Research Statement

Akarsh Prabhakara (Ph.D. Candidate at Carnegie Mellon University)

I am a wireless and cyber-physical systems researcher that builds **compact wireless systems with high quality sensing capabilities**. I achieve this by developing new hardware, leveraging machine learning and novel signal processing, and balancing system constraints on communication and sensing computation. I build end-to-end systems with transformative implications spanning cyber-physical systems, wireless communication and robotics.

Radio Frequency (RF) sensors are indispensable for imaging through occlusions. They enable flexible capture zooming in to sub-millimeter object scales (e.g: assembly line seeing through cardboard packages) and zooming out to meter-scale objects (e.g: elderly monitoring at homes seeing through walls). However, RF sensors have been restricted to large and bulky platforms, drastically confining the scope of possibilities. Miniaturization opens up embedded scale platforms to leverage the benefits of RF. But, this comes at a fundamental cost of reduced imaging fidelity. My vision is a compact, RF sensing system that can fit in an embedded form factor (e.g: phone) with (1) camera-quality videos in all conditions and (2) arbitrarily "zoom in and out" to focus on all object scales. Such a system would fundamentally change how devices perceive occlusions and redefine what is possible with **"X-ray vision" on embedded platforms**. This would pave the way for a highly reliable sensor for size-constrained critical cyber-physical systems (CPS), harsh robotics applications and cooperatively enhance 5G/next-G communication performance.

My research builds towards this by holistically considering the entire system stack. I develop novel methodologies to best optimize RF hardware, design battery free and low power tag markers in the environment to assist sensing, develop novel cross-modal machine learning and signal processing techniques and accelerate embedded compute on several Gbps raw data for real time systems. This enables **all-conditions perception** where cameras fail due to adverse weather (rain, fog, snow), dust, debris, smoke and other occluders and empowers following key applications.

- **All-Conditions Cyber-Physical Systems:** CPS are sense-think-actuate systems with an emphasis on reliable performance. My work builds reliable RF sensors for two classic CPS applications where cameras fail - transportation and structural health monitoring. I built the first *electronics free, smart-dust like RF markers* to be embedded in an automotive tire [1]. This addressed major reliability problems from dust and debris for on-board tire health sensors. I also built the first, *long range millimeter wave backscatter hardware tags* and mounted them on critical (e.g stop signs, bridges) infrastructure for car radars to detect and communicate in all weather [2, 3, 4]. My work shows that high quality RF perception is key to enabling futuristic high stakes CPS applications like Level 5 (all conditions) autonomous driving.
- **Intelligent Wireless Communication:** My research seeks to sense and exploit scattering properties of surfaces and complex multipath thereof in dense environments, to improve wireless communication. Rather than relying on analytical propagation models, I developed *data-centric approaches* to sense and characterize in-the-wild radio propagation and material influence [5, 6, 7]. I then show how this high quality sensing can inform access points to enhance signal coverage and throughput by actuating robotic surfaces [8] and positioning satellite receivers [9]. My research creates higher resolution environment awareness for next-G communication systems to exploit.
- **Robotics in Harsh Conditions:** My research opens up new robotic applications with through-occlusion RF perception. [10] makes a futuristic fire fighting robot that deals with thick, dense smoke possible. I developed *super resolution machine learning techniques* and compute accelerations [11] for RF sensors to achieve lidar-like performance, where lidar fails. Lidar is the gold standard for sensors in robotics and is significantly more expensive than RF sensors. [10, 12] show huge promise in democratizing lidar-like performance (in visible and occluded scenes) at a fraction of lidar's cost and building towards cheap robots.

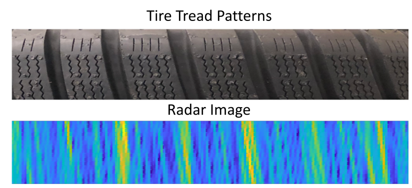
Impact: My research has been published in core wireless and CPS venues — MobiSys (**Best Paper Honorable Mention**) [1], MobiCom [2, 9], IPSN [3], Ubicomp [4] and **interdisciplinary robotics venues** — IROS [12] and ICRA [10]. In the true spirit of systems research, I have demonstrated my research and have been awarded Best Demo (MobiSys'20), Runner-up Demo (MobiCom'21) and Top-5 Demo (MobiCom'23). I was awarded the Corporate Startup Lab Fellowship at CMU to study rural wireless networks and telehealth. Beyond academia, my work has been featured in popular media like Gizmodo, Hackster.io and TedX Innovation Expo, among others. My tire wear sensing system [1] has attracted attention from various companies including Qualcomm Ventures, General Motors, Bailac – a major mining company, and has been **licensed to Bridgestone Inc., a global tire manufacturer**.

