Research Statement

The next generation (NextG) of wireless networks would connect billions of devices using existing and limited natural spectrum resources, all the while making it secure and sustainable with limited power and antennas. My research takes a holistic approach to optimizing these resources to deliver not only high data rates but also enhance reliability and scalability and facilitate practical deployments. Moreover, as the wireless infrastructure is deployed ubiquitously in both indoor (e.g., WiFi) and outdoor (e.g., 5G cellular) environments, there is an opportunity to provide sensing services alongside data communication, eliminating the need for additional sensor deployment. By leveraging existing wireless infrastructure, my research focuses on developing radio-frequency-based sensing solutions such as localization and tracking of mobile devices. Furthermore, my research recognizes that as communication and sensing systems become more accessible, they are vulnerable to security threats such as spoofing and jamming attacks, so I designed and implemented appropriate measures to counter these attacks.

My research advances technologies for these three pillars of NextG networks: Communication, Sensing, and Security.

- **Communication:** Millimeter-wave links are essential for NextG networks due to abundant bandwidth, but they are inherently unreliable due to blockage and struggle to scale for a large number of devices. My research identified a fundamental problem in mmwave links, which rely on a "single directional beam" that creates a single point of failure and limits service to one user direction at a time. In mmReliable [Sigcomm 2021], we challenged the conventional single-beam assumption and introduced a constructive multi-beam system that improves both the reliability and throughput of mmWave links. Furthermore, in mmFlexible [Infocom 2023], we developed a new class of frequency-dependent multi-beams that serve multiple devices in a single timeslot, establishing a scalable and efficient multi-user system.

- **Sensing:** It is extremely hard to deliver on the above promises in a realistic world with hundreds of devices with complicated mobility patterns and complex propagation environments. My approach is to integrate communication radio with novel radio frequency-based sensing (CommRad [Preprint 2023] and LocAP [NSDI 2020]) to bring my technology out of the lab environment to challenging commercial deployments, with support from Qualcomm.

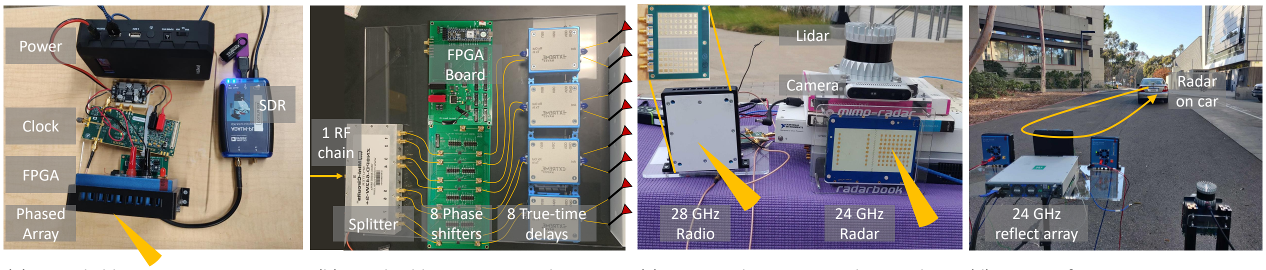
- **Security:** We demonstrated a spoofing attack on automotive radar sensors by employing a mmWave reflect array as a *spoofing device* in mmSpoof [IEEE S&P 2023]. In another initiative, we built an Open-RAN-driven jammer monitoring and anti-jamming system in BeamArmor [IEEE Milcom 2023]. Moreover, I effectively implemented these techniques in a commercial setting at VMware.

Research Methodology: My research methodology bridges the gap between theory and systems. As an MS student at New York University, I established a strong theoretical foundation through projects such as stochastic geometry-based network optimization [JSAC 2018] and theoretical machine learning [MDPI 2019]. Moving forward, during my PhD at UC San Diego, I started building large-scale systems to demonstrate my ideas in practice and achieve real-world impact. Specifically, we built a 28 GHz mmWave testbed called M-Mobile [mmNets 2020], [Sigcomm 2021] based on phased arrays and software-defined radios such as USRPs and FPGAs (Figure 1a).

These experiences helped me follow a threefold approach to addressing fundamental problems in wireless communication. I start with understanding the theory behind the problem, followed by creating a simulation and emulation model to verify my theory, and finally, develop algorithms that actually work on hardware systems.

