My research vision is to enable **sustainable ambient intelligence** through **seamless integration of sensing, learning, and communication technologies in everyday environments.** I work at the intersection of mobile computing, cyber-physical systems, embedded AI, and wireless, developing systems for precision farming, environmental monitoring, and micro-robotics. By reimagining sensing architectures from first principles, I achieve orders of magnitude improvements in energy efficiency and scalability, making intelligent systems practical in highly resource-constrained environments.

Imagine a world where intelligent devices blend seamlessly into our environment, operating autonomously for years on harvested energy. Insect-scale robots navigate disaster zones with unprecedented agility, and sticker-like tags track goods across global supply chains without manual maintenance However, realizing this vision poses fundamental challenges: **How do we bring modern AI capabilities to severely resource-constrained devices? How can we sense, compute, and communicate with minimal energy while maintaining reliability?** My research addresses these challenges by fundamentally reimagining sensing system architectures. Rather than incrementally optimizing existing solutions, I create inherently low-power sensing paradigms that enable transformative applications - from reducing global food waste through automated quality monitoring to enabling environmental conservation long-term sensor deployments.

I integrate techniques from signal processing, machine learning, hardware design, RF circuits, and computer networking, drawing key insights from physics and biology to create novel sensing architectures. Through novel hardware-software co-design, I've enabled breakthrough capabilities - from acoustic microstructure-based robot perception to nationwide asset tracking with battery-free cellular tags and continuous non-invasive food quality monitoring across supply chains.

My research appeared in leading conferences on networking systems, embedded AI, mobile computing, and sensor networks **(MobiSys'21, MobiSys'22, MobiSys'23, SenSys'24, NSDI'25)**. I have been fortunate to receive recognition for some of this work through the **MobiSys'22 best paper** award, several **best demo and poster** awards, and honors including the **Marconi Young Scholar** award and **CPS Rising Star**. The broader implications of my research were highlighted in **SIGMOBILE GetMobile** and **Communications of the ACM**, and I have demonstrated real-world impact through collaborations with Microsoft Research, NEC Labs, Nokia Bell Labs, and Georgia Tech resulting in several patents [1,2].

Contributions and Impact

Structure-Assisted Spatial Intelligence: Spatial sensing systems often rely on bulky sensor arrays and power-hungry ADCs, posing challenges for their integration in wearables, micro-robots, and IoT devices. I developed a bio-inspired approach, utilizing 3D-printed microstructures and embedded AI to passively extract spatial information. This framework addresses a fundamental challenge—single-antenna localization and perception. *SPiDR* [3] enables **single-microphone depth imaging**, eliminating LiDAR in micro-robotics. *Owlet* [4] achieves **3D spatial audio sensing** with **100× lower power**, and *Sirius* [5] provides RF-based **long-range self-localization** with **1000× energy efficiency**, enabling sustainable sensor networks in agriculture and environmental monitoring.

Scalable nextG Systems: Effective tracking of small assets, from personal items to fresh produce in supply chains, requires battery-free, compact sensors operational at a nationwide scale. My research introduces *LiTEfoot* [6], a system that combines **GPS-like accuracy with RFID-like form factor**, enabling sticker tags for location monitoring using cellular towers. This innovation supports applications such as supply chain management, geofencing for vulnerable populations, and personal asset tracking. For infrastructure-free scenarios, I developed *Locate3D* [7], a peer-to-peer localization framework that can **track 100,000 devices in urban environments** with 75% lower latency, facilitating large-scale operations like disaster recovery.

Systems for Sustainability: Approximately 30% of harvested food is wasted globally while 10% of the population faces hunger. Traditional food health monitoring systems are invasive and labor-intensive, making them unsuitable for large-scale deployment. I developed FreshSense [8], a wireless sensing system that **monitors food quality at the pallet level non-invasively**, tracking freshness and generating 3D spoilage maps for items like cheese and lettuce. Developed in collaboration with Microsoft Research, FreshSense integrates real-time assessments into supply chains, demonstrating potential to significantly reduce post-harvest losses.

