Research Statement

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My research vision is to enable the next generation of wireless systems by creating unprecedented communication and sensing capabilities while ensuring that these capabilities run on resource-constrained Internet of Things (IoT) devices. These capabilities include massive-scale communication, Joint Communication and Sensing (JCAS), hyperprecise localization, and high-resolution 3D wireless imaging. My research uniquely exploits modern machine learning methods such as generative models and self-supervised learning, as well as novel hardware primitives to enable this vision. For example, my research has enabled autonomous vehicles to image and detect other cars in rain, fog, and darkness using wireless signals and deep generative models. I have built new hardware that allows even low-power narrowband IoT devices to access and benefit from the massive 5G spectrum. My research has been published in premier venues in networking & systems [SIGCOMM'18, NSDI'19, NSDI'21, NSDI'22, IPSN'23], computer vision [CVPR'20, ECCV'22, CVPR'24], signal processing [ICASSP'23], and circuits [VTS'19, RFIC'20, TMTT'21]. My research has received prestigious awards, including the Qualcomm Innovation Fellowship, ACM Research Highlights, and RFIC'20 Best Paper Finalists.

Wireless connectivity is one of the key foundations of today's societies that is evolving at a fast rate. New applications like autonomous driving, augmented reality, digital agriculture, and network-driven sensing place unprecedented demands on the scale and complexity of modern wireless networks. The vision of future wireless networks also extends to using wireless signals for sensing; Joint communication and sensing is touted as the breakthrough technology for 6G. Because wireless signals penetrate walls, fog, and occlusions, wireless perception is more robust than optical sensors in such challenging scenarios. However, several key challenges stand in the way of this vision: (a) Wireless perception is far behind vision-based perception both in terms of sensor resolution and AI algorithms. (b) Sensing and communication are often optimized in isolation. It is challenging to design networks that can seamlessly integrate both sensing and communication. (c) The benefits of next-generation networks must be accessible to hundreds of billions of IoT devices operating with narrow bandwidths, low power budgets, and low cost.

To overcome these challenges, my approach is to bridge the gap between AI, RF hardware, and wireless networks through hardware-software-AI co-design. I have taken this approach to develop novel hardware-software-AI systems that push the boundaries of wireless connectivity and perception technologies on several fronts.

1. My research leveraged recent advances in generative AI and mmWave radar hardware to elevate **radar perception for autonomous driving** to the next level. I demonstrated, for the first time, 3D high-resolution wireless imaging through fog [CVPR'20] and accurate bounding box detection [ECCV'22, ICASSP'23, CVPR'24].
2. My research pioneered the foundations for **MEMS-enhanced wireless sensing and localization**, where I introduced the first of their kind Micro-Electro-Mechanical-Systems (MEMS) filters that look like spike trains in the frequency domain in the radio front-end. I showed how combining these filters with new sparse recovery algorithms enables energy-efficient spectrum sensing for dynamic spectrum sharing [NSDI'21] and allows narrowband IoT devices to accurately localize themselves leveraging ambient 5G signals [NSDI'22].
3. My research initiated **Networked Noise Cancellation**, which leverages the fact that wireless signals travel a million× faster than sound and uses an IoT wireless network to forward noise sounds over wireless to active noise canceling (ANC) headphones. This provides ANC with a look-ahead into future incoming noises to achieve better noise cancellation [SIGCOMM'18, IPSN'23].
4. Finally, I have introduced approaches that open up new possibilities/applications in **Next-Generation Wireless Networks**, ranging from JCAS in 5G/6G networks [RFIC'20, TMTT'21] to multi-user beam alignment [NSDI'19].

In the rest of this document, I describe my technical contributions in detail.

AI-Enhanced Millimeter Wave Radar Perception For Autonomous Driving

A key focus of my research is to improve radar perception performance, such as high-resolution imaging and semantic scenes. Radar can provide autonomous systems with unprecedented perception capabilities and enable numerous new applications. For example, automotive radar can enable self-driving cars to see through dense fog, smog, snowstorms, and sandstorms, where cameras and LiDARs fail, and even beyond line of sight. Therefore, autonomous vehicles can also navigate reliably in adverse weather conditions and achieve the vision of full autonomy. However, the imaging resolution of radar is nowhere near those of cameras and LiDARs and radar imaging also suffers from artifacts such as specularity, where signals exhibit mirror-like reflections that result in missing major parts of the image. My research consolidates the latest advances in mmWave radar hardware, radar signal processing algorithms, and deep learning techniques to overcome these limitations and enable vision-like performance for radar perception.

