Research Statement

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> "It is generally not possible for radios to receive and transmit on the same frequency band because of the interference that results." Wireless Communication, Andrea Goldsmith, 2005 [16].

Professor Goldsmith's quote captures a long held assumption in wireless communication that a full-duplex radio, or a radio that can transmit and receive at the same time on the same frequency, was impossible to create. My research invalidates this fundamental assumption. The key challenge in full-duplex radios is that the radio's own transmitted signal causes a strong interference to the signal that it is trying to receive. I designed and prototyped new techniques to infer and completely cancel this *self-interference*, thus enabling devices that can transmit and receive simultaneously in the same frequency band. This set of techniques, referred to as self-interference cancellation, immediately doubles the spectral efficiency. I played a leading role in commercializing this research at a startup, and the product underwent successful commercial field trials by major Tier 1 network providers worldwide. Thus in a span of six years, full duplex radios went from being considered impossible to being commercially deployed.

A surprising realization during the course of my research was that the ability to listen while transmitting is a fundamental capability which has applications well beyond full duplex communication. For example, if a relay wants to receive a signal from a neighboring node and simultaneously transmit the same signal to another node, or if a radar wants to receive the reflections of it's transmitted signal, in both cases, it faces the challenge of receiving while transmitting. However, in each of these scenarios, we cannot apply directly the cancellation techniques developed for full-duplex communication. The next major contribution of my research is to *enhance and develop the fundamental techniques of self-interference cancellation as tools, upon which a variety of systems can be built in wireless networks, wireless sensing, IoT connectivity and virtual reality.*

Stepping back, my longer term research vision is to design robust and efficient wireless networks and wireless sensing technologies that will form the bedrock of our connected world. Motivated by this vision, my approach is to identify research problems that serve as the fundamental primitives. This approach will not only solve bottlenecks in existing systems but also lead to the design of new systems. This is evident from my work on self-interference cancellation which was a fundamental primitive to solve the lack of available spectrum as well as enable new wireless sensing modalities. My approach to solve problems is three-fold. First, I break a problem into multiple tractable sub-problems. Next, I formulate a mathematical framework to understand each one. Finally, I solve each of them by drawing on techniques from different areas of systems (hardware and circuit design), mathematics and theory (compressed sensing, queuing theory, signal processing, circuit theory, information theory and communication theory). Solving the self-interference cancellation problem required a hybrid cancellation design that canceled interference via two successive stages of analog and digital cancellation, and required the combination of signal processing, optimization and circuit design to build a practical solution.

My work naturally bridges techniques from EE, CS and Math to provide innovative solutions in other domains as well. For example, my work on new relaying algorithms led to the design of a wireless virtual reality headset. Inference algorithms built on top of my work on estimating self-interference using super resolution algorithms formed fundamental primitives to build a low power IoT connectivity solution using backscatter. My future work will embody this inter-disciplinary approach. Finally, I strongly believe in translating research lab-prototypes into real world products to create a meaningful impact. In particular, I have already done this with my research on full-duplex radios.

Research impact

My research work has appeared at top conferences in networking [MobiCom'11, SIGCOMM'13, HOTNETS'13, NSDI'14, SIGCOMM'14a, SIGCOMM '14b, NSDI '15, SIGCOMM '15a, SIGCOMM '15b, SIGCOMM '16a, SIGCOMM '16b, HOTNETS '16, SENSYS '16, NSDI '17] and some of this work has already translated into industry products. The research has also won several awards, including a MIT TR35 [5] and Paul Baron Young Scholar Award [4]. Beyond this, it has succeeded in generating excitemnent in the popular press, the research on full duplex radios has been covered by MIT Technology Review [3, 2], Wall Street Journal [15], Techcruch [6], EEtimes [10], RCR wireless [13], CNBC [7], Fierce Wireless [11, 12], and other media outlets.

Due to its potential to double spectral efficiency, our work on full duplex radios received tremendous interest from industry, academia and venture capital. My research formed the foundation of a startup Kumu Networks, which was able to raise $55 million in funding [8] from leading venture capital firms to commercialize full duplex radio technology. At Kumu Networks, I led the technology (both architecture and algorithm design) for in-band full duplex radios to build a commercial product [1]. The product completed successful field trials with major Tier 1 network providers – Deutsche Telekom [9] and SK Telecom [14] and is now being commercially deployed. To this date, it is the only successful commercial demonstration of full duplex radios.

Due to its proven commercial viability and promise, full duplex is now actively being designed into next-generation wireless standards. Both 5G cellular and next-generation WiFi standards are incorporating full duplex or self-interference cancellation technology in various forms.

Research Contributions

My research spans wireless networks, wireless sensing and data-center networking. The common theme of my research has been to build self-interference cancellation techniques, and enhance them to enable a variety of applications in wireless networks, wireless sensing, low power IoT connectivity and virtual reality. Below I briefly describe my past work.

