

Nearly half of the global population is yet to get connected to the Internet. Even for the already connected half, Internet applications and their service requirements are rapidly evolving. My work explores infrastructure, protocol, and application design for addressing these ever-changing demands. I look forward to building frameworks that monitor the evolution of the Internet, analyze and improve the performance of protocols that drive it, and design future networks that play a crucial role in providing global connectivity.

Current & Past Research

Satellite mega-constellations

For the last one and a half years, SpaceX has been deploying Low Earth Orbit (LEO) satellites at an incredible pace of roughly two launches per month. Their long-term plan is to deploy tens of thousands of LEO satellites to build the Starlink constellation that would beam Internet connectivity from space. Amazon's Kuiper, Telesat's Lightspeed, and OneWeb are some other mega-constellations at different stages of design and deployment. Significant reduction in launch costs by virtue of reusable boosters, and compact satellite design, has ushered in this new age of space race that is here to last. These new constellations differ from any prior such attempts in their large scale, their service goals, and their technology. For instance, SpaceX's constellation is already an order of magnitude larger than the largest earlier deployed constellations, and aims to carry a substantial fraction of Internet traffic (as opposed to serving narrow niches), and promises latency at least 10-times better than prior satellite-based Internet services.

These LEO networks, on one hand, promise significant improvements in communication latencies beyond today's Internet, but, on the other hand, pose new design challenges to network researchers, some of which were discussed in our paper [2] at HotNets'18. We are entering an era where network elements (these satellites) fly at more than twice the speed of sound in air. Such incomparable dynamicity leads to both continuous and abrupt changes in the structure and properties of paths within these networks. No terrestrial network has such properties, and the few deployed geosynchronous communication satellites have either no or very limited mobility. In order to efficiently deliver traffic over such a globally spanning dynamic network, one needs to rethink all the core network design challenges. How do we place satellites and connect them together? How do we route packets through the network given the link conditions and end-to-end paths change all the time? How do communicating endpoints cope up with a highly dynamic network infrastructure?

How do we achieve inter-satellite connectivity? LEO constellations are deployed at heights of a few hundred kilometers. Satellites are placed in multiple orbital planes, usually at uniform separation from each other, with each plane consisting of multiple uniformly separated satellites. Orbits are usually inclined with respect to the Equator to provide better coverage at heavily populated lower latitudes. Terrestrial user terminals are connected to satellites transiently using radio, while satellites connect to each other with laser. Inter-satellite connectivity is constrained by atmospheric impact, power budget, and laser transceiver capabilities. Our work [5] on satellite topology design shows how nearby satellites could be systematically connected with inter-satellite lasers in order to improve performance beyond baseline connectivity. It essentially offers a Pareto frontier of design choices in the latency-capacity tradeoff space to the network operators. This work also quantifies, in-depth, how traditional network design techniques, used in terrestrial Internet as well as data centers, fall short in the face of LEO dynamics. This work also carefully considers the entire parameter space so that network operators can pick design choices based on their hardware constraints. This work, published at CoNEXT'19, has been recognized by IETF/IRTF with the *Applied Networking Research Prize*, 2020. A follow-up work [8] analyzes the impact of foregoing inter-satellite links on LEO network performance.

How do we enable satellite networking research? Despite the excitement (3 positional HotNets'18 papers) around the upcoming planned LEO constellations, there has been a serious dearth of analysis tools for such unforeseen networks. We built Hypatia [9], a packet-level simulator, which models the inherent dynamicity of LEO networks, and allows network enthusiasts to simulate and analyze these networks under varied settings, traffic demands, and protocol assumptions. This work also quantifies how both routing and end-to-end transport are affected due to network dynamics. Hypatia received the *Best Paper Award* at IMC'20 because of its significant contribution as an engine for future satellite networking research.