Accurate Radar Based Object Detection [ECCV'22, ICASSP'23, CVPR'24]: We designed *Radatron*, a system capable of accurate object detection using cascaded Multiple Input Multiple Output (MIMO) radars, which combine multiple radar devices to improve angular resolutions. However, high-resolution cascaded MIMO radars suffer from motion smearing in moving scenes caused by Doppler shift during the transmission interval of multiple transmitters. Consequently, reflections of objects appear in the wrong locations, resulting in inaccurate bounding-box predictions as shown in Fig. 1(c).

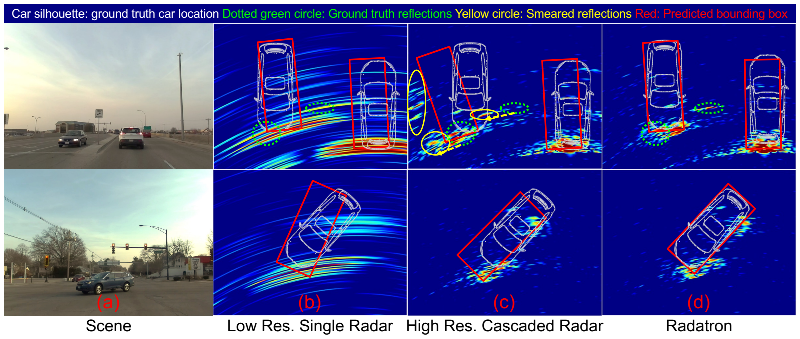

Figure 1: *Radatron* accurately detects bounding boxes in radar heatmaps.

Radatron overcomes this challenge and achieves accurate object detection with a combination of radar signal processing and deep learning solutions. On the signal processing front, we exploit a variety of virtual array topologies to disentangle and compensate for Doppler-induced motion smearing, and to resolve Doppler ambiguities [ICASSP'23]. On the deep learning front, we design an object detection network that jointly leverages high- and low-resolution radar heatmaps to predict precise bounding boxes of cars without being misleaded by faulty information due to motion smearing [ECCV'22]. To enable *Radatron*, I created a first-of-its-kind high-resolution radar dataset in practical self-driving scenarios. I also designed a self-supervised learning framework to learn general representations for radar data from large-scale unlabeled frames that can bootstrap various downstream tasks [CVPR'24].

Through Fog High Resolution mmWave Radar Imaging [CVPR'20]: I introduced *HawkEye*, the first mmWave radar imaging system that can reconstruct high-resolution 3D images for autonomous vehicles, even through fog and smog. We reformulated the problem of vision-like radar imaging into a learning problem where the objective is to recover high-frequency shapes of the underlying physical objects from the raw mmWave radar reflections. Specifically, we employed a conditional Generative Adversarial Network (cGAN) that consumes low-resolution 3D radar heatmaps and predicts high-frequency shapes. GANs can effectively leverage priors on shapes of cars and provide robustness to hard-to-model radar reflections and specularity. In addition, a cGAN architecture further regulates the generator to the underlying object features (e.g., shape and orientations) in the radar reflections instead of simply outputting a realistic image of cars. *HawkEye* won the Qualcomm Innovation Fellowship 2020.

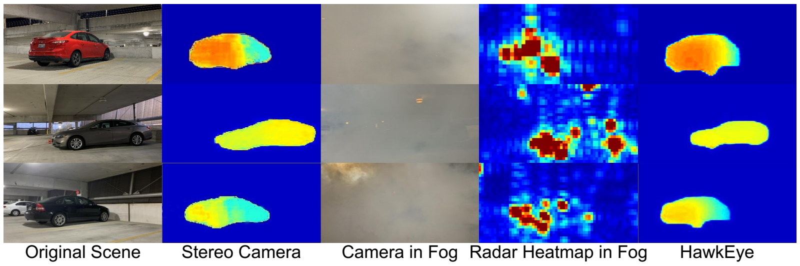

Figure 2: *HawkEye* reconstructs high-resolution radar images through fog.

MEMS-Enhanced Energy-Efficient Spectrum Sensing & Localization

I design innovative RF devices and hardware to solve fundamental problems in wireless networks. Together with MEMS resonator experts, I introduced first-of-its-kind RF spike-train filters with many narrow, sharp, and periodic passbands. Figure 3 illustrates their spike-train-shaped frequency response. I co-designed the filter hardware and sparse recovery algorithm software to enable energy-efficient spectrum sensing and accurate IoT self-localization.