Research Impact: The interdisciplinary approach of connecting theory and systems is reflected in my publications across prominent venues, including IEEE/MDPI Journals and Top-Tier ACM systems conferences, and resulted in six patent submissions, with two already granted. Besides this, my research has also caught attention in the popular press, including Interesting Engineering [1], TechXplore [2], InceptiveMind [3], and Science Daily [4], among others. The impact of my research extends to various platforms and awards. I have been selected for the Marconi Society Scholar in Residence program, contributed to the Escribamos Ciencia program for K12 students, earned the best poster runner-up award at Hotmobile'23, and received the best 3-minute thesis presentation award at ACM Mobisys'20, Mobicom'21, and Mobicom'22. My open-sourced datasets and code have been used by multiple universities, including UCLA, NYU, and Texas A&M University.

Furthermore, I have successfully translated my work into commercial deployments. For instance, my research on Open-RAN-driven anti-jamming and interference management is deployed at VMware and has secured a grant of $240,000 to further advance this research. Additionally, my work on joint sensing and communication has received support through the Qualcomm Innovation Fellowship ($100,000).



(a) mmReliable setup: A 28 GHz mmWave testbed (mMobile) with real-time beam-scan using FPGA

(b) mmFlexible setup: An analog delay-phased array with 8 antennas prototyped for wideband sub-6 GHz

(c) CommRad setup: A synchronized radio and radar platform for joint sensing and communication

(d) mmSpoof setup: A mmWave reflect array as a `spoofing device' to spoof commercial automotive radars

Figure 1: Experimental testbeds I built to demonstrate my research in real-world settings for (a) mmReliable [Sigcomm 2021], (b) mmFlexible [Infocom 2023], (c) CommRad [Preprint 2023], (d) mmSPoof [IEEE S&P 2023].

1 Reliable and scalable communication for NextG networks

Reliable communication through constructive multi-beamforming:

Millimeter-wave technology has proven highly effective for high-throughput applications such as vehicular connectivity and video streaming. However, its deployment has predominantly been limited to fixed wireless settings and has yet to make substantial inroads into mobile access deployments. A critical challenge stems from mmWave's inability to offer a reliable link similar to sub-6 frequencies, where signals often degrade due to mobile users and obstacles. Traditional single-beam solutions are particularly susceptible to blockages because they create a single point of failure. I built a system called mmReliable [Sigcomm 2021] that deploys two or more beams at the same time to the same user to improve reliability. Intuitively, if one path to the user is blocked, an alternate path via some reflector is immediately available to maintain a reliable link (Fig. 2).

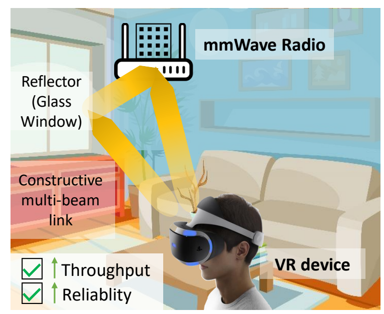


Figure 2: Reliable constructive multi-beams.

One significant challenge with multi-beams is the potential reduction in per-beam power, which could reduce overall throughput. Remarkably, my research demonstrates that mmReliable not only maintains high throughput alongside high reliability but can also effectively double throughput under favorable channel conditions. The key idea was to create *constructive multi-beams* wherein the phase and power of each beam are optimized to ensure per-beam signals add constructively at the receiver. I implemented mmReliable with a single RF-chain-based testbed with 5G NR waveforms and demonstrated close to 100% reliability in mobile environments.

Scalable communication through frequency-dependent multi-beamforming:

Millimeter-wave bands support 100× more bandwidth than sub-6 systems, which could have easily been used to scale mmWave connectivity to hundreds or thousands of devices in a network, but it is limited to only a few devices. The underlying problem is not the availability of resources but the inefficient distribution of those resources to all users. The resource distribution in mmWave is limited to time-based scheduling, which serves one user at a time using a single directional beam. So, one user gets the entire bandwidth in that timeslot independent of the user's demand, leading to wastage of spectrum resources.

