Research Statement

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The Internet is a complex global system offering connectivity to billions of users. Nevertheless, nearly half of the global population is yet to get connected to the Internet. For the already connected half, the demand for latency-critical applications is on the rise. Even for popular applications, low communication latency now translates directly to revenue. The Internet is thus faced with coverage and new performance challenges. My work explores infrastructure, protocol, and application design for addressing these ever-changing demands.

Current research

Satellite mega-constellations

For the last one and a half years, SpaceX has been deploying Low Earth Orbit (LEO) satellites at an incredible cadence 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 LEO networks, on one hand, improve communication latencies significantly beyond today's Internet, but, on the other hand, pose new design challenges to network researchers [2]. 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 properties and behavior of these networks. No terrestrial network has such disruptive 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 100 km. 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 under such extreme 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 has been recognized by IETF/IRTF with the Applied Networking Research Prize, 2020. A follow-up work [8] analyzes the impact of foregoing ISLs on LEO network performance.

How do we enable satellite networking research? Although the interest in LEO networking research has been recently renewed following the 3 HotNets'18 papers on the topic, there has been a serious dearth of simulation tools for such unforeseen networks. Indeed there was a smaller wave of research during the Iridium boom in the late nineties, which subsided fast with cellular networks dominating satellite Internet for the next 2 decades. Back then, the scales of deployment were orders of magnitude smaller, and hence the primary objective was to guarantee coverage, which now comes for free with tens of thousands of satellites getting deployed. 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 in being able to accelerate satellite networking research.

Faster terrestrial core

Latency in today's Internet is limited by fiber refractivity and deployment choices. While cellular networks aim to reduce the last-mile latency, Internet applications would also largely benefit from faster transit. As our work on header-bidding [1] (a new online-advertising technique), which received the Best Dataset Award at PAM'20, shows, time-to-first-byte dominates the latency overhead, and there is a lack of adoption of low-latency protocols like TLS1.3 and QUIC. Hence, it is critical to build low-latency network infrastructure which would reduce both time-to-first-byte and overhead due to protocol inefficiencies and is completely orthogonal to protocol improvements. The idea is to use series of radio towers to build large terrestrial point-to-point microwave networks that operate at the speed of light in air [4]. One can learn the design choices [3] from time-tested high-frequency trading networks, although being more pragmatic about the latency-capacity tradeoff in order to cater efficiently to the application demands. Such a pragmatic approach reduces the cost per GB beyond what is currently being offered by several VPN services to online gamers, thus making such deployments commercially viable.

Cloud consolidation of the Web

A large fraction of the Web is deployed in or very close to only a few public cloud data centers [7]. This interesting observation allows us to propose a reverse-proxy-based Web delivery model [6]. Users leverage persistent connectivity with a few nodes, strategically placed across public cloud data centers, to fetch 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.

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 issues like speed-mismatch and robustness-mismatch 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 several possibilities: 1. Do techniques like HTTP server push make sense given the last-mile latency evolution and protocol changes? If yes, how can server push see wide-spread adoption? 2. Given the reduction in last-mile latency, where should Web services place content – in public cloud or CDN's points of presence? Is there a performance-cost tradeoff? 3. How would the role of CDNs evolve with time? Would they continue to actively cache content, or would they be passive participants offering private interconnects to public cloud serving content?

Contrary to popular belief that the Internet has ossified, it is ever-expanding to accommodate new network models and serve new applications. 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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