Energy-Efficient Real-Time Wideband Spectrum Sensing [NSDI'21]: Dynamic spectrum sharing is a long-standing vision in wireless networks where devices share the currently underutilized spectrum, creating GHz-wide shareable spectrum to accommodate new wireless services. However, a major obstacle precluding this vision is the need for radios to sense GHz of spectrum in real-time to quickly identify occupied bands, which consumes a lot of power because they need to sample the wireless signal at GigaSample/s. My goal is to monitor wide spectra that are already densely occupied in real time using cheap and low-power low-speed analog-to-digital converters (ADCs).

Toward this goal, I introduced S^3 (Spectrum Sensing Spike-train), a system that samples the spectrum in the frequency domain using the MEMS spike-train filter and only monitors the small fraction of bandwidth in every wireless channel to infer channel occupancies. The benefit of doing so is that even if the wideband spectrum is densely occupied, the frequency-sampled spectrum becomes significantly sparser. Therefore, S^3 can sample the

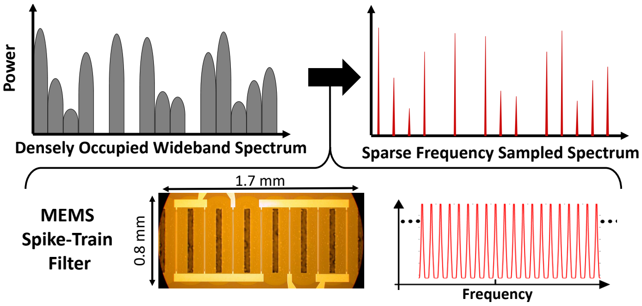

Figure 3: MEMS Spike-Train Filter can sparsify crowded spectrum.

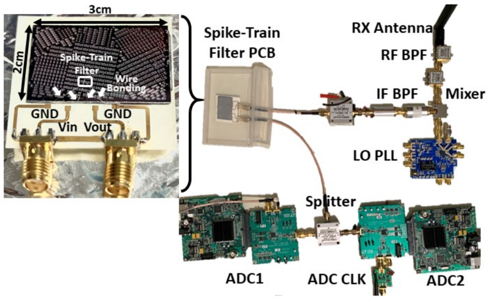

Figure 4: Circuitry of S^3 Prototype System.

spectrum 8.5× below the Nyquist sampling rate and still recover the wideband spectra with a unique sparse recovery algorithm designed in conjunction with the filter hardware. We fabricated a chip-scale MEMS spike-train filter and integrated it into a prototype of a S^3 spectrum sensor using low-power off-the-shelf components, as shown in Fig. 4.

IoT Self-Localization reusing Ambient 5G Signals (*ISLA*) [NSDI'22]: We expanded S^3 from only recovering wideband power spectra to reconstructing wideband channel responses, which we then leveraged to enable low-power IoT devices to accurately localize themselves by reusing ambient 5G signals. The wide bandwidth (up to 400 MHz) of 5G can be translated into a high time-of-flight resolution (up to 75 cm) and high localization accuracy. However, exploiting wideband 5G signals is challenging for power-constrained IoT devices equipped with low-speed ADCs. *ISLA* manages to stretch the effective localization bandwidth of narrowband IoT nodes by 16x using spike-train filters coupled with co-designed sparse recovery algorithms, which improves the localization accuracy by 4-11×. Furthermore, *ISLA* nodes localize themselves by passively listening to ambient 5G signals and do not require any coordination with 5G base stations or modification of the 5G protocol, so they can scale to a large number of nodes.

Next-Generation Wireless Networks and IoTs

My research agenda also expanded to emerging applications of Next-Gen wireless networks, including joint communication and sensing, multi-user beam alignment in mmWave networks, and noise cancelation using IoT networks.

Joint Communication and Sensing in one of the central visions of Next-Gen wireless networks. Leveraging the GHz-wide bandwidth in above 6 GHz and mmWave bands and large phased array antennas, capable of forming and steering highly directional beams, we can create a digital twin of the physical world. In [RFIC'20, TMTT'21], I introduce an overlay sensing system for 5G base stations that can recreate high-resolution radar-like 3D images of the environment from reflected communication signals. I developed a signal processing pipeline to accurately estimate time-of-light of the reflected signals and improve the range resolution by coherently aggregating information in separate frequency bands. In combination with precise phased array beam steering, the prototype base station achieves 2° angular and 15 cm range resolutions. Most importantly, the communication functionality and performance of the base stations are not affected, because there is no modification to the 5G waveform, protocol, or transmitter.

