivery at all. Those guarantees are implemented within the transport layer, whose view of the network layer is simply as a best-effort medium. While this bare-bones layering architecture led to rapid development by setting clear boundaries and defining specific, apparently separate objectives of protocol design, such as routing, recovery from loss (reliability), resilience to congestion, and spectrum sharing (medium access control), it presents a major roadblock to future architectural innovations and the development of applications driven by cross-layer design and optimization [3]. We have since learned that these various objectives are not completely orthogonal, and breaking the layering structure via cross-layer design approaches is a major driver for current explorations of transformational FIND architectures.

Often, a lower-layer technology can perform additional functionality, but cannot provide this functionality to applications. This is because the higher layers are designed to assume that lower layers only satisfy the bare-bones minimum requirements. The optical networking layer can for example meet numerous QoS requirements, but when run under IP, applications have no straightforward means to invoke these QoS options to derive direct benefit. While higher layers maintain a simplified, bare-bones view of the layers beneath them, lower layers are not supposed to have any “view” at all of the layers above them. For instance, the network layer is supposed to handle all packets toward a destination in an identical fashion, and not distinguish them based on their application’s transport needs such as low-latency, high throughput, or high resilience.

Architectural approaches for cross-layer design facilitate mechanisms for information exchange between the layers of a protocol stack. This exchange of information across layers can be used to finely tune performance, provide additional functionality, or enhance the robustness and security of the network. Although significant research have focused on developing architectures for cross-layer communications and messaging, these efforts are largely decoupled from the heterogeneous physical layer and in particular the optical substrate. It is however critical for the future realization of the FIND networking paradigms to engage the optical layer and enable deeper exposure of the cross-layer design. It will simply not be possible to carry out the transformational networking research agenda without full architectural integration and exploitation of the emerging heterogeneous physical layer.

Our objective for this proposed exploratory effort is to develop a platform for executing FIND clean slate architectural research that enables deeper cross-layer engagement, control, and exploitation of the emerging heterogeneous substrate. The focus will be on the optical physical layer since it represents the network layer that has least been explored in the context of cross-layer design. Advanced optical networking systems are designed and employed primarily as high-capacity static transport pipes. State-of-the-art optical networking technologies can provide substantial functionalities but in current architectures applications have no straightforward means of deriving performance benefits by invoking these capabilities. Conversely, network layers viewing the optical substrate as a “black box” are forced to handle all data in identical fashion, irrespective of their applications’ transport needs (latency, throughput, resilience, etc.). Today’s era of explosive information growth, driven by the computation/communications convergence across the networking infrastructure is increasingly challenging this paradigm for the optical layer [4]. It is broadly accepted that over the course of the next generation Internet evolving under the FIND vision, emerging optical substrate technologies addressing these challenges will play an increasingly central role in future network architectures.

3.0 Architecture for Programmable Access to Optical Layer

Our proposal focuses on design exploration of an architecture that provides deeper exposure and programmable control of the optical layer to enable integrative cross-layer design and optimization. A key
element of the approach is to develop the cross-layer platform in a manner that provides the architectural option, but not requirement, to exploit the programmable optical layer. In this fashion, cross-layer information exchange and user programmable control into the optical substrate is invoked as an option and can be used to facilitate specific applications, routing algorithms, or traffic flows. Importantly, this approach maintains an environment where standard layered networking models that are advantageous to other classes of applications can coexist.

The proposed program goal is to develop an architecture that will facilitate design, analysis, experimentation and deployment of cross-layer mechanisms for invoking programmable access to the optical layer. The planned research activities will progress along the following tasks:

- Design exploration of applications driven functionality requirements for the programmable optical layer, including development of metrics for packet/circuit switching, QoS delivery and reliability under dynamic and quasi-static impairments, traffic engineering, granularity of resource sharing, etc.
- Development of control plane and programmable interface to optical layer for bi-directional information exchange and actuation of optical router, enabling use of physical layer performance data for traffic engineering, dynamic routing decisions, real-time adaptation to network conditions and delivery of diverse services.
- Experimental platform development, leveraging extensive existing programmable optical routing test-bed, for measurements and validation of cross-layer architectural design.

4.0 Proposed Research Plan

Architectural support for diverse QoS via cross-layer communications: Optical networks today provide a highly reliable and broadband communications infrastructure to the end user, with end-to-end bit error ratios (BERs) well below $10^{-15}$ and typical link outage probabilities of $10^{-6}$ (less than 1 minute per year). These stringent QoS requirements, which apply to the entire physical layer of optical networking, are based on commercial carriers’ need to provide highly reliable end-to-end connectivity to most of their customers. This high degree of network reliability comes at the expense of substantial margins allocated in the design of optical systems, accounting for dynamic system impairments (such as polarization-mode dispersion or power transients), for quasi-static impairments (like changing WDM channel loading or chromatic dispersion variations), as well as for component and subsystem ageing, e.g., over the 15-year lifespan of a system.

