Research Statement

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My research is at the intersection of wireless, mobile and cyber-physical systems. The goal of my research is to **empower the low-power Internet-of-Things(IoT) sensors deployed on earth and space by enabling better connectivity, sensing capability and scalability**. My projects develop novel wireless physical layer solutions that co-optimize higher layer network and application objectives of the city-wide low-power wide area network infrastructure with the client throughput. Such approach improves the range, battery life and throughput of IoT clients and reduces latency for data-driven inference applications at scale such as forest fire detection and real-time satellite monitoring. My work has been published at premier cyber-physical systems and mobile systems venues like IPSN, NSDI, MobiCom, and ICC. My papers have received the Best Paper Awards at IPSN 2018 and IPSN 2020. My talk was awarded the Best Presentation Award at the IPSN PhD Forum 2020. I have also received the ACM SIGBED-SIGSOFT Frank Anger Memorial Award 2021 for my cross-disciplinary research across embedded systems and software engineering. My work on IoT security and privacy was recognized with the CyLab Presidential Fellowship 2020-21.

My research focuses on improving the capabilities of IoT wireless technologies for smart cities and satellite connectivity. IoT deployments are inherently asymmetric where more resourceful base stations and cloud infrastructure lie on the other side of a IoT clients' bandwidth starved link. This precludes the possibility of data-driven applications on IoT deployments for large scale sensing such as smart agriculture, automated traffic signals and micro-climate monitoring. While some smart-home sensors can communicate large amounts of data to enable low-latency complex inference applications, the big data revolution has eluded low-power IoT sensors from realizing their true potential.

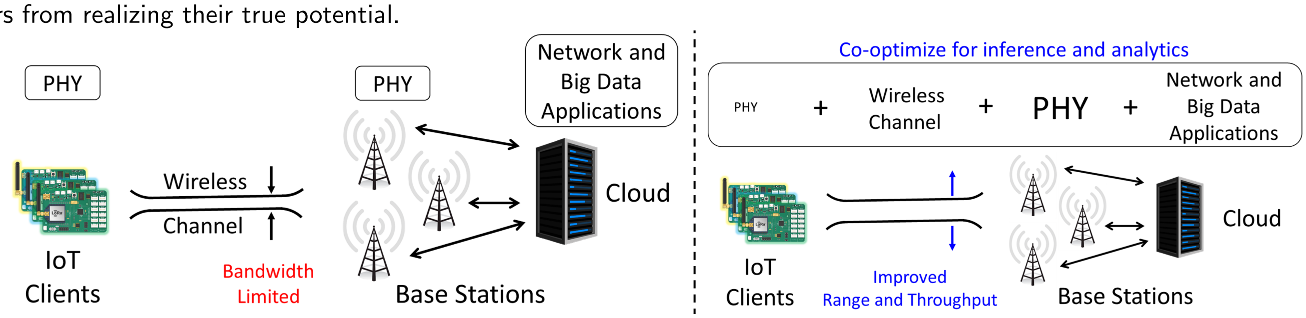

Figure 1: While traditional research has focused on improving the wireless and higher level application objectives in silos, my work enables big data analytics on long-range low-power IoT sensors by co-optimizing these components together and enabling robust base station collaboration to reduce client wireless burden.

My research overcomes fundamental limitations of IoT wireless technologies and builds systems that enable such data driven applications at scale. Firstly, we develop solutions that can push the wireless and compute operations from these low-power IoT clients to the much more powerful base stations. We further take a cross-layer approach to enable data-driven applications on these IoT sensors at scale by **co-optimizing their wireless physical layer to improve client range and throughput while reducing latency for higher level network and inference objectives**. My solutions apply these principles for improving low-power wide-area networks (LP-WANs), a class of low-power IoT technologies with 10 km range and 10 year battery lives but low throughput ($\sim$ few kbps), where this asymmetry is particularly stark. My approach has pushed the capabilities of low-power IoT by:

Improving client throughput and range: We enable base station collaboration which allows us to push components of the physical layer from the clients to the base stations and the shared cloud infrastructure. This off-loading of the IoT client physical layer operations, e.g. frequency selection, can improve the range and throughput by $4\times$ and triple client battery lives [1, 2]. This collaborative base station framework can also enable decameter-level location tracking [3].

