Research Statement

Moinak Ghoshal
Northeastern University
https://sites.google.com/view/moinak-ghoshal
ghoshal.m@northeastern.edu

"Measure what is measurable, and make measurable what is not so." – Galileo Galilei

This principle guides my work: advancing wireless networking by grounding progress in empirical observation while developing new ways to quantify aspects of modern networks that remain opaque. My research lies at the intersection of wireless networking, mobile systems, and real-world experimentation, with a focus on understanding, evaluating, and shaping the evolution of the next-generation of wireless networks. As wireless technologies increasingly underpin applications with stringent bandwidth and latency requirements – from AR/VR and connected autonomous vehicles (CAVs) to the Metaverse – there is an urgent need to bridge the gap between theoretical capabilities and real-world performance. My work aims to bridge this gap by understanding the real-world performance of mobile wireless networks, especially 5G networks, from the perspective of the end-user, and how we can further improve the end-user's Quality of Experience (QoE), paving the way for a more connected and technologically empowered future.

Since its rollout, 5G has promised unprecedented data rates and ultra-low latency, with the potential to enable bandwidth-intensive and latency-critical applications and significantly outperform its predecessor, 4G LTE. Yet, realizing this promise in practice has proven challenging. The use of higher frequency bands, while ensuring higher throughput, comes at the cost of reduced range and greater susceptibility to performance fluctuations. Moreover, the introduction of multiple frequency bands, the coexistence with LTE, and the availability of different deployment modes (Non Standalone and Standalone 5G) have made the cellular ecosystem increasingly complex. Hence, wide adoption of 5G networks faces a significant new challenge – its actual deployment plays a significant role in the user-perceived performance. While testbeds designed by academia and industrial research offer valuable insights, they often fail to capture the full range of real-world scenarios, as different network operators implement unique policies and configurations that are difficult to replicate in controlled environments.

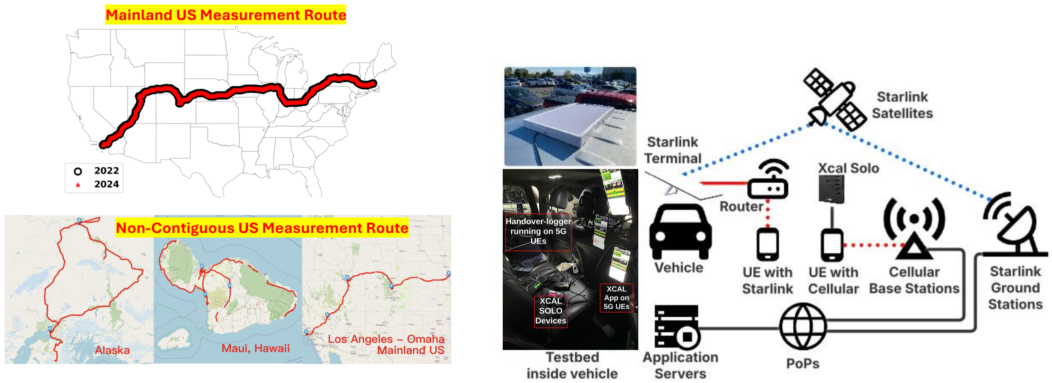
Motivated by these challenges, my PhD. research has focused on understanding the real-world coverage and performance of operational 5G networks and tracking their evolution, while also demystifying operator policies that often pose as black boxes to the end-user. To this end, I have carried out large-scale measurement campaigns to address pressing challenges in real-world deployments. Through extensive in-the-wild experiments across diverse geographic regions in the U.S. and Europe, I have developed a comprehensive understanding of how 5G networks are deployed and how they perform in practice. My investigations have spanned critical areas such as network performance, handover dynamics, coverage gaps, the progression of standalone deployments, and the impact of these factors on the quality of experience for bandwidth-intensive and latency-sensitive applications. Building on these measurement-driven insights, I have pursued system prototyping with the overarching goal of advancing 5G and paving the way toward beyond-5G networks.

During my PhD, I have published a total of 35 technical papers in journals, conferences, workshops, posters, and demos. My publications include 13 top-tier conference papers in ACM IMC (3), ACM CoNEXT (3), ACM SIGMETRICS, ACM MobiHoc, IEEE INFOCOM, PAM (4); and 3 top-tier journal papers in ACM/IEEE Transactions on Networking and Elsevier Computer Communications (2).

