Research Statement: Suraj Jog

My research interests are in the area of wireless networking and sensing systems, with a focus on next-generation wireless technologies. The next-generation of wireless networks will provide unprecedented capabilities – gigabyte communication speeds, hyper-precise localization, and vision-like environmental perception. This will enable new applications such as wireless VR/AR, fully-autonomous driving, space communications, precision agriculture in connected farms, and high-performance computing (HPC). My research aims to pave the way for next-gen wireless networks by developing hardware-software systems that push the boundaries of technology and applications in terms of scale and function. To do so, my approach draws on tools from diverse areas including networking, signal processing, deep learning, computer architecture and RF-acoustics microsystems. I build on a deep understanding of wireless signals and work across hardware-software boundaries to solve core problems in networking and sensing. My research also takes an interdisciplinary approach that couples core networking innovations with application domain specific knowledge.

In particular my research has made the following contributions. First, millimeter-wave (mmWave) technology is at the center of next generation wireless networks since it can enable multi-gigabits per second speeds. However, the technology cannot scale well to multiple simultaneous users due to the narrow directional nature of transmissions which renders today's medium sharing schemes ineffective. In [NSDI'19, NSDI'21b], I designed and implemented the first millimeter-wave networks that can enable multiple densely packed users to transmit and receive simultaneously without interfering or compromising per user throughput. Doing so required rethinking the interference model between links, and adopting an end-to-end context-aware design approach, where the networking protocols combine information from the physical propagation environment and the antenna beam patterns, all the way to the application layer. Second, past work in the HPC community has shown that parallel processing performance can significantly benefit from millimeter-wave wireless networks-on-chip, since it can reduce the cache coherency latencies between cores by an order of magnitude. However, as the multiprocessors grow in number of cores, their performance is bottlenecked by the communication overheads of the wireless interconnect. In [NSDI'21a], I show how to scale wireless networks-on-chip to hundreds of cores, by introducing new self-learning networking protocols that can adapt and optimize for the underlying traffic statistics and execution dependencies in parallel applications.

My contributions are not limited to networking, but extend to wireless imaging and localization which are becoming integral to next-generation networks. In [CVPR'20], we introduced the first high resolution 3D mmWave imaging system for self-driving cars that can work even in fog and bad weather. As compared to vision, wireless imaging suffers from much lower resolution and artifacts such as specular reflections. These limitations are dictated by the laws of physics that describe how different frequency waves interact with objects. As a result, wireless imaging today alone can never match the resolution or interpretability from vision sensors. My research shows that by combining the wireless modality with environmental priors and deep learning algorithms, we can overcome these limitations and enable vision-like performance for self-driving cars using wireless imaging. In [NSDI'22], I introduce the first localization algorithm that enables low power narrowband IoT nodes to accurately self localize themselves simply by listening to ambient 5G signals, without any coordination with or modifications to the base stations. To do so, my research adapts the latest advances in MEMS (Micro-Electro-Mechanical Systems) acoustic resonators, which allows us to stretch the effective localization resolution by up to 16× on narrowband IoT devices, where the resolution is traditionally limited by their low-power hardware.

Recognition and Impact: My research has had academic and industrial impact. My research has been published in the premier venues in networking and vision ([NSDI'19, NSDI'21a, NSDI'21b, NSDI'22, ToN'19, CVPR'20]). I have been awarded the Qualcomm Innovation Fellowship for our work on "High Resolution Millimeter-Wave Imaging Using Deep Adversarial Learning". In addition, my research has also been recognized with the Joan and Lalit Bahl Fellowship, Mavis Future Faculty Fellowship, M.E. Van Valkenburg Fellowship and the Rambus Computer Engineering Fellowship. My work on "Enabling Dense Spatial Reuse in mmWave Networks" secured the First Position in the ACM SIGCOMM 2018 Student Research Competition. My work on data-driven precision agriculture, as part of FarmBeats, where I designed and prototyped a low-cost RF-based wind speed and direction sensor gained interest from top executives at Microsoft – I presented a working demo of my sensor to Bill Gates and Kevin Scott (CTO, Microsoft), and Bill Gates published a video and blog post on GatesNotes describing our work.