Millimeter Wave Networks form the core of Next-Gen wireless networking, including 5G/6G cellular networks and 802.11 WLANs because the GHz-wide spectra support Gbps data rates. However, mmWave networks must use directional beams to compensate for higher path losses, resulting in challenges in mobility, medium access, and control overhead. To study and address these challenges in mmWave networks, I built a 24 GHz phased array radio and designed an online phased array calibration method to optimize the beam patterns [VTS'19]. Using our custom-built phased arrays, we developed the first "Many-to-Many" beam alignment protocol, *BounceNet* [NSDI'19], that can enable extremely dense spatial reuse in mmWave networks where many links can communicate simultaneously at multi-Gbps without interference. Utilizing direct and reflected propagation paths to route signals and pack as many links as possible *BounceNet* can deliver 3.1-13.5× higher throughput per client in dense networks.

Networked Noise Cancellation: Microphones have become ubiquitous, from mobile phones to smart homes and voice interfaces like Amazon Echo and Google Home, to earbuds and wearable devices. Our work explores the domain of the Acoustic Internet of Things and particularly re-envisioned the area of Active Noise Cancellation. We designed an IoT network that can forward acoustic noise to noise-canceling headphones using wireless radios. Since wireless travels a million times faster than sound, the noise canceling device gets a future look-ahead into the incoming noise, allowing us to design better noise canceling algorithms and more comfortable hollow noise canceling earphones. The first system we developed, *MUTE* [SIGCOMM'18] initiated this concept and showcased single source noise cancelation with a single IoT microphone node. In [IPSN'23], we scaled *MUTE* into a framework that leverages a wireless network of IoT microphones to simultaneously cancel multiple noise sources.

Future Plan

My research plan is to push the boundaries of wireless technologies. In the near future, I plan to push along 3 topics:

(1) Radar Vision for Autonomous Systems: I plan to equip autonomous systems like self-driving vehicles, robots, and drones with the ability to see things that are invisible to human eyes, such as beyond occlusions, around corners, and in conditions where cameras fail like fog and smog. This requires innovations along three fronts:

- *Hardware:* Despite the rapid advances in wireless sensing hardware, e.g. 4D imaging radars, in the past decade, the imaging resolution of radar is still nowhere near that of cameras and LiDARs. I plan to build mmWave radar hardware that is capable of generating extremely large virtual antenna arrays that deliver LiDAR-like angular resolution by creating a distributed coherent aperture with synchronized MIMO radars and building on the rich literature of sparse arrays to minimize system complexity and cost.
- *Machine Learning Models:* Radar-based learning currently has to cope with the small-data regime and even within the few available datasets, various radar hardware, configurations, and data formats are used, which leads to a practical challenge in generalizing radar-based models. Moreover, without a foundation model for wireless and radar data that can take full advantage of high-dimensional but sparse wireless data, the full power of AI cannot be unleashed in the radar domain. In particular, the finer-grained phase information embedded in complex wireless signals and Doppler information have not been successfully exploited thus far. Therefore, I will dedicate myself to developing foundation models for radar data, incorporating a deep understanding of radar hardware, the wireless channel, and signal processing into deep learning architectures.
- *Robotics:* I plan to study how best to incorporate wireless perception into the robotic control loop. At the same time, I also plan to study how to incorporate robotic automation and control into wireless perception systems to provide additional degrees of freedom to improve perception performance. For example, leveraging robotic maneuvers to emulate a much wider synthetic aperture can significantly improve angular resolution.

(2) 6G Joint Comm. & Sensing: I am passionate about using pervasive 6G wireless networks to create digital twins of the physical and biological worlds. Wireless communication and sensing functions have mostly been optimized independently, but I believe that their cooperation can greatly benefit both parties. This is challenging because communication and radar sensing require specialized waveforms and hardware. For example, the OFDM waveform is optimized for communication and requires a digital processing pipeline, while the FMCW radar waveform utilizes analog circuitry to minimize sampling rate and synchronization offsets. To overcome these challenges, I plan to take advantage of emerging large MIMO and phased array antenna systems as well as RAN virtualization to co-design wireless sensing applications and communication networks in the joint waveform, beam pattern, and protocol spaces.

(3) Satellite Networks & Imaging: I also plan to apply my expertise in mmWave networks and radar imaging to solve research problems in the emerging industry of commercial satellite constellation. First, the use of phased array antennas has enabled high-throughput satellite networks, but the extremely high mobility and long distances also expose unprecedented challenges in beam alignment and handover. Second, satellite clusters can be exploited for new remote sensing capabilities; By coherently combining radar signals from a swarm of tiny satellites, one can emulate a massive virtual antenna aperture to reconstruct high-resolution 3D models and digital twins of the Earth.

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