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## *Research Statement*

The Internet, as we know it today, is rapidly evolving due to quite a few exciting developments – satellite mega-constellations beaming Internet from space, the advent of 5G, and the emergence of many latency-critical applications. My work explores infrastructure, protocol, and application design that align with the future Internet. I look forward to building large-scale next-gen platforms for measuring such network performance, improving the performance of protocols that drive today's Internet, and designing future networks that play a crucial role in providing global connectivity.

## Current & Past Research

### Satellite mega-constellations

Due to breakthrough technical advances in satellite launching and design, the cost of sending payload to space has reduced by orders of magnitude in the last few years. Such developments have led to strong growth along $3$ verticals in space – space-based broadband connectivity, satellite imagery and sensing, and compute in space. Low-Earth orbit (LEO) satellite broadband is the fastest growing space segment with a CAGR[1] of $11.33\%$ (space economy is growing at a CAGR of $6.26\%$; estimated cumulative revenue of $\$1.25T$ by $2030$). SpaceX (Starlink constellation), OneWeb, Telesat (LightSpeed), Amazon (Kuiper), and many others have started designing and deploying LEO mega-constellations consisting of tens of thousands of satellites and inter-satellite laser to offer global low-latency Internet coverage. SpaceX has deployed $3{,}000+$ satellites already and has started offering services in $30+$ countries across the globe. 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 global broadband opportunities do come with a significant challenge to solve – high dynamicity (imagine routers flying at $27{,}000$ km/h!) resulting in frequent hand-offs and continuous network latency changes. As a PhD candidate at ETH Zürich, I wrote one of the first papers [2] in this area quantifying these opportunities and challenges. No terrestrial network faces such challenges, and the few deployed geosynchronous communication satellites have either no or very limited mobility. In order to efficiently deliver traffic over such globally spanning dynamic networks, one needs to revisit all the core network design decisions. How do we place satellites (trajectory design challenge) and connect them together (topology design challenge)? How do we route (routing & traffic engineering challenge) 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 (transport & congestion control challenge)?

**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 trade-off space to the network operators. This work also quantifies how traditional network design techniques, used in terrestrial Internet as well as data centers, fall short in the face of LEO dynamics. It 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[2] with the *Applied Networking Research Prize,* $2020$ (typically awarded to $4$-$6$ networks papers globally each year). A follow-up work [8] analyzes the impact of foregoing inter-satellite links on LEO network performance.

**How do we enable LEO satellite networking research?** Despite the excitement (multiple global corporations announcing space offerings, IETF/IRTF discussions, relevant papers in recent flagship conferences and workshops in networking, etc.) around the upcoming LEO constellations, there has been a serious dearth of analysis tools for

[1] CAGR: Compound Annual Growth Rate. [2] IETF: Internet Engineering Task Force; IRTF: Internet Research Task Force.

these dynamic LEO networks. When I started working on LEO networks $\sim 5$ years back, SpaceX had just launched their first $2$ test satellites, and various players were filing with FCC[3] and ITU[4] to seek early approvals to their proposals. I started doing a painstaking exercise of going diligently through all such filings, and modeling these networks to reasonably quantify their performance and identify bottlenecks. I realized the need for LEO network simulation/measurement infrastructure very soon.

- *LEO simulations:* At ETH Zürich, 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'$20$. Hypatia is still one of the most popular vehicles for LEO networking research and has been heavily cited by work published in many flagship conferences and journals.
- *Towards a global LEO testbed:* We are currently building a global testbed for these massive LEO broadband constellations, similar in flavor to PlanetLab or M-Lab for the terrestrial Internet. This is an ongoing collaboration between multiple Microsoft Research Labs, Microsoft's Azure Space team, the University of Surrey, UK, and Telefonica, Spain. We are deploying LEO user terminals (small antennas) across the globe to run network measurement and application performance benchmarking experiments at scale. Given that LEO network performance varies across time and space due to the geometry of the Earth and the constellation, interference from geosynchronous satellites, differences in weather and traffic demands, and the evolution of these constellations, it is important to understand performance bottlenecks that might arise due to these differences. Such a testbed should open up LEO research to the larger community and the exhaustive benchmarking should drive innovation across different layers of the network stack.
- *Social media insights:* One could leverage recent advances in language and vision capabilities to mine social media and understand users' perception of broadband LEO network performance and events. We recently built such a framework that could complement LEO broadband measurement tools by offering a user-centric view of these networks. This work is currently under submission.

## Network latency

Today's Internet infrastructure and protocols are simply not geared toward low latency. While past efforts have been focused on laying more fiber and increasing bandwidth, many applications (online gaming, interactive video conferencing, collaborative office suite, remote driving, remote jamming, AR/VR[5], etc.) today demand low network latency to offer a reasonable experience to users. Even as such infrastructure (5G ultra-reliable low-latency communications or URLLC, LEO laser links) becomes more available, today's protocols are often not efficient enough to fully leverage such low-latency channels. Hence, it is important to quantify the impact of latency on application performance, demonstrate the utility of and build low latency infrastructure, and right-size the application-network interface to better leverage infrastructural latency improvements.

**Measuring latency and its impact.** I have worked on multiple research projects that aim to quantify network latency and/or how it impacts application performance and, hence, user experience.

