Research Statement

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My research has focused on enabling cross-layer programmability in large-scale systems to optimize their efficiency and reliability. To this end, my research has traced two trajectories in the systems and networking area. The first, a body of work in optical networking (§1), focuses on enabling programmability between the IP and the physical layers of the networking stack. The second, a body of work in congestion control (§2), focuses on enabling programmability between the application, kernel, and Network Interface Card (NIC) of the end-host stack.

My work stands out from other research in these areas because it sits at the balance between theory and practice. I am driven by the intellectual challenge of making a real-world impact with solutions that have provable theoretical properties. Thus, my research philosophy has been to employ an iterative process between theoretical formulation and practical tractability in real-world systems. This passion has led to algorithms and systems that are now deployed in large-scale production systems at Google and Microsoft (§3). For instance, my work on programmable optical networks has moved Microsoft to invest in building an entire infrastructure for optical software-defined networking in its networks [1, 2, 3, 4] and my work on delay-based congestion control is in production at Google [5].

My research methodology can be summed up in four steps: (1) measure the system to understand it and find the root cause of inefficiency; (2) formulate a well-stated optimization problem, with particular attention to the inefficiencies introduced by different layers of the stack; (3) find practical abstractions that enable a programmable interaction across layers of the stack to solve the optimization problem; and (4) build and evaluate the new system to determine how well it solves the problem. I focus on network efficiency and reliability throughout the research process and construct solutions that are tested with simulations and real hardware at scale. This focus on designing and building systems with rigorous properties defines my niche as a researcher.

1 Optical Networking

Optical communication is the workhorse of modern systems. Today, nearly all wide-area and data center communications are carried over fiber optics equipment making optics a billion dollar industry. Optics is poised to play an even bigger role in next-generation networks. The high bandwidth and ultra-low latency requirements, imposed by large-scale in-memory workloads, such as those for machine learning and business analytics, are hard to achieve in a cost-effective manner with traditional electrical devices. Looking ahead, as the world is moving towards 400Gbps+ networks, electrical chips are unlikely to simultaneously deliver high port bandwidth and low end-to-end latency. Hence, the next level of high performance systems cannot come without an in-depth understanding of the optical layer. However, the majority of current systems treat the optical layer as a static black box. This impasse is likely due to a holdover from IEEE standards targeted for the telecom world ossifying a gap between the physical layer and other layers of the networking stack.

This is where my research on optical networks comes in. My collaborators and I have designed novel network architectures that improve the efficiency of networks by enabling reconfigurability in the physical layer [6, 4, 3]. We have also defined practical graph abstractions that enable adoption of programmable topologies in the real world [7, 1], and we have formulated cross-layer optimization problems that improve the cost and reliability of networks [8, 9, 2].

Novel Network Architectures. Conceptually, having a reconfigurable physical layer revolutionizes the way we think of a network. It enables a realm where the network is no longer a static entity, but a dynamic structure of interconnections that may change depending on the workload. This line of thought opens a novel area of research applicable to present workloads and also to future ones with unpredictable traffic patterns, such as machine learning, artificial intelligence, genome analysis, Internet of Things, and edge computing. Accordingly, I am making a concentrated effort to understand the unique properties of programmable topologies in both data center and wide-area networks.
For instance, ProjecToR [6] makes a radical departure from present norms in building data center networks by removing all cables above Top-of-Rack (ToR) switches. It uses free-space optics to provide one-hop connectivity between ToR switches in the data center by disaggregating transmit and receive elements. A ProjecToR interconnect has a fan-out of 18,000 ports (60 × higher than current optical switches) and can switch between different ports in 12 µs (2500 × faster than current optical switches). Its high fan-out and high agility is enabled by digital micromirror devices (DMDs), commodity products from Texas Instruments which are ubiquitous in digital projection technology, and disco-ball shaped mirror assemblies (Fig. 1). A remarkable advantage of our optical setup is that it provides a “sea” of transmitters and receivers that can be linked in a multitude of ways, creating a scheduling and traffic routing scenario akin to that used in traditional switch scheduling problems, albeit with two important distinctions. First, ProjecToR’s setting is two-tiered: although the traffic demand is between ToRs, links are between lasers and photodetectors, and many laser-photodetector combinations can serve traffic between a pair of ToRs. Current switch scheduling algorithms do not tackle this two-tier case. Second, unlike earlier approaches, to scale to large data centers, the scheduling algorithm needs to be fully decentralized. To solve these challenges, we proposed an asynchronous and decentralized scheduling algorithm that is provably within a constant factor of an optimal oracle able to predict traffic demands. We built a ProjecToR prototype using real hardware (Fig. 2) and showed that DMD-based communication provide throughput comparable to optical fiber cables, can cover long distances, and can switch rapidly between receivers.