Enabling inference on terrestrial deployments at scale: We co-design the client physical layer with the inference models to optimize for inference quality within the constraints of client limits. Our solution QuAiL [4] builds a distributed LP-WAN physical layer that can perform complex low-latency statistical, spatial and inference queries from thousands of clients. It can be extended to perform time-series analytics with reduction in energy cost [5].

Enabling low-latency inference on LoRa-enabled CubeSats: Another context where low-power clients face similar throughput bottlenecks are small satellites operating in low-earth orbit, popularly known as CubeSats. We show that by co-designing higher level data-driven applications with the limitations of the LoRa satellite-to-ground-station physical layer can lead to multi-fold improvement in inference quality [6].

My solutions were deployed and evaluated on a multi-base station testbed spanning the city of Pittsburgh. Further, my research on LoRa-enabled CubeSats was evaluated on traces from a LoRa-enabled CubeSat V-R3X launched in collaboration with NASA. Our research has built several artifacts that have been broadly adapted by the community – large-scale measurement studies, open hardware platforms for base stations and clients, and open-source code and data for all our solutions. My research on low-power IoT has featured in the popular press - IEEE ComSoc Blog, 90.5 FM WESA, Washington Post. My ongoing work with Microsoft Azure Global has been filed for patent and under way to be productized with the potential to save hundreds of thousands of dollars for sellers, customers and the supply chain companies.

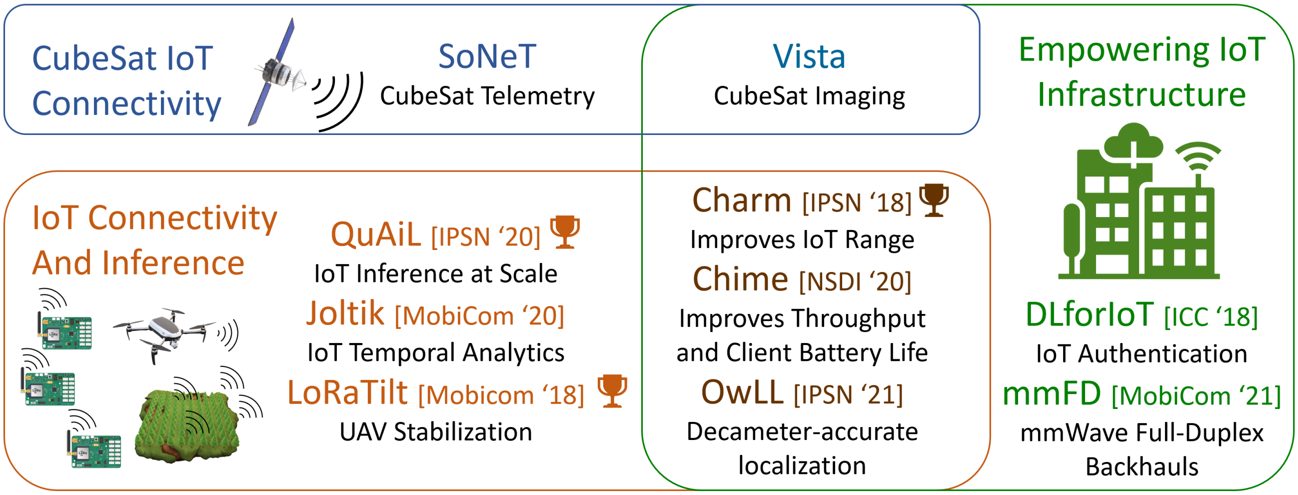

Figure 2: My research has developed novel wireless solutions for empowering low-power IoT deployed on earth and space by: (1) improving IoT client range, throughput and battery life; (2) enabling low-latency temporal, spatial, and inference analytics at scale for IoT technologies; (3) enabling fine-grained imaging and practical inference for CubeSats

Improving low-power IoT client communication and base station collaboration

An important objective for any LP-WAN deployment is to maximize the throughput and battery-life of the clients. Yet, maximizing the efficiency of low-power IoT clients leveraging existing infrastructure and limited spectrum would require collaboration and ability to co-optimize service for the growing number of wireless sensors. Such collaboration can only be possible with synchronization between the base stations, an efficient compute resource for optimization and a robust backhaul to connect the base stations to the compute resource.

My approach builds a synchronization framework for LoRa base stations that enables each of them to measure the phase of the same packet relative to a master base station. This unleashes the untapped potential of phase-based solutions for low-power IoT devices. Our evaluation on the multi-base station deployment demonstrates that these distributed phase measurements can be leveraged to enable automated radio configuration to improve throughput (Chime [1]), coherent combining to quadruple the range (Charm [2]) and accurate localization of clients upto a few meters (OwLL [3]).