- Time-tested high-frequency trading networks operate at the bleeding edge of low latency connectivity. Our measurement platform [4] 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 TLS$1.3$[6] and QUIC[7].
- A large fraction of the Web is deployed in or very close to only a few public cloud data centers [7]. This observation 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.
- we are currently working on quantifying the impact of network performance (with a focus on latency) on user engagement and experience for interactive video conferencing and cloud gaming. For a popular enterprise-grade

[3] FCC: Federal Communications Commission [4] ITU: International Telecommunication Union [5] AR/VR: Augmented Reality/Virtual Reality [6] TLS: Transport Layer Security [7] QUIC: Quick UDP Internet Connections

video conferencing application, we could quantify how users often resort to explicit actions, like muting themselves, turning the video off, or dropping off early, to different degrees when faced with poor network performance. Leveraging our insights on the impact of network performance and other non-networking factors on user actions and experience, we have built a classifier to accurately predict explicit user feedback. Early results show the detrimental effects of network latency on cloud gaming.

**Novel infrastructures for low-latency networking.** Latency in today's Internet is limited by the performance of fiber – the 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 a 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. Our work [3], published at NSDI'22, aimed at designing, simulating, and analyzing the economic viability of such networks.

## Future Plans

**Global LEO testbed and its uses.** While the global LEO testbed is being currently built and rolled out, we should note that the platform is an enabler of broad research on LEO networks. *a.* Understanding the hand-offs, latency, and jitter in LEO paths could help quantify and mitigate the transport-layer performance bottlenecks. One could use this testbed to benchmark transport performance across existing congestion control schemes (like Cubic, NewReno, BBR[8], PCC[9], Copa, etc.) and eventually design a transport for delivering application traffic optimally over LEO. *b.* It is also important to quantify throughput and reliability – throughput, for example, could vary due to changes in demand over time and space, changes in satellite positions relative to the user terminal, different weather conditions, and the unique geometry (satellite trajectories) of these constellations. *c.* LEO network performance could be affected at lower latitudes due to GEO-arc avoidance. FCC & ITU have guidelines on LEO versus GEO (geostationary) interference avoidance, and different constellations have different strategies – the simpler ones simply shut down the radio, as needed. It is important to quantify, at scale, the impact of such strategies and propose newer ones if needed. There are many more large-scale network, transport, as well as application-level experiments one could run on this testbed. There has been a significant uptrend in the last few years in the number of papers on LEO networks being published at flagship systems conferences and workshops. Research in this space should receive a significant boost as the global testbed is rolled out.

I am also playing a pivotal role in bringing the LEO networking research community together since 2020. As I started working in this area, I realized it is necessary to bring the academia and industry closer together – while the industry has domain knowledge, hardware, deployment, and data, the academic community has strong and time-tested systems research expertise. I started engaging with IETF/IRTF by giving technical talks and organizing meetings on LEO broadband networks. I also started organizing LEOCONN events which have drawn significant attention from both industry and academia. LEOCONN 2021, a 2-day webinar on LEO, managed to generate significant interest and broad participation: 150+ industry attendees, 30+ attendees in top leadership positions, 20+ professors from top-50 universities, 100+ academic attendees from top-50 universities, 10 Government space agencies, and 38 countries. This was followed by LEOCONN 2022, a 1-day tutorial on LEO, co-located with MobiCom. I am soon to start organizing a recurring LEOCONN Webinar Series which will host talks from both industry and academia. LEOCONN has managed to/will host speakers from key industry players like OneWeb, SES, Microsoft's Azure Space, Planet, KSAT, Mynaric, and others. I plan to keep investing time on such community-building efforts which should eventually pay off by advancing the field beyond existing frontiers.

**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 every day. 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 toward better performance. I have recently started collaborating with IIT Kanpur on this thread of research ideas.

**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

[8] Bottleneck Bandwidth and Round-trip propagation time [9] PCC: Performance-oriented Congestion Control

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 widespread 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 revisiting 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 of 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.

**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 trade-offs 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.

**Leveraging multi-access connectivity.** While terrestrial high-bandwidth fiber connectivity is broadly available today, soon Internet users will have access to low-latency shallow buffer network channels like 5G URLLC and long-distance LEO laser. Are applications ready to efficiently consume multiple largely different network channels? Simply sending all packets via the low-latency channel does not work – shallow or no buffer would lead to congestion, and this approach will incur higher costs assuming such channels will be premium offerings by ISPs. While recent work proposes socket intents (applications stating network resource demands to the operating system) and heuristic-based forwarding of packets in Web browsing, it largely remains an open problem. The packet forwarding stub could consume application demands, dense feedback (network performance metrics) coming from the multiple network channels, and much sparser feedback from the applications (quality of experience and user engagement metrics). We should think of coming up with an intelligent packet forwarding module that learns over time how to efficiently consume these diverse input feeds and engineer traffic towards optimizing the application performance. I have recently started collaborating with the University of Illinois Urbana-Champaign (UIUC) on this brainchild of mine. Such solutions could eventually be deployed either at the endpoints or on the MEC[10] workers in future networks.

**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.

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 gearing it towards low latency. These gears include low-latency infrastructure, newer protocols, and better traffic engineering. Note that these two threads of research are not disjoint, but rather symbiotic – while exploring traditional protocols and techniques in the context of LEO networks might highlight

[10] MEC: Multi-access Edge Compute

their shortcomings thus evolving them in the process, upgrading existing techniques and infrastructure would prepare us better for networks and applications of the future. My research spans network topology, routing, and transport design and analyses to embrace such changes and effectively unleash the opportunities that come along.

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