(a) Full Duplex Radios

A long held precept of radio design is that radios cannot simultaneously transmit and receive on the same frequency due to the enormous amount of self-interference from the transmitted signal to the received signal, quite similar to how we cannot hear a weak whisper when we are shouting. The fundamental challenge in achieving full-duplex radios is that the radio's own transmission acts as a strong self-interference to the signal it's trying to receive. In fact, this self-interference is 100 billion times stronger than the receive signal and hence has left this problem open for many decades. Furthermore, the self-interference is a function of the environment in which radio is placed, and therefore changes dynamically. Thus, to be able to enable full-duplex radios, one needs to continuously estimate the self-interference and dynamically cancel it.

My key observation in tackling this problem was that self-interference cancellation required a mixed-signal approach, i.e it needed a combination of analog and digital cancellation techniques. Self-interference is too strong to be cancelled in a single domain alone, cancelling purely in analog is impossible given the imprecision and noise naturally involved in analog circuits, while cancelling completely in digital would require prohibitive power consumption in the analog domain to digitize the self-interference as well as the received signal. My work invented a novel analog RF circuit design and DSP(digital signal processing) algorithms that adaptively eliminate self-interference and enable full-duplex operation [MobiCom'11, SIGCOMM'13, SIGCOMM '14b], thus enabling single antenna full duplex radios.

However, all modern day radios use multiple antennas (also referred to as MIMO communication). The key challenge in achieving full-duplex MIMO operation is that each antenna's transmitted signal acts as self-interference to every other neighboring antenna as well. In an m-antenna MIMO radio, each antenna's transmitted signal is self-interference to itself and every other antennas, leading to a total of quadratic number of (m^2) self-interference components. Thus, we need m^2 cancellation circuits, *which is infeasible in practice due to cost and power constraints*. I designed a m-antenna full-duplex MIMO radio that can cancel all m^2 self-interference components with just m cancellation circuits [NSDI'14]. The key insight is that all the m-antenna's are close by, and hence they experience a similar environment, resulting in similar self-interference, thus allowing us to share the cancellation circuits across the antennas.

(b) Full Duplex Relays

Relays can be used to build scalable wireless networks. However, traditional relays either receive from the source or transmit to the destination, as they cannot transmit and receive at the same time. Hence, these relays can extend range, but at the loss of capacity due to the inability to both transmit and receive. The ability to receive while transmitting motivates the design of a new class of wireless repeaters. To this end, I designed a relay that operates in full-duplex mode called FastForward, which is the first design to not only provide the extension of range but also increase the capacity.

In contrast to full-duplex radios where the self-interference and the intended received signal are different and uncorrelated, in wireless repeaters, the signal being transmitted is same as the received signal. As a result, the self-interference and the signal received by relay are correlated. Thus, cancellation needs additional algorithms to dis-entangle the self-interference and signal received by relay. We built a novel cancellation technique that exploits the fact that the received signal and self-interference are separated in time domain, i.e. self-interference is a time delayed copy of the received signal. The cancellation algorithm builds a inference technique to separate the two signals with different time delay. We leveraged this technique to build FastForward, a new wireless relay design that can extend both the range and throughput simultaneously for WiFi and LTE networks.

FastForward relays were designed for WiFi and LTE networks that can provide hundreds of megabits of connectivity. Recently a newer radio technology using mm-wave frequencies such as WiGig is becoming viable which can be used to provide multi-gigabit (around 6Gbps) connectivity. This has exciting consequences for personal connectivity, for example it can be used to replace the HDMI cables that are needed to connect virtual reality (VR) headsets to the computer generating the VR content. However, mmWave/WiGig cannot provide untethered connectivity of 6 Gbps all the time; in fact, it can only provide this data-rate in line of sight scenarios using directional antennas and fails to work in scenarios with obstructions. Full duplex relaying for mm-wave links can solve this problem, the idea is to build a full duplex mm-wave relay that receives the signal from the VR content generator (typically a PC) and re-transmits it in the direction of the headset. The mmWave full duplex relay provides an additional direction to form LOS connectivity to the VR headset, deploying multiple of these mirrors will enable us to provide VR with untethered connectivity. The mmWave mirror was designed to be very cheap, consisting of directional receive and transmit antennas connected via an amplifier. It was the first full duplex relay to have no transceiver to adapt the gain of amplifier and beam direction of transmit and receive antenna and yet adapt such that throughput is maximized [NSDI'17, HOTNETS'16].

(c) Low power IoT connectivity

IoT devices need very low power connectivity to the Internet so they can be deployed for years without having to replace batteries. Further, IoT adoption can be accelerated if IoT devices can connect to widely used infrastructure such as WiFi access points, in other words if connectivity is via a standard WiFi AP used for regular WiFi connectivity and yet while consuming tens of microwatts of power consumption for IoT communication. My research tackled this problem via two systems: BackFi and HitchHike. BackFi is a novel system where low power IoT radios communicate by reflecting ambient WiFi signals back to the WiFi APs transmitting them. The reflections are modulated in such a manner as to communicate data from the IoT device. The challenge for the WiFi AP is to be able to listen to these weak reflections while still transmitting a regular WiFi packet to a standard WiFi client. This is again a self-interference problem, where the WiFi transmission acts as self-interference to the IoT signal being received. The challenge again is that the IoT signal is highly correlated to the WiFi signal being transmitted since the IoT radio is simply reflecting the same WiFi signal in a controlled manner. We built a new cancellation-inference technique which eliminates all the self-interference except the information embedded reflection [SIGCOMM'15a]. BackFi leverages this cancellation-inference and new decoding algorithms to decode the tag information. BackFi can backscatter all ubiquitous ongoing signals like WiFi, LTE, etc to provide IoT connectivity.