NETWORKING IN NEXT-GEN WIRELESS SYSTEMS

Enabling Dense Spatial Reuse in Millimeter-Wave WLANs [NSDI'19]: Millimeter-Wave (mmWave) networks can deliver multi-Gbps wireless links which will enable new applications like multi-user wireless VR and AR for education and professional training, 8K video content streaming, and large scale robotic factory automation which relies on real-time video feeds. Enabling the above vision, however, requires scaling mmWave networks from a single communication link to a network of many links without compromising the throughput of each user. Fortunately, next-gen millimeter-wave radios offer a new dimension for scalability, since they use very directional steerable narrow beams. This allows for dense spatial reuse that can enable many links to simultaneously communicate without interfering. In order to communicate at the highest data rates, the mmWave APs and clients need to align their narrow beams towards each other. While past work focuses on developing algorithms and protocols to quickly find the best alignment for a single communication link, in [NSDI'19] I show that in a network with multiple links, selfishly choosing the best alignment for each AP-client link independent of other links can create significant interference due to multipath reflections. I propose **BounceNet**, a system that addresses this scalability bottleneck and introduces the first *"Many-to-Many Beam Alignment"* protocol that can enable extremely dense spatial reuse in millimeter-wave networks where many links can communicate simultaneously at multi-Gbps without interfering.

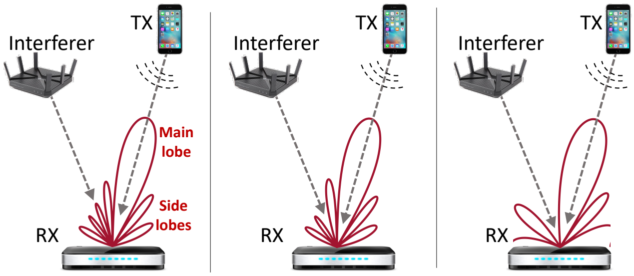
BounceNet's key intuition is to leverage the sparsity in the mmWave wireless channel to reformulate the many-to-many alignment problem as a signal level routing problem at the physical layer using multi-layered graph constructs. I demonstrate that such a cross-layer protocol design which optimizes across both the sparsity in the mmWave PHY along with the network-layer configuration of the links, allows BounceNet to leverage both direct and reflected propagation paths to route the signals and densely pack as many links as possible. I show that in dense networks, BounceNet is able to deliver 3.1×-13.5× higher throughput per client, thus allowing the network to scale easily. BounceNet introduces a new bridge between the link layer and PHY layer of the mmWave network stack to enable *"Physical Signal Routing"*, and was awarded the First Position in the ACM SIGCOMM'18 Student Research Competition.

(a) Traditional Wireless LAN (b) Millimeter Wave Wireless LAN

Figure 1—Spatial Reuse in traditional WiFi vs mmWave networks.

Practical Null Steering in Millimeter-Wave WLANs [NSDI'21b]: We build on BounceNet in **NulliFi** [NSDI'21b], where rather than simply aligning the beams of many links in a manner that avoids interference, NulliFi modifies the beam pattern to suppress interference by creating nulls, i.e. directions in the beam pattern where almost no power is received. Creating nulls in practice is challenging due to hardware imperfections and limited control in setting the hardware parameters such as the extremely low resolution in controlling the phase shifters on the antenna elements in phased arrays. In addition to hardware limitations, there are also network-level challenges, where due to estimation errors in the interferer direction, a practical system must be able to create wide nulls that can suppress the interferer within a margin of estimation error.

NulliFi presents the first practical mmWave null steering system that is able to null interference on commercial off-the-shelf phased arrays. NulliFi addresses the above challenges by combining a new theoretically optimal algorithm that accounts for limited hardware control with a novel discrete optimization framework that leverages evolutionary genetic algorithms to overcome the hardware imperfections and enable both multiple and wider nulls. In practice, NulliFi is able to reduce interference by two orders of magnitude and can further increase BounceNet's network throughput by 3×.



(a) No Nulling (b) Single Null (c) Wide Null

Figure 2—Creating nulls in directional mmWave networks.

Wireless Network-on-Chip using Deep Reinforcement Learning [NSDI'21a]: Wireless Network-on-Chip (NoC) has emerged as a promising solution to scale chip multicore processors to hundreds and thousands of cores. The broadcast nature of a wireless network allows it to significantly reduce the latency and overhead of many-to-many multicast and broadcast communications, which forms the bulk of the NoC traffic. However, the traffic patterns on wireless NoCs tend to be very dynamic and can change drastically across different cores, different time intervals and different applications.