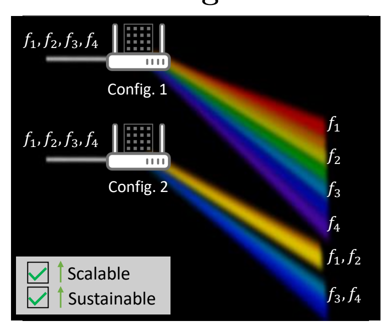


Figure 3: Flexible Frequency-dependent multi-beams.

I built mmFlexible [Infocom 2023] with the goal of distributing both time and frequency resources to multiple users in a flexible manner that scales with user demand. I introduced a special class of frequency-dependent multi-beams that can distribute different frequency bands to different users. A key feature of this system is the ability to assign an arbitrary set of frequencies to an arbitrary set of directions, much like a configurable prism (Fig. 3). I achieved this flexibility by introducing a true-time delay element in the phased array and jointly programming the delays and phases at each antenna. In fact, for the first time, I have mathematically derived a closed-form formula for this problem and built the founding stones for a new area of research in flexible frequency-dependent beamforming. My ongoing research in this direction includes building a hardware prototype for the new antenna system (Fig. 1b) and exploring new applications in concurrent sensing and communication.

2 Concurrent Sensing and Communication for NextG Networks

I developed an RF-based localization system in LocAP and joint optimization of communication and radar sensing in CommRad.

Radio-Frequency-based sensing: As Wi-Fi radios and NextG cellular networks are ubiquitously deployed in indoor and outdoor environments, these radios can also provide accurate sensing (e.g., positioning and tracking) of mobile devices in the event that traditional sensors such as GPS fail, e.g., under obfuscation by buildings and foliage. As part of a collaborative project, I demonstrated LocAP [NSDI 2020], a radio-frequency-based navigation system that is accurate and does not require prior knowledge about the WiFi infrastructure. To this end, we deployed an autonomous bot, loaded with a WiFi sensor, to estimate the location, orientation, and antenna spacing of all WiFi access points in that environment. Here, I contributed to conceptualizing and simulating the core algorithm that enabled millimeter-accurate localization of access point antennas.

Radar Sensing-aided Communication: The millimeter-wave network for mobile access requires tracking of mobile users to maintain directional links with them. Notably, 5G New Radio employs periodic beam scanning to estimate beam directions with mobile devices. However, this approach suffers from a trade-off between accuracy and time overhead. Achieving precise beams comes at the cost of increased overhead, manifested in prolonged beam scanning duration and higher periodicity of the 5G beam scan procedure, which can reach as high as 25% overhead (5 ms beam scan duration at a 20 ms interval). The more time allocated to beam scanning, the less time remains (only 75%) for conveying valuable information bits to user devices.

In CommRad [Preprint 2023], we integrated a mono-static radar sensor with mmWave radio to sense and track mobile users (Fig 1c). A key challenge with mono-static radar sensing is that radar sees many objects in its view, but it lacks context, i.e., it cannot distinguish whether the objects represent communicating users or non-communicating entities. Similarly, it cannot differentiate between reflectors that can assist or obstruct communication links. My solution in CommRad is inspired by the realization that this contextual information can be obtained by the communicating radio itself. We used the communication waveform to obtain the context in the form of the user and reflector identification in a cluttered environment and integrated it with the radar tracking system. This combined radar-radio framework, dubbed collaborative learning, helps provide the context to the radar sensor in terms of initial user and reflector location, and in return, the radar aids in user tracking and sustains mobile links even in obstructed scenarios, resulting in robust directional links for all mobile users while providing a ten-fold reduction in the radio beam scanning overhead.

3 Security in NextG Communication and Sensing

I explored security vulnerabilities in next-generation sensing (mmSpoof) and communication (BeamArmor).