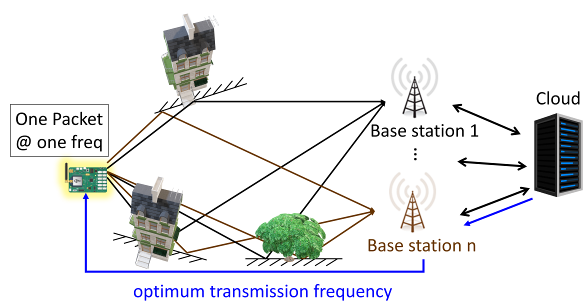

Figure 3: Chime enables base-station collaboration and leverages cloud to perform automated radio configuration for LP-WANs

While cloud is a perfect compute resource for LoRa especially due to lax latency constraints, it requires distributed base stations to receive wireless signals and haul them to the cloud. We build a custom hardware-platform for the base station [2] that can data-efficiently stream the received wireless signals and retrieve the output of the computation. Finally, to enable efficient wireless backhaul for remote base stations, we present the first bidirectional mmWave full-duplex communication system that can lead 1.67× improvement in throughput for links to the cloud (mmFD [7]).

Enabling inference applications on terrestrial low-power IoT deployments

An important impediment to develop sensing and inference applications with increasing number of clients is the ability to retrieve information from them. Traditional approaches of retrieval are either too latency intensive or do not scale when the number of clients becomes large (hundreds to thousands). Unlike prior approaches that focus on individual client or developing data-efficient inference algorithms, my approach co-optimizes the wireless physical layer for information retrieval and inference simultaneously.

A key observation that drives my approach is that performing an inference query on a large deployment only requires a small linear projection of the vast raw data. My solution QuAiL [4] identifies when packets of all clients are transmitted simultaneously, their energies add up linearly at an average. Thus, we develop a distributed wireless physical layer than ensures robust, channel-aware collisions from thousands of clients. We show how this linear wireless layer can substitute the first layer of inference on popularly used

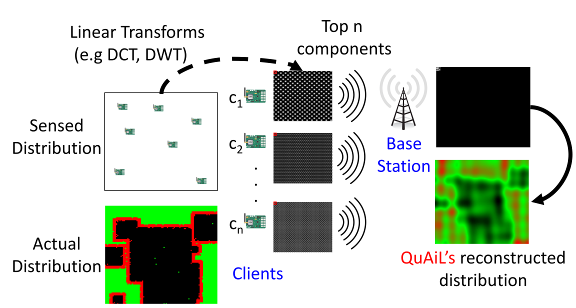

Figure 4: QuAiL builds a distributed wireless physical layer to perform spatial and big data analytics on low-power IoT sensors at scale

statistical, spatial and machine learning inference queries. Our evaluation shows a latency of several milliseconds to retrieve information from tens of thousands of nodes, significantly better than the state-of-the-art.

Another important type of data analysis typically performed on measured values of these low-power IoT sensors are temporal analytics. Unfortunately, transmitting large swaths of time-series data over the bandwidth-bottlenecked links is infeasible. However, we make a key observation that most of these temporal statistics are simple functions of the frequency distribution of the sensed value. We leverage this insight and recent advances in universal sketching to build a constant size encoding to capture these distributions. Our evaluation shows that such energy-efficient aggregation over time reduces the power consumption for temporal analytics from these low-power sensors by 24.7× (Joltik [5]).

Low-latency inference on LoRa-enabled CubeSats

The advent of small and cheap-to-deploy satellites, known as CubeSats, in the low-earth orbit is opening up new opportunities to study the behavior of satellite communication links and improve their capabilities. One key problem that most satellite deployments face is that of latency. Using proprietary technologies allows space companies to enable high downlink throughput at the cost of deploying costly specialized base stations. However, a recent trend, particularly adapted by new entrants in the CubeSat domain, is the use of existing long range communication infrastructure of LoRa to communicate with the satellites.

While the global prevalance of LoRa ground station infrastructure reduces the latency of downlink, it does so at a drastic cost of throughput. This problem is further exacerbated by the fact that such low-power IoT technologies were not designed to communicate with fast moving CubeSats. While these satellites are still being improved, most of them communicate only paltry diagnostic data or location data every hour. We instead ask a simple question,"How do we design practical LoRa-enabled CubeSats using existing ground infrastructure for rich applications including satellite imagery?"