Further, due to thread synchronization primitives likes barriers and locks that are commonly used in parallel programming, the wireless NoC exhibits complex hard-to-model dependencies between packet delivery time on the NoC and the progress of execution on the threads. As a result, traditional wireless MAC protocols perform very poorly in wireless NoCs since they remain agnostic to these domain specific dependencies and cannot adapt to the fast varying traffic.

To address this challenge, I proposed a unified approach in **NeuMAC** [NSDI'21a], that combines networking, architecture, and deep learning to generate highly adaptive medium access protocols for wireless NoC architectures that can directly optimize for the non-trivial dependencies between threads purely through experience. NeuMAC leverages the key insight that many building block functions like FFT, graph search and sorting, repeatedly appear in many applications as common subroutines, which leads to predictability in traffic traces. NeuMAC capitalizes on this predictability by leveraging a reinforcement learning framework with deep neural networks to generate new MAC policies that can learn the structure, correlations and statistics of the traffic patterns. NeuMAC can adapt quickly to optimize performance for different applications leading to low latency, high throughput and an overall reduction in execution time of 1.37×-3.74× for a diverse set of parallel applications.

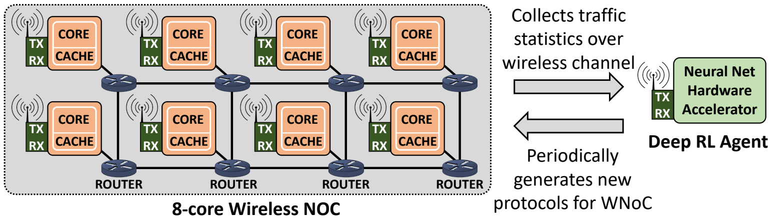
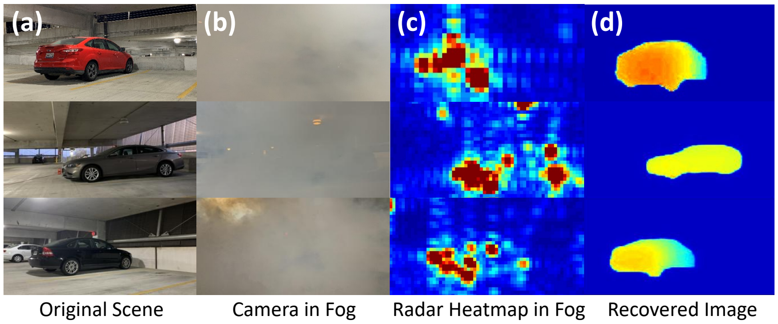


Figure 3—Deep reinforcement learning driven MAC protocols for wireless NoCs

SENSING AND LOCALIZATION IN NEXT-GEN WIRELESS SYSTEMS

Through Fog High Resolution Imaging Using Millimeter-Wave Radar [CVPR'20]: Autonomous vehicles, today, mainly use cameras and LiDARs for environmental mapping, which suffer in low visibility and severe weather conditions such as dense fog, smog, snowstorms, and sandstorms. In contrast, millimeter-wave (mmWave) radars offer more favorable characteristics due to their ability to work at night and penetrate through fog, snow and dust. Despite these benefits, car manufacturers today only use mmWave radar for the sole purpose of unidirectional ranging, i.e., to determine the distance to other vehicles. This is because mmWave imaging produce very coarse-grained and low resolution images, and also suffer from artifacts due to multipath reflections which results in ghost objects, and specularity where signals exhibit mirror-like reflections that result in missing major parts of the image. These are fundamental limitations of the wireless modality, and as a result, there remains a big gap today between wireless and vision-based imaging.

To close this gap, we propose **HawkEye** [CVPR'20], which consolidates advances in 5G mmWave hardware, deep learning, and radar signal processing, to enable the first mmWave radar imaging system that can deliver high-resolution 3D imaging even through fog and smog for self-driving cars. Specifically, advances in 5G has enabled massive 2D phased arrays which can be steered electronically in real time and can be repurposed to provide a 3D image of the environment. We employ a conditional GAN (Generative Adversarial Network) architecture to reformulate the problem of high-resolution imaging using radio waves, into a learning problem where the objective is to sense and recover high frequency shapes from the raw low resolution mmWave images. GANs allow us to effectively leverage priors on shapes of cars and other streetside objects, and also provide robustness to hard-to-model radar reflections and sources of noise like specularity and multipath. However, GANs have been mainly designed and optimized for vision. The specific nature of mmWave signals required several innovations in the use of GANs for wireless imaging, including redesigning key components of the network architecture like skip connections, and formulating customized RF-specific loss functions. We also built a realistic radar synthesizer that captures the unique characteristics of radar propagation for training data augmentation. Our work was awarded the Qualcomm Innovation Fellowship 2020.