On the other hand, emerging heterogeneous technologies and applications that will drive network bandwidths in the future Internet, would likely not require nor would support such a high transport quality. For example, in a heterogeneous transaction across a network that spans both wireline and wireless transport, the typical packet loss rate on the wireless air interface is $\sim 10^{-2}$ which is much worse than the wire line packet loss rate of $<10^{-11}$. Hence, the question arises whether there is a need for a “one-size-fits-all” reliability model at the optical layer. By making the physical QoS characteristics of the optical layer visible to the higher layers via a suitable traffic engineering entity, it is possible to create a more flexible physical layer via cross-layer communications.

We will perform a comprehensive assessment of advanced application driven requirements for cross-layer exposure of the optical physical layer performance. This task will include close iteration with the FIND research community and collection of input to capture possible application scenarios. We will quantify the benefit of employing cross-layer performance information for delivering dynamically flexible and diverse QoS as well as resilience to failure and attack using appropriate simulation and design tools.
Optical layer aware resilient routing through true path diversity: One way to sustain traffic flow in the presence of link failures is to transmit the flow across several diverse paths. However, the layer in which the multi-path routing protocol is implemented often has an inaccurate view of the true underlying physical structure, such that paths that appear at the higher layer to be diverse are not truly diverse. The cross-layer platform will enable dynamic introspection of the optical physical network to facilitate true path diversity routing. Under this architectural platform the network can dynamically and seamlessly adapt itself to the needs of higher-layer applications. Future applications will increasingly use physical-layer information to perform traffic engineering and routing decisions.

In this task we will implement a programmable interface control plane to our experimental optical router network with bi-directional cross-layer communication protocols and driver specifications to extract optical layer performance metrics as well as actuate the optical router [5,6]. This work represents the first experimental investigation into the types of cross layer performance metrics that will be necessary for a flexible and programmable optical layer.

![Figure 1: Enabling infrastructure for cross-layer information exchange among the network layers via a programmable control plane that penetrates the optical physical layer. A service driven multicasting requirement is communicated through the control plane interface directly to the programmable photonic switch fabric. The control plane interface transparently processes multi-wavelength optical messages and dynamically reconfigures the switching fabric to instantiate the multicast light path topology.](image)

**Experimental design exploration and validation in network test-bed:** An experimental environment that leverages our extensive optical router test-bed facilities will be used to perform architectural explorations and validation of the cross-layer platform [7]. We will experimentally investigate networking across varied applications and traffic scenarios that specifically exploit the programmable optical layer. A necessary requirement for this platform is exploring the interactions between topology, physical layer functionalities, link layer protocols, and application-driven performance requirements. Our initial goal for will be to demonstrate programmable multi-wavelength multicasting among a number of optical nodes. Multicasting is clearly one of the most critical and challenging network functions for a multitude of applications.
A schematic of these initial experiments is illustrated in Fig. 1. As shown, each optical node consists of an interface control plane that can transparently process multi-wavelength optical messages and is capable of bi-directional signaling with the network management software. The control plane interoperates directly with the programmable physical layer packet switched fabric. The broadband switching fabric consists of individually addressable FPGA programmable optical gate elements. The sub-ns switching will enable immediate experimental architectural explorations for driving performance metrics and required functionalities for executing simultaneous circuit and packet switched traffic scenarios. The developed optical information exchange via this control plane builds upon our recent work on congestion control in optical packet switched networks using direct cross-layer signaling to realize active queue management. The experimental platform will form the basis for multiple network research efforts, including dynamic bandwidth allocation, rapid load balancing, and path diversity.

The proposed research program aims to explore a networking architecture for the future Internet that encompasses the capabilities of a fully programmable optical layer through the development of an integrated cross-layer platform that enables bi-directional information exchange and control. The program includes an experimental effort for performance and architecture validation in an extensive optical routing network test-bed.

5.0 Broader Impact

The proposed program aims to tackle the critical challenge of creating a unifying architectural platform that brings cross-layer information exchange and programmability directly to the optical layer. This architectural approach will enable users and applications at the upper layers of the network to directly drive and exploit emerging heterogeneous technologies, thereby broadening the use to the networking community. The cross-layer platform provides a new framework for concretely bridging the gap between the future Internet architectural research efforts and the underlying emerging technologies. The proposed research seamlessly evolves the network architecture to take advantage of the optical layer’s functionalities in an integrated fashion with the needs and requirements of future Internet applications. In our broader outreach we will coordinate and work closely with the FIND research community to develop this platform in a manner that facilitates the realization of the broader architectural research goals.