**Practical Graph Abstractions.** Similar to data center networks, modern optical devices such as Reconfigurable Optical Add/Drop Multiplexers (ROADMs), enable the reconfiguration of a wide-area network’s (WAN) topology by programming wavelengths on each fiber. Yet the physical layer of today’s backbones has remained static mainly because (i) there is no simple way to predict the throughput gains of implementing a programmable topology in the WAN, and (ii) there is no clear path to the practical insertion of programmable topologies into the already complex WAN traffic engineering (TE) schemes. To overcome these challenges, we proposed a theoretical bound on throughput gains of programmable WANs [7]. We showed that the gains of enabling topology programmability (TP) on a graph can vary widely across topologies. To shed light on this variance, we quantified the gains of TP based on the topology and proved that the throughput gain factor is between one and $O(\Delta)$, where $\Delta$ is the maximum degree in the graph. We showed that this bound holds for “any graph” and under “any edge failure” scenario. To address the second challenge, we proposed a graph abstraction, called the ReFlow graph, that permits topology programmability in the TE algorithm (i.e., multi-commodity flow optimization) without having to rewrite the TE itself (Fig. 3). We showed that this graph abstraction is expressive enough to capture a wide variety of TE formulations while achieving throughput within 99% of the optimal solution. We then used a testbed to benchmark key abstraction assumptions in practice and showed an end-to-end working scheme (Fig. 4).
2 Congestion Control

Today, congestion control plays a central role in a data center’s efficiency and its tenants’ quality of experience. However, the protocols and the stack are typically borrowed from solutions optimized for the Internet. This results in poor performance from using protocols such as TCP in a regime for which it was not designed. For example, incast collisions cause exacerbated straggler behavior and the inability to correctly detect and handle congestion creates more complex applications leading to much higher costs. My research has focused on congestion control abstractions, algorithms, and systems that broadly explore the above issues with particular interest in improving end-to-end latency and building massive-scale solutions.

Language Abstractions for Congestion Control in Hardware. Recently, there has been a surge in the adoption of FPGA-based NICs offering a programmable environment for hardware acceleration of network functions. This presents a unique opportunity to enable programmable congestion control algorithms, as new approaches are introduced either by humans or machine learning techniques. To realize this vision, we proposed implementing the entire congestion control algorithm in programmable NICs [10]. To do so, we identified the absence of hardware-aware programming abstractions as the most immediate challenge and solved it using a high-level domain specific language. Our language lies at a sweet spot between the ability to express a broad set of congestion control algorithms and efficient hardware implementation. It offers a set of hardware-aware congestion control abstractions that enable operators to specify their algorithm without having to worry about low-level hardware primitives. A sample implementation of a token-bucket credit manager is shown in Fig. 5.

Congestion Control Algorithms for RDMA. The Remote Direct Memory Access (RDMA) technology offers high throughput, low latency, and low CPU overhead by bypassing the end-host kernels allowing the NIC to transfer data in and out of pre-registered memory buffers. Research has favored RDMA over Converged Ethernet (RoCE) since it is compatible with current IP and Ethernet based data center networks, but enabling RoCE can cause deadlock problems at large scale. To solve this problem, we designed the first delay-based congestion control protocol for large-scale data centers [5, 11]. The key insight in our design is that advances in NIC hardware have made latency measurements possible with microsecond accuracy (Fig. 6). Furthermore, we showed that hardware-based timestamp measurements are sufficient to estimate switch queueing. Our algorithm is in production at Google and has won their Technical Infrastructure award, as it outperforms the state-of-the-art data center congestion control algorithm by 13 times.