Next, I elaborate on some of my research contributions, followed by my plans for future research.

A Structure-Assisted Spatial Intelligence

Spatial perception systems fundamentally rely on sensor arrays spanning multiple wavelengths, consuming 100s of mW power and substantial space. This dependency on arrays creates a critical barrier for **resource-constrained devices** like micro-robots and IoT sensors. I developed a radically different approach that achieves spatial sensing without arrays by combining **intelligent passive structures** with minimal active components. These structures perform initial neural-like signal processing, reducing the computational and power requirements of subsequent digital processing.

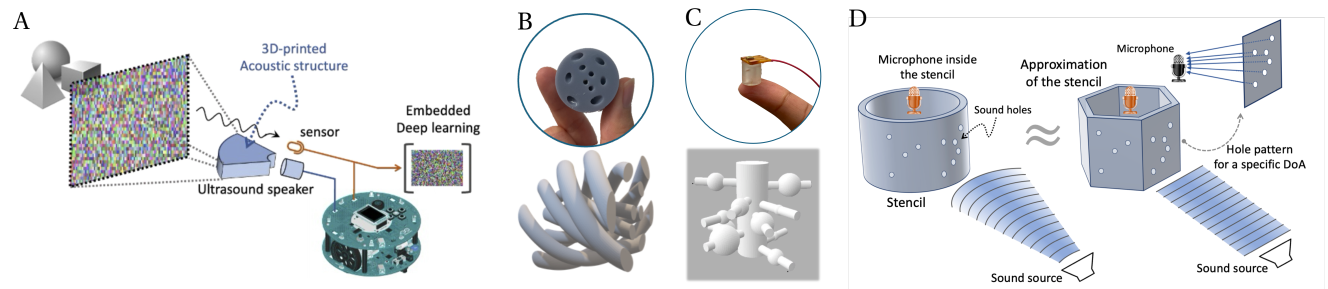

Figure 1: Structure-assisted sensing systems: (A) *SPiDR*'s depth imaging using 3D-printed acoustic metamaterial, (B) *SPiDR*'s acoustic stencil and its internal spatial filtering channels, (C) *Owlet*'s acoustic stencil and its internal direction-finding channels, (D) *Owlet*'s direction finding with passive acoustic structures.

Bio-inspired Spatial Audio Sensing [4,9,10]: Direction finding in acoustic systems requires multiple synchronized microphones separated by half-wavelength distances. While reducing the number of microphones is possible, it fundamentally compromises angular resolution and noise resilience. Drawing inspiration from nature - how owls achieve precise sound localization through asymmetric ear structures, I developed *Owlet* - a system that fundamentally reimagines direction estimation. The key insight lies in leveraging **diffraction and Helmholtz resonance** through carefully designed 3D-printed metamaterials to create direction-dependent acoustic filtering (Figure 1). By wrapping a single microphone with a structured pattern of holes and resonant cavities, each direction creates a unique signature. I solved the critical challenge of environmental robustness through a novel two-microphone architecture that eliminates both source and environmental dependencies. The system achieves 3.6° error - **matching a 9-microphone array while using** 100× **less power**. Extending this approach to spectral analysis, I drew inspiration from how the human cochlea naturally decomposes sound into frequencies. Using **standing wave resonators** that leverage wave interference patterns, *Lyra* achieves FFT-like spectral analysis without power-hungry ADCs or digital processing, enabling always-on acoustic monitoring with microwatt power consumption. Please watch the demo at https://youtu.be/ig45lHUjvjs?si=IjzzJZxDca9xv1zq.