Research Contributions

1. Large-Scale Performance Characterization of Next-Gen Wireless Networks

Over the past four years, I have conducted cross-layer measurements over all three major US operators in more than a dozen US cities and through four cross-country road trips spanning a total of 15,000+ km. My work spans three major directions: (i) evaluating and tracking the evolution of 5G performance, (ii)



(a) Measurement Routes (b) Testbed setup.

Figure 1: Selected measurement routes and testbed.

demystifying cellular operator policies related to handovers, resource allocation, beam management, etc., and (iii) understanding 5G's limitations and potential to support a new set of bandwidth-intensive, latency-critical 5G "killer apps" – augmented reality (AR), virtual reality (VR), connected autonomous vehicles (CAVs), 360^o/volumetric video streaming, and cloud gaming. All the datasets (several TB of data) [1] are publicly available. The insights from my studies and the datasets are critical in (i) enabling the development of realistic 5G simulation/emulation models and testbeds that mimic real-world configurations and (ii) guiding the design of ML-/data-driven algorithms for NextG networks that address the limitations of today's 5G deployments.

Large-scale measurements pose unique challenges and require a systematic approach to address them. Under mobility, several factors can limit performance, including operator infrastructure and policies, vehicle speed, app design, and server location. Furthermore, performing analysis from the end-user perspective adds additional complexities, as commercial devices rarely expose lower-layer KPIs need for deeper analysis, and coverage characterization is difficult due to operator-specific policies dictating LTE or 5G connectivity. Finally, most 5G "killer apps" are not yet commercially available. To address these challenges, I built *Testbed-on-the-Move* (Fig. 1b) – a measurement platform comprising multiple smartphones, laptops, NTN devices, and power supplies; cloud and edge servers across the US; professional tools for collecting network KPIs and control-plane events; custom-built and readily available 5G "killer apps"; and a custom-built software that includes a suite of tests (throughput, RTT, application QoE) and procedures for synchronization and post-processing of logs from different software and different layers of the protocol stack.

Empirical Evaluation and Evolution Study of 5G Networks. My work published at ACM IMC23 [2] was the first large-scale evaluation of the performance of cellular networks under driving via an 8-day cross-country driving trip, from Los Angeles, CA to Boston, MA (Fig. 1a (top)), studying network coverage, network performance, and QoE of a set of "5G killer" apps over the three major US operators, while analyzing the impact of several lower layer KPIs on these metrics. Our results showed disappointingly low coverage of 5G networks under driving and highly fragmented coverage by cellular technologies. More importantly, network and application performance were often poor under driving even in areas with full 5G coverage, suggesting that the cellular networks were not ready to support the next generation of mobile applications.

Two years later, we repeated the same study, driving along the same route. Our study, published at ACM IMC 2025 [3], revealed a substantial increase in 5G coverage and a corresponding boost in network performance, but 2 out of the 3 operators still exhibit less than 50% 5G coverage along the driving route. In this work, we also introduced a head-to-head comparison of cellular networks with Starlink's LEO satellite network along the same route. Our study revealed that, in the mainland US, Starlink achieves nearly 100% availability and offers lower RTT than cellular networks, with comparable median downlink performance – making it a strong competitor in underserved regions where cellular networks struggle. Building on this, I conducted the first large-scale head-to-head evaluation of Starlink and cellular networks in non-contiguous US regions [4] – Alaska and Hawaii (Fig. 1a (bottom)). Our study shows a persistent digital divide between mainland and non-contiguous US for cellular networks in terms of coverage and performance, highlighting the challenges of cellular deployments in non-contiguous US regions. Starlink provides substantially higher performance than cellular networks most of the time, but area-specific challenges significantly degrade Starlink performance in non-contiguous US compared to the mainland US. Additionally, we explore the spatiotemporal diversity between cellular and Starlink performance and study the potential of multipath transport to bridge the connectivity gap in non-contiguous US regions.

Additional contributions of my work in this area include: (i) The *first large-scale study of 5G Standalone (SA) deployment in the US* [5], analyzing its evolution while comparing it head-to-head with 5G NSA over an 18-month period. Our results show that 5G SA typically provides better performance than 5G NSA but, surprisingly, suffers from longer handover durations due to the interplay between signaling complexity and security mechanisms. (ii) The *first large-scale study of potential of multi-carrier access in the 5G era* [6], where we observed significant performance diversity across operators at a given time and location. Using trace-driven analysis we were able to show link aggregation and link selection schemes can provide significant gains over single-operator performance. (iii) *5G Longitudinal and Cross-sectional Studies:* The first study [7, 8] assesses 5G deployment maturity through a one year-long uplink measurement campaigns: a crowd-sourced study across eight cities in Europe and North America, and a controlled mmWave study in Boston. Our datasets show that 5G deployment in major cities appears to have matured, but it still lacks consistent latency and performance advantages over LTE. In the second study [9], over a period of four years, we conducted the first longitudinal 'metamorphosis' analysis of 5G, using 2.65M+ Ookla Speedtest measurements across nine U.S. and European cities from 2020–2023. We reveal the evolution of 5G coverage, throughput, and latency at quarterly granularity, compare cross-city performance diversity, and uncover factors influencing user experience, including device adoption and network load.