Systems for Optimizing Congestion Control. During my PhD, I worked on building systems to improve the status quo of congestion control in terms of end-to-end latency by taking a closer look at TCP [12, 13, 14, 15]. The framework I designed, OpenTCP, allows network operators to define congestion control policies to adapt TCP as a function of network and traffic demand. As part of my thesis, I implemented modules to monitor and modify TCP’s parameters on the Linux kernel. I also studied the challenges of conducting time-sensitive network experiments and provided guidelines and tools to eliminate sources of inaccuracy in time-sensitive network experiments [16]. In another work, my colleagues and I designed and implemented (i) Caliper, a highly accurate packet injection tool, and (ii) NetThreads, a new platform that dramatically simplifies the development of low-level network applications on the NetFPGA board [17]. Caliper takes packets generated on a host computer and transmits them onto a gigabit Ethernet network with precise inter-transmission times. It is implemented using NetThreads and both are publicly available to the research community on github. Our work received 2nd place award at the NetFPGA Workshop.
Research Impact

My most satisfying research experiences, and the work I most appreciate from other researchers, are the ones that have an impact on the world. In an era of increased engagement with technology on many fronts—health, business, science, and social life—computer scientists have a unique opportunity to change the world for the betterment of mankind. I am driven by this passion, and I plan to continue seeking ways to contribute to this vision. During my career, I have always searched for the problems with real-world impact. I believe an academic environment will foster this vision, and I have followed these tenets at Google and Microsoft.

Measurement Driven Insights. Even though optical links are a fundamental component of modern networks, little is known about their operational characteristics. This lack of knowledge is limiting because enabling innovation at any layer of the networking stack requires us to understand it first. As the first researcher in the networking community to undertake this challenge, my work has produced many insights into the optical layer of both the data centers and the WANs, which will pave the way toward significant improvements in the future.

For instance, we analyzed the signal-to-noise ratio (SNR) of over 2000 optical wavelengths in Microsoft’s backbone for 2.5 years [3, 1, 4]. We showed that the capacity of 80% of the links could be augmented by 75% or more, leading to an overall capacity gain of 145 Tbps without touching the fiber or amplifiers. Inspired by wireless networks, we also showed that link failures are not always binary events. In fact, some failures are degradation of the SNR, as opposed to complete loss-of-light, and can be replaced by link flaps wherein the capacity is adjusted according to the new SNR. Based on these results, and because of the significant cost savings offered by this work, Microsoft decided to stop purchasing transceivers at fixed 100 Gbps capacity. The company is now installing bandwidth variable transceivers that can vary the modulation between 100, 150, and 200 Gbps depending on the SNR of the fiber path. The data is publicly available and is unique across optics and systems communities, which was recognized by our best dataset award at the ACM Internet Measurement Conference in 2016.

In another study, we conducted a large-scale study of millions of operational optical links across entire Microsoft’s data centers. Our analysis was the first in the community to show that data center links are massively over-engineered: 99.9% of the links have incoming optical signal quality that is higher than the IEEE standard threshold, while the median is 6 times higher [9]. Motivated by this observation, we proposed using transceivers for distances beyond their specified IEEE standard in practice. Our analysis has opened the door to relaxed specifications in transceiver design by showing that commodity transceivers can be used for distances up to four times greater than IEEE specifies. We further correlated this data with hundreds of repair ticket logs from data center field operators and found that a significant source of packet loss can be traced to packet corruptions due to dirty connectors, damaged fibers, or malfunctioning transceivers. To alleviate this issue, we designed a recommendation engine to repair links based on learning of common symptoms of different root causes of corruption. Our recommendation engine is deployed across all Azure data centers worldwide with 85% recommendation accuracy [8].

Practical Algorithms in Production. I have designed, developed, and maintained routing protocols, load-balancing software, and congestion control algorithms for Google’s production systems. Specifically, my work on hardware time-stamping of RDMA messages enabled a large-scale deployment of delay-based congestion control system called TIMELY [5]. To the best of my knowledge, the algorithms are still in production at Google. In another study, during an internship at Google, I studied YouTube traffic and showed that it is bursty and these bursts trigger packet losses and stress router queues, causing TCP’s congestion control algorithm to kick in. I then designed a server-side pacing mechanism using TCP itself to rate limit YouTube video streaming [13]. A newer version of the pacing mechanism I designed is currently in production at Google. As a side-project, I teamed up with Google’s TCP team to explore some of the weaknesses of TCP’s standard fast recovery algorithm described in RFC 3517, as well as algorithms implemented in Linux. We studied key statistics of the nature of TCP retransmissions by instrumenting Google Web and YouTube servers and found that the fast recovery algorithms deviate from their intended behavior in the real world. We proposed a new design to control transmission in fast recovery phase to recover from losses quickly, smoothly, and accurately by pacing out retransmissions across received acknowledgement packets [12]. This algorithm is in the mainline Linux as the default fast recovery algorithm.
4 Future Research