Vision for Ubiquitous Tiny Robots [3,11–13]: Insect-scale robots operating in unknown environments require depth perception for navigation, but existing solutions like LiDAR and ultrasound arrays are power-hungry (100s of mW) and large (>10cm). The key challenge lies in achieving high-resolution spatial sensing without mechanical scanning or multiple synchronized sensors. Drawing inspiration from computational imaging, I developed *SPiDR* - a fundamentally new approach to depth perception using a single microphone-speaker pair. The key idea is to **spatially encoding the channel** through a metamaterial "stencil" that creates unique acoustic signatures for each point in 3D space. These physics-optimized waveguides embed both direction and distance information in single measurements, eliminating the need for scanning or arrays. Through sparse recovery algorithms informed by wave interference, *SPiDR* achieves **centimeter-level depth accuracy** while consuming only 0.83mJ per frame - **a 400× improvement** over traditional solutions. This work establishes new possibilities for perception in resource-constrained robotics.

RF Self-localization for IoT [5, 14]: Building on *Owlet*'s and *SPiDR*'s success in structure-assisted spatial coding, I extended these principles to RF signals with *Sirius*. Large-scale tracking of IoT devices across agriculture fields, supply chains, and wildlife habitats demands low-power localization, but existing solutions require either power-hungry GPS ($25mJ$ per fix) or complex infrastructure. While passive structures worked well for acoustic sensing, the small wavelength diversity in RF due to light's high speed necessitates a different approach. I developed a **gain-pattern reconfigurable antenna** that dynamically embeds direction-specific codes in received signals. Recent advances show envelope detectors enable ultra-low-power communication, but they cannot extract phase information needed for spatial sensing. I solved this through a novel neural pipeline that learns to decode spatial information directly from signal amplitudes, achieving 7° error while consuming **1000× less-energy** than array-based positioning systems.

B Scalable Collaborative Positioning for Next Billion Devices

From tracking perishable goods to monitoring elderly patients with dementia, continuous location tracking of small assets and individuals has become critical. However, existing solutions like GPS rely on batteries or infrastructure, creating fundamental barriers to widespread deployment. I developed two complementary systems that reimagine global positioning for resource-constrained scenarios, enabling seamless tracking from nationwide supply chains to dense urban environments.

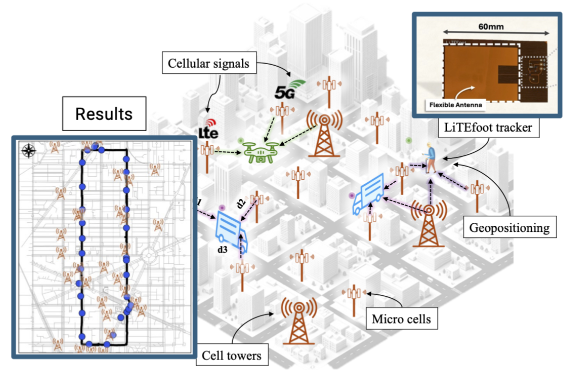

Figure 2: *LiTEfoot* leverages cellular signals for nationwide tracking using an ultra-low-power miniaturized receiver.

Ultra-low-power Location Tracking [6, 15]: Traditional cellular localization requires frequency hopping across multi-GHz bandwidths using power-hungry oscillators and IQ demodulators consuming over 100mW. I developed *LiTEfoot*, a cellular-based self-localization system that uses non-linear intermodulation to simultaneously **capture synchronization signals across 3GHz** through a passive envelope detector. The system decodes Physical Cell Identities from the folded spectrum and performs multilateration, achieving 19m accuracy while consuming only 40μJ - a **625× reduction compared to GPS**. This enables 11-year operation on a coin cell battery for nationwide asset tracking in supply chains, precision agriculture, wildlife conservation and healthcare monitoring, all without requiring dedicated infrastructure.

Infrastructure-free 6DoF Tracking at Scale [7, 16]: I developed *Locate3D*, a peer-to-peer system enabling infrastructure-free 6DoF tracking using UWB radios for massive-scale networks. The system introduces angle measurements alongside ranging to reduce the minimum edges needed for unique topology realization by 4×. Using my rigidity-aware spanning tree optimization and non-rigid graph decomposition, *Locate3D* achieves 0.86m accuracy in building-scale networks and 12.09m in city-scale deployments while reducing latency by 75%. The system seamlessly scales to **track 100,000 devices across across cities**, enabling transformative applications from coordinating disaster response teams to managing autonomous delivery fleets and monitoring smart city infrastructure.