Demystifying Operator Policies in Operational 5G Networks. I have conducted three major operator policy demystifying studies, and they are as follows: (i) The *first systematic study of resource allocation policies in operational 5G mmWave networks* [10, 11]. Our results show that operators employ simple threshold-based policies, instead of the popular proportional fairness policy, and often over-allocate resources to new flows with low traffic demands or reserve some capacity for future usage. Interestingly, these policies vary not only among operators but also for the same operator in different cities. (ii) The *first large-scale empirical study of beam management in operational 5G mmWave networks* [12]. Our results show that beam management procedures select near-optimal beams most of the time; however, the reporting overhead can be high, especially when beam refinement is applied on top of coarse beams. (iii) The *first in-depth measurement study of handover configurations* across the 3 major US operators over a 3-year period [13]. Our study reveals (a) operator-wise diversity in handover configurations, which also differ across bands, 5G architectures, and geographic locations for the same operator, but significantly lower diversity in 5G compared to LTE, and (b) suboptimal handover configurations/decisions leading to poor pre- or post-handover performance.

Exploring 5G's Capability to Support Emerging Latency-Critical Applications. I have conducted a series of studies to understand the capabilities and constraints of emerging "killer" applications over 5G networks. In my first work [14], I examined whether 5G mmWave, coupled with in-network edge computing, can support edge-assisted object detection for augmented reality (AR). We quantified the gains from retrofitting pre-5G era app-level optimizations and upgrading edge hardware, both of which substantially improved performance, yet 5G mmWave's advantage over LTE remained minimal—highlighting that 5G mmWave is not the decisive factor for enabling edge-assisted AR.

Building on these insights, I evaluated real-time multi-user AR interactions using a Google demo app [15] over 5G mmWave and LTE [16]. While 5G mmWave reduced uplink visual data latency, other app components independent of network technology dominated end-to-end delay. In a followup study, we also found that application design plays a crucial role: architectures employing asynchronous SLAM significantly reduce latency, enabling smoother real-time interactions. In addition, as part of our cross-country measurement campaigns [2, 3], I evaluated other bandwidth-intensive and latency-critical applications—including connected autonomous vehicles (CAVs), cloud gaming, and 360° video streaming—across 5G and LTE networks. Although performance has improved in recent years, our results show that application-level optimizations remain essential to achieve satisfactory user QoE.

Additional Wireless Studies. In the early years of my PhD., I worked on 60 GHz Wi-Fi (802.11ad) networks.

I conducted extensive measurement studies [17, 18] analyzing performance, energy efficiency, interference characteristics, and application performance on 60 GHz-enabled smartphones, comparing them against conventional 5 GHz devices. Building on these insights, I enabled Multipath TCP (MPTCP) [19] on a dual-band smartphone equipped with both 802.11ad and 802.11ac radios. To sustain high data rates with MPTCP, we identified and addressed several system-level challenges, implementing optimizations that achieved near-optimal throughput. We also evaluated the power consumption of dual-radio operation and proposed design guidelines for an energy-aware MPTCP scheduler. In a separate study [20], I investigated the predictability of network throughput for 802.11ad devices under mobility—a key scenario for VR/AR applications. Our findings showed that throughput could be accurately predicted at timescales from 10 ms to 2 s, and we identified the key features influencing predictability in such dynamic environments.

2. Systems for Next-Gen Wireless Networks

My extensive measurement studies of 5G performance over the past four years have shown that current 5G deployments are not yet ready to support the next generation of latency-critical applications. Enabling such applications requires both application-aware network algorithms and network-aware application optimizations. During my PhD., I have collaborated with many industry partners through internships, applying insights and data from my measurement campaigns to design systems that advance the next generation of wireless networks. In collaboration with researchers at InterDigital, we developed an ML-driven optimization framework [21] that proactively reconfigures PHY frames based on real-time predictions of wireless channel conditions, addressing the limitations of fixed frame configurations in commercial 5G networks. With researchers at Futurewei, we explored a solution [22] that integrates ISAC with the advanced analytics capabilities of 5G core network to enable smarter and more energy-efficient network operation by dynamically optimizing base station transmit power while balancing the trade-off between energy consumption and performance.