I look forward to building upon my experience in cross-layer system design, and to expand my research in computer systems and networking, while sustaining my relationship with large service providers and device manufacturers. In addition, I would like to explore relationships with campus, enterprise, and regional networks as new sources of data and fertile ground for new research problems. In moving to an academic environment, I intend to place greater emphasis on the following problems.

**Systems for Next-generation Workloads.** An exciting research avenue is to develop systems support for emerging next-generation workloads, such as machine learning, Internet of Things, autonomous driving, and biotechnology. The explosive growth in these applications means a flood of data-intensive workloads is headed for the world’s data centers. I consider designing new systems that will optimize for these workloads to be a top-priority challenge. Such dedicated designs will lead to the development of new paradigms for high speed, low-latency serving of real-time queries that is vital for these applications. The challenges include finding solutions that optimize hardware, firmware, and software across the entire stack—switching, NICs, drivers, protocols, applications—to achieve high efficiency in tightly-controlled deployments.

**Rearchitecting the Stack with Programmable Devices.** Providing end-to-end latency guarantees continues to be a challenging problem in data center networks. Existing network and end-host stacks do not provide flexible resource allocation to latency-sensitive applications with many bottlenecks that can change over time between resources. I intend to examine the boundaries between different layers in the network and end-host stacks with the goal to develop a clean-slate resource allocation scheme that takes advantage of programmable network devices, such as reconfigurable switches and programmable NICs. I believe the solution lies with replacing the traditional layering model with a flexible stack that allows for programmable resource schedulers by enabling the flow of control information between the various layers.

**Photonic Integrated Data Centers.** I am the co-PI of a 4.4 million dollar grant from ARPA-E ENLITENED program. This work is a collaboration between Columbia University (main PI: Prof. Keren Bergman), Microsoft, Cisco, Nvidia, Freedom Photonics, UCSB, SUNY-Poly CNSE, and Lawrence Berkeley National Lab. Our proposal is a data center architecture to support data-intensive workloads while optimizing energy efficiency. The Photonic Integrated Networked Energy Efficient (PINE) vision is built on three main pillars: (i) redesigning the network’s architecture based on disaggregation of compute and memory resources over a unified photonic interconnect with programmable optical topologies to improve resource allocation throughout the data center, (ii) introducing a concept of embedded data center nodes consisting of various multi-chip modules interconnected in a unique interposer platform via high bandwidth density integrated photonics, and (iii) developing a new generation of ultra-energy efficient silicon photonic links.

**The Internet Infrastructure.** The Internet infrastructure is a critical resource for modern life. Yet it is vulnerable, unreliable, and inefficient. One of the clearest needs of the future Internet is to improve the robustness, reliability, and efficiency of the regional and wide-area networks that connect points-of-presence around the globe. I plan to extend my recent work on improving wide-area performance and failure recovery and aim to address important unresolved issues concerning robustness of public Internet. I believe a successful solution involves creating a common understanding of the Internet as a complex system of interdependent nodes while bridging between the requirements of physical, network, and application layers. I also plan to explore new challenges that are introduced by the emergence of Internet of Things and edge computing. For instance, connecting millions of devices will be one of the biggest challenges of the future of Internet of Things as it will defy the very structure of current Internet models and the underlying technologies.

The above problems present a flavor of the research I am inspired to work on. They all share the following theme at their core: creating solutions to make networks more efficient and reliable. I enjoy finding fundamental problems in networks and systems, and innovate for highly practical solutions. I believe networking research is interdisciplinary by nature, integrating low-level physical devices and high-level systems software. Hence, I intend to work closely with computer theorists, hardware engineers, and industry developers to create opportunities for integration of tools and ideas for highly impactful research.
References