My research innovates on hardware, processing, communication and computation to enhance sensing resolution of compact wireless systems.

All-Conditions Cyber-Physical Systems

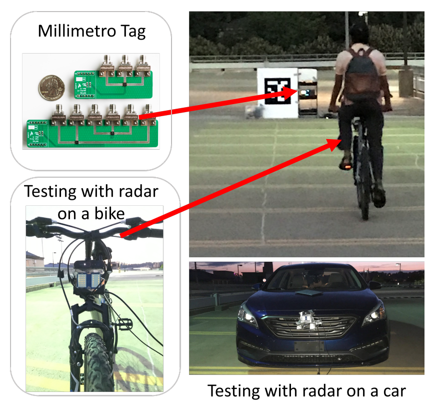
Reliable perception is essential to ensuring overall CPS performance. My research has addressed pressing problems in three classical CPS domains — on-vehicle sensing (e.g: vehicle vital sign monitoring), off-vehicle infrastructure (e.g: road signs, lane markers) and structural health monitoring (e.g: bridges) — when exposed to harsh conditions.

On-Vehicle Sensing: Tire wear and tear is a major contributor to vehicular safety. Building tire wear sensors is challenging due to the tire's extreme temperature and pressure. Past works yield poor accuracy because of the accumulation of road debris (mud, snow, stones) in the grooves. My solution Osprey [1], leverages a compact, millimeter wave (mmWave) radar that is mounted in the tire well. But the compact radar's imaging quality is very poor. My key idea is to leverage natural rotation of the tire to perform resolution-enhancing techniques like synthetic-aperture radar. The presence of debris in the grooves is still a major challenge as it can throw off the imaging system. I engineered battery-free metal foils with spatial coded patterns to be laid out in the tire complying with safety. These foils serve as groove-markers resilient to the accumulation of any foreign debris in the groove. I demonstrated sub-millimeter wear measurements directly impacting both the safety and performance of automobiles. Osprey has now been successfully licensed to a tire manufacturer — Bridgestone Inc.



High Resolution RF Tire Image

Low Power Road-side Beacons: Auto makers are striving towards Level 5 automation (aka, all-conditions self driving). We need to rethink our public infrastructure (traffic lights, road signs and lane markers) necessary to support this level of autonomy. I developed Millimetro [2], a low power, add-on marker to road infrastructure to enable on-vehicle automotive radars to perceive critical information even in the most adversarial conditions. Unlike past work, I optimized the marker to reflect maximum energy back to the radar. This is the first mmWave backscatter system allowing detection over 100m while consuming low power. This allows vehicles to detect markers from far away to react in time. These markers essentially convey information about infrastructure (signs, lane markers, lights) as unique temporal codes. I also designed temporal modulation schemes so that a radar can simultaneously detect 10s of markers – a stop sign, a traffic light and lane markers all at the same time as necessary on the road. Millimetro has spurred rich follow up research in designing mmWave markers for a variety of different use cases.



Structural Health Monitoring: For long-term public infrastructure (e.g: bridges) structural health monitors have to be immune to the elements of weather. While the majority of past work has focused on large-scale structures, Platypus [3] paves the way for fine-grained monitoring of small-scale crack developments. My solution shows high resolution monitoring of bridge structures for sub-millimeter level displacement sensing. It uses a combination of (1) custom designed low power tags that last for 10 years on a coin cell battery and (2) novel signal processing to extract micro-displacements. These techniques are essential to unlock new possibilities for fine-grained localization and tracking.

Platypus on a bridge structure

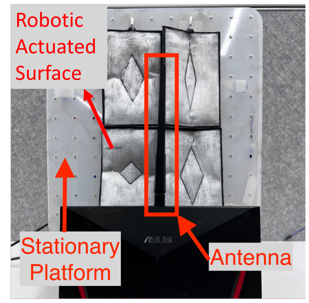
Intelligent Wireless Communication Systems

For long, RF sensing has piggybacked on top of communication. This limits the potential of sensing to what communication devices can offer. My research seeks to build high resolution RF sensors that can push the limits of sensing quality. With this, I want sensing to mutually coexist and tie the loop to make communication systems better. One

All-Conditions Cyber-Physical Systems					Intelligent Wireless Communication Systems					Robotics in Harsh Conditions	
Osprey [1] [MobiSys 20]	Millimetro [2] [MobiCom 21]	Platypus [3] [IPSN 23]	TagFi [4] [Ubicomp 21]	ZoomOut [11] [PAST 22]	Quasar [9] [MobiCom 21]	MetaMorph [8] [In Submission]	DART [5] [In Submission]	Hydra [7] [In Submission]	CAMIO [6] [In Preparation]	RadarHD [10] [ICRA 23]	Metamoran [12] [IROS 22]

of the core problems in wireless is accurate radio propagation modeling and using it to position access points and base stations. Large-scale simulations are slow and require explicit 3D modeling and material characterization. Moreover, extreme mobility and access to emerging new physical layer paradigms, call for a rethinking of how we sense and model electromagnetic wave propagation in real time.