In a separate line of work, inspired by my earlier XR studies, I designed and developed a co-located multiplayer XR game [23] that operates over Wi-Fi and supports both AR and VR modes on head-mounted display devices. I conducted a user study with 26 participants to examine how AR and VR differ in shaping co-located immersive experiences. Additionally, during my early work with 60 GHz Wi-Fi, I contributed to the design of a practical, standards-compliant link adaptation framework [24] that leverages machine learning and PHY-layer information to decide when to trigger link adaptation and which adaptation mechanism to apply.

Future Work

I plan to continue my research toward evaluating the next generation of wireless networks and enabling emerging mobile applications to run efficiently over 5G and beyond networks. My long-term vision is to amalgamate measurement-driven insights with system design innovations to pave the way for more intelligent, adaptive, and resilient NextG networks. In the following, I outline three key thrusts that will guide my future research efforts.

Large-Scale Studies and System Prototyping for 5G and Beyond: Focus on NTNs and NTN–Cellular Integration. I plan to continue conducting large-scale measurement studies of next-generation mobile networks—5G and beyond—with a particular emphasis on Non-Terrestrial Networks (NTNs). NTNs are rapidly emerging as a key component of the wireless ecosystem, and our results from mainland and non-contiguous U.S. regions [3, 4] show their significant potential. Integrating terrestrial cellular networks with NTNs represents a crucial step toward seamless global connectivity in 6G, as envisioned in 3GPP Releases 17 and 18 and the O-RAN Next Generation Research Group's 6G roadmap. However, NTNs differ fundamentally from terrestrial networks and face significant challenges in scaling to meet 6G's stringent requirements, including dynamic topologies, high propagation latency, complex network management, spectrum coexistence, and strict power, thermal, and spatial constraints that limit AI integration. To address these challenges, I plan to approach the problem from two complementary perspectives. On the client side, I am exploring the integration of cellular and LEO satellite networks through multipath transport solutions such as MPTCP and MP-QUIC. This direction builds on insights from our multi-day drive tests in regions with limited 5G coverage (Mainland US, Alaska, and Hawaii), where we simultaneously measured cellular and Starlink performance. On the infrastructure side, I plan to leverage O-RAN principles for NTNs, drawing on my experience with 5G O-RAN testbeds (as demonstrated in my IEEE PIMRC work [21]). My goal is to enable coordinated, closed-loop control across multiple timescales by treating satellites as adaptive edge computing nodes within a scalable and interoperable framework. I plan to design distributed "Space-RICs" operating on satellites and integrate them with terrestrial infrastructure to support real-time adaptation, optimized resource allocation, and energy-efficient service delivery powered by AI across hybrid NTN–terrestrial environments.

Exploration of Private 5G and Its Convergence with Wi-Fi. In my current internship at HPE, I am exploring private 5G (P5G) networks, focusing on their capabilities, limitations, and potential as a viable alternative to enterprise-grade Wi-Fi systems. A key strength of P5G lies in its highly configurable architecture—unlike public 5G networks—which enables fine-grained control over spectrum, latency, and QoS, opening the door to a new class of mobile enterprise applications. I also see significant potential in the convergence of P5G and Wi-Fi to achieve improved performance, reliability, and flexibility through intelligent joint management of both networks. This is a rapidly evolving area, and I plan to continue advancing research on P5G–Wi-Fi integration, including unified management, mobility, and multipath transport for seamless enterprise connectivity.

Intent-Driven Networking with AI-Augmented Policy Understanding. Building on my experience in demystifying 5G operator policies and analyzing how they influence user-perceived performance, I aim to advance the emerging field of intent-driven networking. My vision is to design systems that bridge the gap between high-level service intents (e.g., latency guarantees for XR or reliability for emergency communications) and the network's low-level control mechanisms (e.g., scheduling, slicing, and beam management). With the advent of Large Language Models (LLMs), there is a unique opportunity to leverage network logs, telemetry, and configuration data to develop AI-driven control loops that proactively adapt policies, automate root-cause analysis, and ensure networks behave in alignment with service intents. This direction combines my measurement expertise with the growing paradigm of semantic and intent-based networking to create more autonomous, resilient, and user-aware networks.

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