Our solution Vista [6] achieves this by co-designing the wireless physical layer and the compression-based inference algorithms. Specifically, we leverage the existing knowledge of images, tasks and the wireless channels to encode the image information optimally. Our data-task-channel aware auto-encoder optimizes for inference output and also ensures resilience to wireless channel losses over the air. We also develop solutions at the ground infrastructure to enhance the Doppler resilience of the CubeSat packet. Our evaluation on real channel-traces retrieved from LoRa-enabled CubeSat V-R3X, show that Vista can provide an effective 4.56 dB improvement in image retrieval SNR and 1.38× improvement in classification tasks over the image.

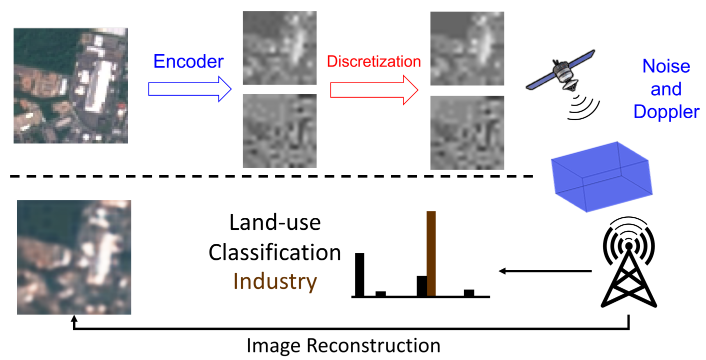

Figure 5: Vista builds data-driven channel-aware encoding scheme and performs trajectory estimation to enable imaging inference atop LoRa-enabled CubeSats

Future Work

While much of my current work has focused on improving communication for LP-WANs, my future work will focus on building systems for new and upcoming industries where wireless research has just scraped the surface of its true potential. These industries such as satellites and automated farming are undergoing a technological revolution, with democratization of research with the reduction in cost of satellite launches and development of new wireless sensing technologies such as mmWave and ultra wide-band radars. My research will bring my expertise in wireless, mobile and cyber-physical systems to tackle the essential problems of these industries in the connected future.

Satellite Constellations: We are undergoing a space exploration revolution with a multi-fold increase in the investment for deploying communication, imaging and exploration satellites. This expansion has triggered the rise of new paradigms of computation and wireless communication such as CubeSat Swarms and Starlink constellation for providing internet connectivity. Further, the ubiquitous availability of data and CubeSat deployments has brought the possibility of performing wireless physical layer innovations for satellites finally in the public domain. My research would leverage my pre-existing experience in communicating with satellites, to explore critical design decisions about the right wireless framework to communicate with these novel constellation deployments. I would also investigate the potential implications of having multiple constellations in the sky for improving base station design as well as applications atop received data.

Multi-Modal Sensing and Inference for Industry: With the advent of Industry 4.0, Internet-of-Things is gradually permeating the physical processes and operations by bringing in the gains of data-driven solutions. Yet, today's popular solutions use existing technologies to provide connectivity and sensing capabilities instead of redesigning technologies to maximize utility in the industry. My ongoing research [8] in the supply chain industry, in collaboration with Microsoft Research, identifies that a multi-modal design for specialized industry tasks such as damage detection can improve efficiency multi-fold and save hundreds of thousands of dollars for sellers, customers and the supply chain company. Further, in the coming years, with wireless technologies, ranging from battery-free RF-ID stickers to 60 GHz WiFi, pervading the industry environment, my research will build multi-modal sensing systems that will enable early-detection systems that monitor the interaction of workers with automated equipment and robots detecting anomalies before they can cause physical harm.

Sensing Plant Health for Automated Farming: As the population of the world increases, it is becoming more and more critical to improve food generation and supply chain to enable a good quality of life for everyone on the planet. Yet, while improving and optimizing supply chain issues is indeed critical as stated above, another approach touted to succeed in this direction has been automated farming. Indeed, there has been tremendous investment and innovation in the area of sensing farm and plant health from both the government and enterprise equally. Yet, most solutions today perform latent sensing of plant health by measuring the soil, atmosphere and weather as alibi of plant health. However, with the advent of mmWave and ultra-wide band radars, there is an opportunity to actively sense plant behavior in situ. My research will develop plant imaging and health analytics systems ($\sim$similar to X-Ray or MRI in humans) that detect and address plant health actively in an automated manner.

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