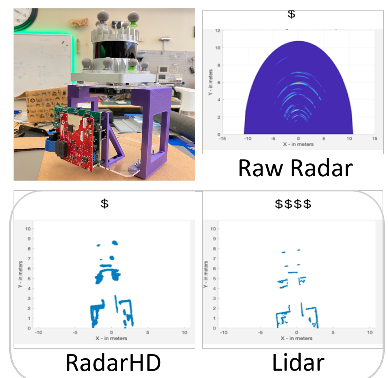
DART [5] uses a sensor data centric approach to *implicitly* derive 3D world models and propagation physics from sensor measurements. By employing Neural Radiance Field based approaches, DART can understand transmissive and scattering properties of materials accurately. This allows us to (1) accurately model multipath and inform communication devices to exploit it; (2) create realistic radar simulators that minimize disparity between simple ray-trace simulations and the real world. In mobile, dynamic scenes, my work [8, 9] leverages this multipath scattering understanding to (1) robotically actuate reflective surfaces; (2) position tiny hand held satellite receivers such that it best maximizes signal coverage and throughput. CAMIO [6] and Hydra [7] further exploits this material interaction understanding to enhance RF sensing resolution.



Metamorph senses and exploits multipath with robotic actuation

Robotics in Harsh Conditions

Conventional robotics sensors, cameras and lidars, suffer in dense smoke. My research makes a futuristic first-responder robot that answers a 911 fire emergency possible. A compact mmWave radar on such a robot is ideal, but its poor resolution makes it challenging for robotic navigation tasks. For this unique problem context, I developed a machine learning based super-resolution solution, RadarHD [10], that takes in low resolution radar and outputs orders of magnitude higher resolution, lidar-like point clouds. I detonated smoke bombs of varying intensities to create thick smoke and tested our system robustly. With such high quality point clouds, I further showed improvements to downstream robotic (odometry and mapping) tasks. This work paves the way for a cheap and inferior radar to mimic and replace expensive and superior sensors (lidar) in harsh conditions. RadarHD code and data are completely open-sourced and have inspired several developers to build on top of it in a short time span.



RadarHD mimics lidar
High-res point clouds even in smoke

In the future, I want to span the electromagnetic spectrum by cooperatively leveraging frequencies with benefits. Building towards this, I show in [12] that there is rich harmony in cameras cooperating with RF to jointly enhance resolution. [12] shows that for robotic geo-fencing applications, we can replace a suite of cameras with a single camera and radar. This makes way for large-area automated surveillance from a compact setup and cheap installation and calibration costs. By building embedded-scale, high resolution RF sensors, we are entering a new world where RF sensors become mainstream like camera and audio, and enable several applications.

Future Work

Communication radios and cameras are ubiquitous today. My overarching goal is to make compact wireless devices that *both communicates in high fidelity and captures camera-like RF images* a practical reality. I will harness innovation across layers: wireless device architectures, novel physical interactions and machine learning for reliable CPS.

Multi-purpose Reconfigurable RF Surfaces: Intelligent surfaces are a new paradigm (neither at the client nor at the access point). Being midway between the client and access-point, surfaces not only offer better communication SNRs, but can physically have large apertures (thereby, better imaging resolution). I want to build on this intuition and develop general-purpose surfaces that can mutually coexist imaging with communication. This is in contrast to surfaces only for signal coverage extension. This would require (1) new surface architectures (support both radar-like-imaging and communication-like); (2) balancing compute between heavy sensing and lightweight-forwarding communication workloads; (3) managing latency implications of choosing communication over imaging dynamic objects (leading to blurred images). I want to leverage low power antenna arrays and metasurfaces that can enable both sensing and communications, but develop them to support large apertures. Building on top of [2, 8], I propose to embed edge compute nodes in the surfaces to collaborate between nearby surfaces to jointly balance compute and latency.