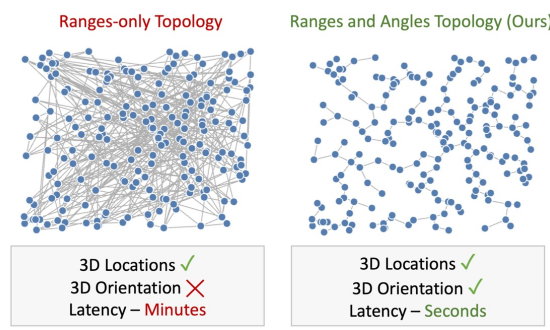

Figure 3: *Locate3D* enables infrastructure-free tracking at scale through optimized peer-to-peer measurements.

C Systems for Sustainability

While 800 million people face hunger globally, nearly 40% of food produced is lost to waste, primarily due to inadequate monitoring during distribution. In collaboration with Microsoft Research, I developed transformative sensing systems to enable data-driven food quality monitoring across global supply chains.

Non-invasive Food Quality Monitoring [8]: Current food quality assessment methods are invasive, making continuous monitoring challenging. I developed FreshSense, a wireless sensing system that **monitors dry matter content non-invasively at the pallet level.** The key challenge lies in measuring subtle changes in water content through densely-packed produce where traditional RF sensing fails due to complex multi-path effects. I solved this through a novel dispersion-based sensing approach that exploits frequency-dependent wave propagation in water-rich environments. By analyzing these electromagnetic delays with physics-informed neural networks, FreshSense achieves robust quality assessment while eliminating environmental variations.

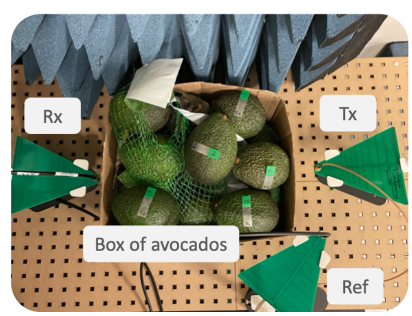

Figure 4: Non-invasive food quality sensing using RF dispersion through densely-packed produce.

Building on this foundation, I am developing **RF tomography for 3D reconstruction** of food quality within pallets. The key innovation lies in formulating radio propagation through heterogeneous media as an inverse scattering problem, combining principles from diffraction tomography and Neural Radiance Fields (NeRF). Our approach leverages a physicsconstrained neural architecture that models electromagnetic wave diffraction and material-dependent dispersion effects. Through adaptive beamforming and differentiable volumetric rendering techniques inspired by NeRF, we create high-resolution 3D maps of dielectric variations that indicate food quality. This system enables precise localization of spoilage zones in densely-packed food pallets - from identifying moisture clusters in grain containers to detecting quality variations in cheese wheels - without requiring package opening or manual inspection. By using commodity 2.4 GHz radios, our solution seamlessly integrates into existing supply chain infrastructure, enabling automated, maintenance-free monitoring that could dramatically reduce waste in global food distribution networks.

D Embedded AI and Security Works

I have also developed novel solutions across **security, AI verification, and audio processing**, demonstrating the breadth and impact of my research:

Security and Self-defense for Drones [17]: As drones emerge as trusted delivery systems and law enforcement tools, they become targets of mid-air attacks and vandalism. I developed DopplerDodge, a novel acoustic sensing system enabling low-power, real-time threat detection and avoidance in resource-constrained drones. Using just a single microphone and doppler effect based techniques, the system achieves perfect accuracy in detecting incoming projectiles with 100ms advance warning, enabling autonomous evasive maneuvers while consuming minimal power. This work establishes a new direction in embedded defense systems for tiny autonomous vehicles.