Original Scene
Camera in Fog
Radar Heatmap in Fog
Recovered Image

Figure 4—HawkEye's Radar Imaging Results through Dense Fog

IoT Self-Localization with Ambient 5G Signals Using MEMS Acoustic Resonators [NSDI'22]: Recent years have witnessed a tremendous growth in the number of connected IoT devices, and with such ubiquitous deployment of IoT nodes, the ability to localize and track them with high accuracy is critical. In [NSDI'22], I propose **ISLA**, which enables low power IoT devices to accurately self-localize themselves simply by snooping on ambient 5G signals, without requiring any coordination or synchronization with 5G base stations. The 5G standard supports very high communication bandwidths (up to 400 MHz), which in turn enables very high resolution in ToF (Time-of-Flight) estimates (up to 75 cm resolution) for localization. Further, the ability to self-localize allows ease of deployment since there is no need to modify the 5G base stations to support the localization feature.

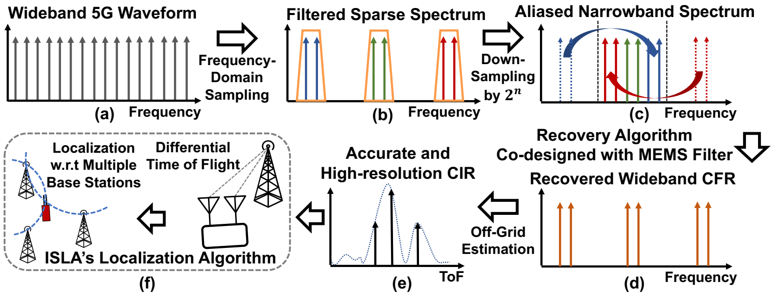


Figure 5—ISLA can leverage wideband 5G signals for high resolution self-localization on narrowband IoT devices.

However, leveraging these opportunities on power-constrained and low-cost IoT devices is challenging. IoT devices are equipped with cheap and low-speed Analog-to-Digital converters (ADCs) which cannot capture the large bandwidth of 5G signals, and in turn significantly lose out on the ToF resolution. In ISLA, I introduce the first RF-acoustic system that leverages MEMS acoustic resonators to design a new kind of filter that can stretch the effective localization bandwidth by 16× on these narrowband IoT devices. Specifically, we design a MEMS filter that emulates a spike-train in the frequency domain. This allows us to subsample and sparsify the 5G signal in the frequency domain such that the end-to-end bandwidth spanned by the filtered signal is preserved. This, in turn, means that the high ToF resolution is also preserved. The sparsified signal is then subsampled below Nyquist by the IoT device which causes aliasing. To retrieve the wideband channel measurements from this aliased spectrum, I introduce a novel channel recovery algorithm that co-designs the MEMS hardware with the subsampling rate, and formulate a joint inverse problem that optimizes for the channel ToF's in the continuous domain to achieve super-resolution. Through extensive experiments in three large outdoor testbeds, we demonstrate that ISLA can improve localization accuracy by 4-11×, and it achieves localization performance that is comparable to having a broadband 100 MHz receiver despite using a narrowband IoT receiver at 16× lower sampling rate.

Repurposing IoT Radios For Wind Sensing in Farms [In Preparation]: Data-driven techniques help boost agricultural productivity by increasing yields and cutting down input costs. Detailed information about rainfall, moisture levels, and wind speeds at a fine-granularity scale in the farm, can help farmers make optimized decisions for precision irrigation and spraying of insecticides and pesticides. However, these techniques have seen sparse adoption owing to the high costs of dense sensor deployments and manual data collection in large farms. In this work, I propose a novel antenna design that utilizes a simple mechanical attachment to the deployed IoT radios in the farm, such that it can repurpose existing IoT infrastructure to perform ubiquitous and automated wind sensing without affecting the underlying ongoing communications of the IoT network. The key insight here is that we can leverage the mechanical motion generated from the kinetic energy in wind to add an extra layer of physical signal modulation atop the ongoing communications, and information about the wind speed and direction can be retrieved from these tiny channel fluctuations. I developed a novel sparse FFT algorithm that can quickly estimate the wind information from the channel measurements, and prototyped the system to demonstrate accurate wind speed and direction sensing. I was fortunate to be able to demo my work to Bill Gates and Kevin Scott (CTO, Microsoft) during their visit to our deployment site in Washington, and Bill Gates published a video and blog post on GatesNotes featuring our work.