Low latency connectivity

Latency measurements. In order to improve Internet connectivity, it is important to measure and analyze existing networks and applications. We conducted the following studies to understand the ecosystem better:

- Time-tested high-frequency trading networks operate at the bleeding edge of low latency connectivity. Our measurement platform [3] systematically uncovers such networks and highlights important properties. The derived

knowledge could be used to design larger networks offering low latency transit.

- Our work on header-bidding [1] (an online-advertising technique), which received the *Best Dataset Award* at PAM'20, shows, round-trip times dominate the latency overheads, and there is also a lack of adoption of low-latency protocols like TLS1.3 and QUIC. Hence, it is important to build low-latency network infrastructure which would reduce both round-trip times and protocol overheads and is orthogonal to protocol improvements.
- A large fraction of the Web is deployed in or very close to only a few public cloud data centers [7]. This observation opens up new possibilities for efficient Web content delivery by leveraging public cloud.

Novel infrastructures for low-latency networking. Latency in today's Internet is limited by the performance of fiber – fiber routes are often circuitous and the speed of light in fiber is significantly lower than in air. While cellular networks aim to reduce the last-mile latency, Internet applications would also largely benefit from faster transit. The idea is to use series of existing radio towers to build large terrestrial point-to-point microwave networks that operate close to geodesic at the speed-of-light in air. Ongoing work [4] is aimed at designing, simulating, and analyzing the economic viability of such networks. This research project is a collaboration among tens of researchers from different universities and research labs.

The cloud consolidation of the Web, as discussed earlier, allows us to propose a public cloud deployed proxy-based Web delivery infrastructure [6]. Few strategically placed proxy nodes can leverage proximity to Web content and optimized transport connectivity with end-users to deliver Web content faster, thus improving the quality of experience.

Future Plans

LEO topology design. As LEO networks get deployed, it is important to explore and analyze various nuances of topology design that are absent in terrestrial networks. Recent advances demonstrate laser connectivity between satellites in largely different trajectories. Such deployments are critical for serving polar regions, where installing terrestrial gateways is difficult. Also, some of these constellations plan to deploy sun-synchronous orbits, which allow similar spatial coverage at the same local time everyday. While the former example opens up a new horizon for topology design where satellites in different planes can communicate using line-of-sight laser, the latter calls for an in-depth analysis of the temporal and spatial variations in global Internet traffic demands, and the alignment of such demands with the supply of resources. A systematic exploration of the whole design space can push these networks towards better performance.

Co-design in LEO networks. In order to improve the performance of a system, it is critical to make the right design choices and have the right interfaces between the individual components. In the context of satellite networks, topology, routing, and end-to-end transport can be co-designed towards a specific operating point in the performance tradeoff space. In a static network with no cross traffic, shortest path routing can be an optimal single-path routing choice, but in a dynamic satellite network, this greedy approach might see frequent path changes affecting end-to-end transport. While compartmentalizing network functionalities was necessary for the evolution of the Internet, new age networks need special treatment. Transport techniques hidden well within the network stack have now become user-space and are currently seeing wide-spread adoption in the Internet. Also, recent work has seen the possibility of applications explicitly stating their demands to transport. Such advances make us optimistic about systematically improving cross-layer communications such that the entire network stack works in synchrony towards the same set of objectives as needed by the applications.

If globally deployed LEO networks start serving a large fraction of the Internet traffic, it is enticing to explore clean-slate network design. It does not necessarily mean reinventing the wheel, but can benefit from re-visiting promising techniques explored in the past. Although network-assisted end-to-end congestion control has seen limited success in data centers, large service providers are yet to see such deployments due to the inherent complexity in today's Internet. If LEO satellite networks start offering end-to-end traffic delivery, they can be great testbeds for such techniques. While one design choice (proactive endpoints) could be to allow the endpoints to advertise their demands to the network every round-trip communication, another choice (proactive network) is to expose the physical layer latency change information to end-to-end transport. More broadly, they can open up the possibility of attacking some core networking problems without necessarily limiting the solution space due to constraints inherent in the Internet.