Cross-Modal Understanding: Each of the three modalities has unique attributes: RF passes through occlusions, cameras have good imaging resolutions and sound can physically create pressure zones of variable indices of refraction. Indeed, associating interactions across modalities is challenging. For instance, pressure zones affect RF backscattering, but it is hard to map a pressure zone to a single camera pixel or RF image pixel. I want to create generalizable basic abstractions across these modalities. While I have drawn associations between camera and RF using signal processing [12], unimodal NEural Radiance Field (NeRF) based approaches such as [5] have shown to represent nuanced interactions missed by analytical models. I aim to develop multimodal NeRFs with an emphasis on understanding in-the-wild RF interactions by learning spatial associations across three modalities. Optimizing for maximum information gain across modalities, I shall custom build a compact sensing hardware that will achieve the best of all worlds.

Reliable RF Machine Learning for CPS: Machine Learning (ML) can transform the way RF sensors are built today: antenna geometries, waveform design, spectrum sensing and application specific tasks (e.g: classification on radar data). I want to leverage ML to redesign purely signal processing based blocks in RF sensing and communication tasks. But, black box ML, although can work remarkably well, loses guarantees that CPS systems enjoy. To rely on ML for RF sensors, we need the networks to be interpretable, explainable and robust to outlier data. In this spirit, [10] interprets model layers using attribution functions to verify what is being learnt. I propose to address robustness to adversarial RF data by drawing inspiration from adversarial ML and customizing defenses to RF adversaries like specular noise with particularly high temporal variance. For human explainability, I want to build on model agnostic functions to characterize dependence between input and model output. Deriving safe operable conditions from these explanations would make for ML driven RF sensors to be deployed in critical CPS applications in practice.

With growing demand for better computation, communication and sensing, I strive to make advances on each front and chart new trajectories in the way computer systems engage and interact with society.

References

[1] A Prabhakara, V Singh, S Kumar, and A Rowe. "Osprey: A mmWave approach to tire wear sensing". In: *ACM MobiSys*. 2020.

[2] E Soltanaghaei*, A Prabhakara*, A Balanuta*, M Anderson, J Rabaey, S Kumar, and A Rowe. "Millimetro: mmWave retro-reflective tags for accurate, long range localization". In: *ACM MobiCom*. 2021.

[3] T Horton King, J He, C Yao, A Prabhakara, M Alipour, S Kumar, A Rowe, and E Soltanaghai. "Platypus: Sub-mm μ-Displacement Sensing with Passive mmWave Tags As Phase Carriers". In: *IEEE/ACM IPSN*. 2023.

[4] E Soltanaghaei, A Dongare, A Prabhakara, S Kumar, A Rowe, and K Whitehouse. "Tagfi: Locating ultra-low power wifi tags using unmodified wifi infrastructure". In: *ACM IMWUT/UbiComp*. 2021.

[5] J Miller*, T Huang*, A Prabhakara, T Jin, T Laroia, Z Kolter, and A Rowe. "Neural Radar Fields". In: *Submission*. 2024.

[6] A Prabhakara, Y Liu, A Rowe, A C Sankaranarayanan, and S Kumar. "Millimeter Wave Imaging from a Single Antenna". In: *Preparation*.

[7] N Mehrotra, D Pandey, A Prabhakara, Y Liu, S Kumar, and A Sabarwal. "Multi-Bounce Scattering to Image beyond mmWave Field of View". In: *Submission*. 2024.

[8] Y Liu, J Zhu, A Prabhakara, and S Kumar. "Reprogramming Wireless Signal Distributions Using Soft Robots". In: *Submission*. 2024.

[9] V Singh, A Prabhakara, D Zhang, O Yağan, and S Kumar. "A community-driven approach to democratize access to satellite ground stations". In: *ACM MobiCom*. 2021.

[10] A Prabhakara, T Jin, A Das, G Bhatt, L Kumari, E Soltanaghai, J Bilmes, S Kumar, and A Rowe. "High resolution point clouds from mmwave radar". In: *IEEE International Conference on Robotics and Automation (ICRA)*. 2023.

[11] T M Low, Y Chi, J Hoe, S Kumar, A Prabhakara, L Shi, U Sridhar, N Tukanov, C Wang, and Y Wu. "Zoom Out: Abstractions for Efficient Radar Algorithms on COTS architectures". In: *IEEE Phased Array Systems & Technology (PAST)*. 2022.

[12] A Prabhakara*, D Zhang*, C Li, S Munir, A C Sankaranarayanan, A Rowe, and S Kumar. "Exploring mmWave Radar and Camera Fusion for High-Resolution and Long-Range Depth Imaging". In: *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 2022.

{.}* - Coprimary Authors