FUTURE WORK

In the long term, I am excited at the prospect of exploring even more new application domains that wireless can transform. Through my efforts as a researcher and academic, I hope to continue to channel my drive to design, build and thoroughly evaluate systems that improve the state-of-the-art. Below are some of the avenues I would like to explore ahead.

Internet-of-Things Networks: IoT deployments are becoming an increasingly critical component of the workflow in a number of diverse industries such as manufacturing, agriculture, retail and transportation. However, today's IoT devices operate in narrow and highly crowded portions of the spectrum, offering extremely low communication data rates (Sigfox offers up to 600 bits per second and LoRaWAN offers up to 27 kilo bits per second). As the deployment scale of these devices runs into the billions, we will face a huge strain on network performance and reliability. I am interested in exploring the possibility of low power millimeter-wave (mmWave) based IoT radios, since the huge bandwidth at mmWave frequencies would allow us to accommodate billions of IoT devices. However, the current state of mmWave technology prohibits us from realizing this goal since mmWave devices are expensive and power hungry. I want to work on minimizing the hardware complexity by eliminating the high-power and expensive radio front-end and RF circuitry, in lieu of cheaper and power efficient components like non-uniformly spaced phased arrays, low resolution ADCs (Analog-to-Digital Converters) and 2-bit phase shifters. I believe that the performance loss resulting from these non-ideal hardware components can be compensated for by leveraging intelligent algorithmic solutions at the upper layer of the network stack, similar to our past work in [NSDI'21b]. In addition, I also want to explore the possibility for new sensing capabilities like environmental monitoring on these low power devices, along with improved security and reliability guarantees.

Next-G Cellular Networks: Next-G wireless networks (5G, 6G and beyond) are positioned to enable unprecedented communication and sensing capabilities for a diverse set of devices, ranging from resource constrained IoT devices to power and throughput hungry smartphones and virtual reality headsets. To achieve this goal, 5G and future cellular networks will leverage many new hardware and software capabilities such as massive antenna arrays, multiple frequency bands and flexible bandwidth and channel allocation. While such a diverse feature set brings flexibility to service a wide variety of communication scenarios, it also significantly increases the complexity of the radio access network (RAN), offering a combinatorially large number of choices for the various control knobs of the wireless links (modulation order, coding rate, OFDM parameters, etc.). Manually configuring these networks for each of the different use cases is going to be challenging and sub-optimal. Towards this end, I want to explore the possibility of leveraging *AI for Self-Organizing Wireless Networks* that can learn from experience and automatically configure itself to achieve the optimal user experience for the specific task at hand. I believe this is a natural step in the evolution of Next-G wireless networks, given that cellular systems are becoming increasingly complex. Additionally, I am also interested in the ongoing efforts to enable imaging and sensing using 5G signals, without modifying the 5G base stations or waveforms. Sensing capabilities are positioned to be one of the core functionalities in 6G cellular networks, and I look forward to extending my work on ambient localization in [NSDI'22] towards a full-fledged environmental imaging system using cellular signals.

Wireless for Autonomous Driving and V2X connectivity: Unlike cameras and LiDARs which fail in low visibility conditions, radar signals can penetrate through fog, snow and dust, and are therefore more favorable for such scenarios. However, despite the benefits of radar, it remains rather underutilized in today's perception systems of cars and is limited to unidirectional ranging. Our past work in [CVPR'20] builds the first-of-its-kind mmWave radar imaging system that expands the capabilities of radar sensing to generate high resolution radar images of cars even through fog and rain. I want to extend this line of work by building a holistic radar imaging system that can create detailed images of the entire scene and capture multiple objects of interest like pedestrians, bikes, trees and traffic signs, in addition to cars. I also want to work on optimizing the form factor and cost of the radar module by leveraging the sparsity of the mmWave environmental reflections, and in turn integrate my radar imaging technology into the detection and control mechanisms of commercial self-driving cars. Finally, I believe that in order to achieve the vision of *fully autonomous traffic networks*, we need to establish a reliable and high throughput V2I and V2V networking infrastructure. We need a networking paradigm where cars share information with each other and with traffic infrastructure to cover blind spots and receive advance notification for safety critical information. I want to explore the design trade-offs and networking protocols in such V2X networks that can provide the required reliability and latency guarantees for the self-driving application.

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