Indistinguishable spoofing attacks on automotive sensing radars: Modern automotive vehicles are equipped with radar, which provides accurate all-weather perception to detect surrounding objects for safer driving. But are these radars safe? We built mmSpoof [S&P 2023], a spoofing system that exploits the radar FMCW waveform to create an 'illusion' of fake objects in the radar view which looks completely realistic to the radar. We achieve this by developing a reflect array as a spoofing device, which receives the radar signal and reflects back with a configurable frequency shift that changes the delay and Doppler profile at the radar, thus creating a fake object in the radar view. We demonstrated a 99% spoofing accuracy through a real-time outdoor testbed (Fig. 1d) with commercial radars. Our system is capable of working with any commercial radar without any prior knowledge of FMCW parameters on the radar, such as chirp duration and slope. These parameters are estimated in real-time using novel estimation algorithms we developed and deployed at the reflect array. We also discussed several anti-spoofing measures, such as multi-radar fusion and designing advanced radar waveforms with frequency-hopping.

Jammer monitoring and anti-jamming in NextG networks: Jamming of NextG cellular networks is a big concern because of interference by nearby base stations in dense small-cell settings and intentional jamming using cheap SDRs like HackRF. Yet, there is a lack of research platforms to understand and provide real-time insight into jammer monitoring in operational RANs. Therefore, we built BeamArmor [Milcom 2023], a RAN controller platform built with the srsRAN software stack to monitor, locate, and mitigate jammer activities using MIMO null-steering techniques, demonstrating bit error rate and SNR improvements by over 15 dB. Broadly, this controller platform can demonstrate many other MIMO-based applications in cellular networks, such as positioning and channel prediction in real-time.

Future Work

My research has been focused on the advancement of mmWave technology, leading to a new era of communication and sensing. As I plan for the future, I envision a multi-modal approach, one that unites a multitude of sensors, from Lidars to cameras, and a diverse array of protocols, including WiFi and UWB. Together, these elements will collaboratively elevate both communication and sensing capabilities. In addition, my exploration extends beyond the boundaries of our terrestrial realm to embrace non-terrestrial mmWave networks, including low-earth orbit satellites, aimed at revolutionizing IoT, internet connectivity, and sensing on a larger scale. My vision also encompasses the creation and deployment of a network of reflective surfaces designed to enhance mmWave coverage sustainably. To this end, I would build an end-end FR2 cellular platform that connects antenna beam switching with higher layers of the cellular stacks, thus bringing opportunity in cross-layer optimization and application awareness in optimizing the cellular networks.

AI for Multi-modal sensing and communications: I have worked towards connecting two sensor modalities, the monostatic radar sensor and bistatic radio sensor, into an integrated framework [CommRad, preprint 2023]. This is just the beginning, and many research opportunities lie in sharing the same time-frequency-antenna resources optimally, designing joint waveforms for communication and sensing, and mitigating interference between radio receiver and sensing receiver for optimal performance. Additionally, adding more sensors such as cameras, Lidars, and IMU into a collaborative learning framework with artificial intelligence and diverse radio-frequency-based sensing protocols such as WiFi, UWB, and mmWave systems provides a unique opportunity to enhance sensing accuracy and resolution while making communication radio more efficient and low overhead.

Reliability in Non-Terrestrial mmWave networks: My research on reliable and scalable communication has applications beyond the terrestrial realm to include non-terrestrial networks such as low-earth orbit satellites. The satellites in mmWave Ku/Ka bands (e.g., Starlink) suffer from similar problems of reliability with narrow 'pencil beams' and interference with terrestrial networks operating in the same bands [5]. These challenges are even magnificent in non-terrestrial links due to higher mobility, broader coverage, and a ground station that is as compact and efficient as today's smartphone. To this end, my research endeavor includes building a testbed for the ground station using phased arrays and measurement campaigns to understand reliability and interference problems and solve them through new architectures (e.g., true-time delay) and theory (e.g., multi-beamforming).

Low-power mmWave/THz infrastructure: A key aspect of my research is to ensure sustainable and low-power mmWave and sub-THz infrastructure while delivering reliable and high-throughput performance. Due to high path loss and low coverage, mmWave infrastructure has to be deployed densely, which would increase the carbon footprint [HotCarbon 2022]. To improve range and reliability with low power, we can deploy repeaters and reflective intelligent surfaces (RIS) in the environment. Having been closely involved in developing a sub-6 RIS in my lab [6], I would leverage this knowledge and connection to build a network of RIS at higher mmWave frequencies. Handling directional links with RIS, channel estimation, user mobility, and integration with my multi-beamforming architecture are challenging problems I aspire to work on.