Side-channel Security in Embedded AI Devices [18]: With the proliferation of edge AI, verifying the trustworthiness of model inference is critical. I developed ThermWare, leveraging thermal side-channels to detect anomalous computations in embedded AI systems. By capturing fine-grained spatiotemporal heat signatures with a thermal camera, the system identifies unauthorized operations with 94% accuracy, enabling non-invasive run-time AI model monitoring. This approach offers a novel way to verify edge AI systems without requiring system-level access or modifications.

Noise-cancellation in Intelligent Earables [19]: To improve voice communication in noisy environments, I developed VoiceFind, a speech enhancement system that uses just two microphones to achieve spatial filtering of desired speech. Through a novel combination of harmonic-based direction finding and conditional generative adversarial networks (cGANs), the system improves speech intelligibility by 16% in real-world environments. This work demonstrates how physics-informed machine learning can enable sophisticated audio processing on resource-constrained wearables.

Future Directions

My research advances **healthcare, agriculture, and communication** through sustainable intelligent systems, including:

In-body and Wearable Health Monitoring: Current medical devices face fundamental challenges in continuous monitoring - from power constraints in implants to signal quality in wearables. One promising approach is to leverage acoustic backscatter for ultra-low power communication from in-body sensors, enabling continuous glucose monitoring and early disease detection. For wearables, direction-aware earables could enable selective hearing aids that isolate conversations while monitoring vital signs. By combining physics-aware neural architectures with novel backscatter techniques, we can achieve orders of magnitude improvements in battery life while maintaining clinical-grade sensing accuracy.

Precision Agriculture and Food Security: Global agriculture needs to increase food production by 70% by 2050 while using fewer resources. Traditional monitoring solutions using drones or manual inspection don't scale. My approach is to repurpose existing wireless infrastructure - cellular networks and satellite constellations - for agricultural sensing. A key insight is that ambient signals' interaction with crops contains rich information about soil moisture and plant health. While these signals were designed for communication, not sensing, novel AI techniques can extract reliable measurements even at low SNRs. This enables continuous crop monitoring at unprecedented scales with minimal infrastructure cost, making data-driven agriculture accessible to farmers worldwide.

Spatial Intelligence for Large AI Models: While modern AI systems excel at processing and understanding content, they fundamentally lack the ability to reason about spatial context - a crucial aspect of human intelligence. Building on my work in direction-aware acoustic sensing (*Owlet*), I aim to develop foundational techniques for integrating spatial awareness into large models. This involves creating physics-informed neural architectures that can process and reason about spatial signals, developing efficient spatiotemporal attention mechanisms, and designing novel multi-modal fusion techniques that combine spatial and semantic understanding. A key focus will be on developing representations that can capture both the content and spatial characteristics of real-world signals while maintaining computational efficiency on resource-constrained devices. This research will enable transformative applications - from **intelligent meeting assistants** that can track and attribute speech to specific participants, to context-aware AR systems that can understand and respond to spatial queries about the environment.

Next-Generation Communication and Sensing: Traditional wireless systems treat sensing and communication as independent functions, leading to inefficient spectrum and energy use. I aim to develop unified architectures that jointly optimize sensing and communication. By embedding sensing capabilities within communication signals, we can achieve simultaneous ranging, imaging, and data transfer.

Longer-term Frontiers: Looking toward the horizon, I am excited to explore several moonshot ideas:

Space IoT: Enabling ultra-low power communication and sensing in low Earth orbit satellite networks through novel physical layer designs. By exploiting predictable orbital dynamics, satellites achieve efficient channel estimation and network synchronization. This reduces power consumption of space-based sensors by orders of magnitude, enabling global environmental monitoring and connecting 2 billion people without internet access.

Neuromorphic 3D Perception: Creating event-driven sensing architectures that achieve efficient 3D reconstruction through biologically-inspired processing. By combining ultra-low power analog computing with adaptive sampling, these systems could enable real-time 3D perception in micro-scale devices.

More broadly, I strive to create transformative technologies addressing fundamental challenges in healthcare, food security, and sustainability. My goal is to enable systems that operate autonomously for years, providing unprecedented insights into human and environmental health.

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