LEO networks need new measurement techniques. Various existing space and satellite geodetic techniques like interferometry, laser ranging, and altimetry also allow us to precisely estimate ionospheric and tropospheric conditions, Earth's gravity field, etc. which would impact the network performance of individual satellites. Assimilating varying sources of information would allow us to predict and validate performance over time. Also, an understanding of the environment and the corresponding network performance will lead us to reconstruct proprietary behavior like encoding and error correction. Existing work, for example, uses player and network state logs to reconstruct video streaming algorithms. Similarly, knowledge of the environment and access to both communicating endpoints can

uncover proprietary satellite network protocols. Such reconstructions would help us explain network performance differences.

Designing low-latency hybrid networks. Given a steady increase in market demand for latency-critical Internet applications, how could we build an infrastructure that supports such demands? Choices like terrestrial point-to-point radio, drones, LEO satellites, hollow-core, and solid glass-core fiber each have their pros and cons. They offer tradeoffs in throughput, latency, robustness, deployment complexity, and cost. It is a grand networking challenge to design topology, routing, queuing, and transport for hybrid low-latency networks catering to varying application demands. One has to take into account the differences in speed and robustness of different media and still meet service-level agreements.

Monitoring the Internet evolution. The Internet is a complex interconnection of tens of thousands of networks and is continually evolving. On one hand, new submarine cables are laid frequently to address bandwidth demands, while on the other hand, networks enter into peering agreements for economic reasons. Continuous monitoring of the Internet latency evolution should allow us to uncover path changes happening due to such developments. Long-term analyses, by leveraging existing and new Internet latency measurements, peering, and submarine cable databases can lead to a performance-focused peering recommendation system for the network providers.

Pushing protocols beyond limits. Today's Internet transport protocols were built with some strong assumptions like moderate available bandwidth, fixed end-to-end propagation delay, moderate loss due to congestion, and fairness to other transport flows. How would one come up with a clean-slate design if any of these strong assumptions change? In our simulations, both loss-based and delay-based transport protocols perform poorly when end-to-end propagation delay varies over time. Also, transport had to change drastically in the past as the Internet community tried to get rid of bufferbloat. Hence, It is important to explore design choices for network models beyond today's Internet. How would we design transport for paths with negligible latencies? Would existing transport cope with 10-times or 100-times bandwidth improvements? Even if one manages to come up with optimal machine-generated protocols for such network models with tools like Remy, it would be interesting to reverse-engineer such protocols, analyze the state machines, and learn and apply techniques to improve the performance of protocols that drive the Internet today.

Next-generation Web content delivery. The Web content ecosystem is undergoing drastic changes both at the level of infrastructure and protocol design. Infrastructure changes include the creation of local service cones as hyper-giant content providers, public cloud, and content delivery networks (CDNs) dominating the market move closer to the end-users. CDNs can now closely monitor network conditions and offer full-site delivery. Also, the last-mile latency is reducing over time, as reported in recent studies. Protocol changes include the evolution of HTTP, the key Web content delivery protocol. While HTTP/3 solves head-of-line blocking, cache-digest allows user clients to share state with servers. These developments open up the following possibilities: 1. Do techniques like HTTP server push, not adopted widely in the past, reface given the last-mile latency evolution and protocol changes? 2. Given that the Web today resides close to only a few public cloud locations, is there a performance-cost tradeoff in placing content in CDN versus public cloud?

While half of the future plans above focus on designing and measuring LEO satellite networks, the other half focus on improving today's Internet by monitoring its evolution and extracting performance from existing choices both at infrastructure and protocol levels. Note that these two lines of research are not disjoint, but rather symbiotic – while exploring traditional protocols and techniques in the context of LEO networks might highlight their shortcomings thus improving them in the process, improving today's Internet would prepare us better for networks and applications of the future. My research spans network topology, routing, and transport design and analyses to embrace the changes and effectively unleash the opportunities that come along.

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