Machine Learning and compute for NextG cellular networks: Cellular networks have become more accessible with the open-RAN initiative and the development of open-source software radio stacks such as srsRAN and Open-Air Interface enhanced by RAN intelligent controllers. Having built my own BeamArmor controller [Milcom 2023] and mmWave testbed, I would work towards building an end-end mmWave cellular stack with software radios aimed at optimizing the cellular network for various applications such as video streaming, AR/VR, and vehicular connectivity. In fact, we have already built an end-end VR streaming pipeline in [WPMC 2022]. Thanks to the decoupling of the RAN and the controller, computation-heavy and machine learning-driven inference can be adopted to optimize the cellular NextG network in real time. Therefore, I would explore these methods to solve open problems in resource scheduling, channel prediction, RAN parameter tuning, and interference management, among others.

My Publications

Infocom 2023	**IK Jain**, RR Vennam, R Subbaraman, D Bharadia, "Flexible and resource efficient multi-user mmWave system", *IEEE Infocom 2023.* *Acceptance 252/ 1312 (19%)*
IEEE S&P 2023	RR Vennam, **IK Jain**, K Bansal, J Orozco, P Shukla, A Ranganathan, D Bharadia, "mmSpoof: Resilient Spoofing of Automotive Millimeter-wave Radars using Reflect Array", *IEEE Security and Privacy 2023.* *Acceptance 115/ 952 (12%)*
Preprint 2023	**IK Jain**, Suriyaa MM, D Bharadia, "CommRad: Collaborative Learning for Sensing-Driven mmWave Network" *Preprint - Under submission to Tier-1 systems conference.*
Milcom 2023	FJ Zumegen, **IK Jain**, D Bharadia, "BeamArmor Demo: Anti-Jamming System in Cellular Networks with srsRAN Software Radios", *IEEE Military Communications (Milcom) Conference 2023.*
HotCarbon 2022	A Gupta, **IK Jain**, D Bharadia, "Multiple smaller base stations are greener than a single powerful one: Densification of Wireless Cellular Networks", *ACM HotCarbon Workshop 2022*
WPMC 2022	T Qiu, **IK Jain**, R Wu, P Cosman, D Bharadia, "Streaming 360-degree video with Viewport-adaptive Truncation", *nternational Symposium on Wireless Personal Multimedia Communications (WPMC) 2022.*
Sigcomm 2021	**IK Jain**, R Subbaraman, D Bharadia, "Two beams are better than one: Towards Reliable and High Throughput mmWave Links", *ACM SIGCOMM 2021.* *Acceptance 55/ 241 (22%)*
NSDI 2020	R Ayyalasomayajula, A Arun, C Wu, S Rajagopalan, S Ganesaraman, A Seetharaman, **IK Jain** and D Bharadia, "LocAP: Autonomous Millimeter Accurate Mapping of WiFi Infrastructure.", *NSDI 2020* *Acceptance 48/ 275 (17%)*
Mobicom—mmNets 2020	**IK Jain**, R Subbaraman, TH Sadarahalli, X Shao, H Lin, D Bharadia, "mMobile: Building a mmWave Testbed to Evaluate and Address Mobility Effects", *4th ACM Workshop on Millimeter-Wave Networks and Sensing Systems (Mobicom Workshop - mmNets)*, 2020.
MDPI Journal 2019	A Choromanska, **IK Jain**, "Extreme Multiclass Classification Criteria", *MDPI Computation Journal*, 2019.
JSAC 2018	**IK Jain**, R Kumar, S Panwar, "The Impact of Mobile Blockers on Millimeter Wave Cellular Systems", *IEEE Journal on selected areas in communications (JSAC)*, 2018.
IEEE ITC 2018	**IK Jain**, R Kumar, S Panwar, "Driven by Capacity or Blockage? A Millimeter-wave Blockage Analysis" *IEEE International Teletraffic Congress (ITC)*, 2018.

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[6] Manideep Dunna, Chi Zhang, Daniel Sievenpiper, and Dinesh Bharadia. Scattermimo: Enabling virtual mimo with smart surfaces. In *Proceedings of the 26th Annual International Conference on Mobile Computing and Networking*, pages 1–14, 2020.