However a drawback of BackFi was that it required self-interference cancellation hardware at the WiFi APs which are not widely available yet. This motivated the next step in this research, could we provide IoT connectivity without making any changes to deployed devices? This led to HitchHike [SENSYS'16], a low power IoT connectivity system that can be deployed entirely using commodity WiFi infrastructure. With HitchHike, a low power tag reflects existing WiFi transmissions from a commodity WiFi transmitter, and the reflected signals looks like a standard WiFi packet and can be decoded by a commodity WiFi receiver. The key innovation is a novel technique called codeword translation, which allows a backscatter tag to embed its information on standard WiFi packets by just translating the original transmitted WiFi codeword to another valid WiFi codeword, in a low power fashion. This allows any WiFi receiver to decode the backscattered packet, thus opening the doors for widespread deployment of low-power backscatter communication using widely available WiFi infrastructure.

(d) Sensing using Wireless Signals

Self-interference is a function of the environment, and hence its cancellation was challenging as it changes with the environment. However this very challenge presents an opportunity, since self-interference structure encodes a lot of information about the environment such as the number of reflectors, which of them are static and mobile and so on. We leveraged our work on self-interference estimation to build a novel system: a motion tracking system using wireless signals, In my research, I built WiDeo, a novel system that enables accurate, high resolution device-free human motion tracking in indoor environments using WiFi signals. The key insight is that self-interference estimation and cancellation requires us to infer the nature of reflections from the environment and track them as they change. Instead of using this estimation to cancel, we use it to track moving objects. Since reflections from static objects do not change over time, we built novel algorithms that can eliminate this static "clutter" and isolate reflections from moving objects. The next step was to design algorithms that could analyze reflections from the moving objects and actually infer the underlying motion that produced these reflections. We solved this problem by using ideas from super-resolution and compressed sensing. We also demonstrated this system using a hardware prototype that performed human motion tracing and presented the research at [NSDI'15].

Current and Future Work

My research goal is to design and build high throughput, reliable and secure wireless networks that can form the connectivity fabric across objects, machines and humans. In particular, I would like to explore the following research topics in near future.

Connectivity for next generation applications

We are seeing two diverging trends that will drive the design of wireless networks in the next decade. On the one end is IoT and the need for ubiquitous, cheap, secure and very low-power connectivity. On the other end are applications like virtual and augmented reality or cellular back-haul which needs untethered, but very high throughput and low latency connectivity. My research will focus on building the fundamental building blocks along both these directions.

For very low-power connectivity, my vision is on building stacks that can optimize energy consumption holistically across sensing, compute and communication. Traditionally, each of these components has been built in an independent, modular fashion. While such an approach enables scalable development, the price we pay is in energy consumption. A cross-layer approach that takes a holistic look at how to lay out sensing, sampling, filtering and compression, communication and higher layer application tasks across the low power IoT device and the cloud can have significant impact on energy consumption.

On the other hand, applications such as augmented and virtual reality need high data-rate and low latency to stream real-time 360 degree video. The advent of newer spectrum (mmWave frequencies) with the availability of ample bandwidth provides an opportunity to provide multiple gigabits of data rate per link. However designing robust networks with such frequencies is challenging due to the propagation characteristics of RF signals in these frequencies. They are very susceptible to blockage for example and do not handle obstruction and reflections well. Building reliable networks that can leverage the bandwidth available at mm-wave frequencies to support these new demanding applications such as VR/AR will be my other focus in the are of connectivity.

Wireless sensing and imaging

Historically, research in wireless communication has been focused on optimizing connectivity. However, with the ubiquity of wireless networks and infrastructure, a second opportunity is emerging, that of using the wireless communication signals as a sensing modality themselves. In other words use the act of communication as a means to sense the environment itself. My research on inferring human motion using wireless signals is a step in this direction. But much work remains. I believe that one can build systems that can not just infer motion but image environments using wireless signals, opening up avenues such as the ability to see beyong walls or around corners. We can also measure and monitor conditions such as human vital statistics, sleep apnea, ECG and so on using wireless signals and their reflections. A second major focus of my research will be to design the building blocks that can enable us to sense motion, breathing, and imaging using wireless signals.

My philosophy in research is to build connections. I identify compelling practical problems, reconstruct them into more fundamental technical problems, and look for connections with areas across EE and CS to solve them. This approach will underpin my research regardless of the research problems I choose to work on.

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