Research Statement of Renjie Zhao

Bell's law of computer classes - roughly every decade a new, lower priced computer class forms based on a new programming platform, network, and interface - captures the evolution of computing platforms. Unlike the evolution from mainframe to personal computer which focused on building new computer architectures, the new computer class - Internet of Things (IoT) requires the development of radio communication interfaces and ubiquitous sensors. This makes IoT a very complicated system, involving design challenges in embedded systems, RF circuits, wireless networking, signal processing, etc.

My research tackles these challenges through a joint design of wireless system architectures and RF hardware. I build new hardware architectures, to enable novel communication and sensing schemes, which can address the root cause of IoT system performance issues. Such an approach is very challenging since it requires a thorough understanding of the whole system, from the application down to the analog and digital circuits. With this approach, I have made contributions to three areas of wireless IoT: (1) extremely low power communication; (2) highly reliable communication and sensing for industry IoT; (3) programmable experimental platforms.

My research has led to publications in the top conferences in computer networks and mobile computing (e.g., MobiCom [1, 2], SIGCOMM [3], and NSDI [4, 5]). My research has demonstrated impacts in both academia and the wireless industry. For example, M-Cube [2], the first massive MIMO Millimeter-Wave (mmWave) software radio, received the **Best Paper Award** in the ACM MobiCom'20 conference (2 out of 384 submissions) and has been highlighted by ACM GetMobile [6] (Top Picks of the ACM SIGMOBILE area). Since early 2021, **more than 15** research institutions have been using M-Cube to conduct research in mmWave communication and sensing.

I also believe that engaging the industry can help me identify important and timely research problems. Many of my recent projects target practical issues in the wireless and IoT industry. For example, NFC+ [3] and RF-CHORD [4] address the problems of high-reliability RFID in Alibaba's global logistic networks. UWB2 [7, 8] explores next-generation RFID targeting high-accuracy location-aware applications. Project ADR-X [9] solves the wireless link adaptation issue under high channel dynamics in Microsoft's Xbox gaming system. These projects are all under transitioning to the commercialization and product units.

My research is inherently interdisciplinary and I am a firm believer in collaboration. My recent works build on collaboration with academic researchers (University of Washington, Baylor University, University of California San Diego, Peking University, etc.), as well as the industry (e.g., Alibaba Group and Microsoft Research). I have also been working with researchers in the fields of material, neuroscience, bioengineering, and computer science from the University of California San Diego, Oregon Health and Science University, and Massachusetts General Hospital, to explore brain-sensing and brain-stimulating platforms. Such collaboration has led to innovative research outcomes and generated impacts beyond the field of wireless IoT.

1 Extremely low power communication

Maintaining the connectivity between the IoT fabric and the existing Internet infrastructure entails non-trivial human efforts, and will ultimately be feasible only if the IoT devices can sustain themselves, e.g., through RF energy harvesting. However, the existing COTS IoT communication hardware, such as BLE, ZigBee, LoRa, Wi-Fi, etc., consumes tens to hundreds of mW peak power, orders of magnitude higher than that available from RF energy harvesting. Their self-sustained operations are feasible only under an extremely low duty cycle (a few dozen bytes per day) or when supported by a bulky energy harvester (e.g., solar panel). I built two extremely low power IoT communication systems to address these challenges, which bring the power consumption down to µW regime.

High-scalability, high-concurrency backscatter communication. Backscatter communication shifts the power-hungry carrier generation from a low-profile client device (i.e., a *tag*) to a host device (i.e., a reader). It can achieve several Mbps throughput with a µW level power consumption on the tag. However, prior backscatter communication techniques fall short of scalability and concurrency, which are crucial for IoT scenarios with a massive number of tags. To address the requirements, I designed OFDMA-BS [1] which for the first time demonstrates how to enable Orthogonal Frequency-Division Multiple Access (OFDMA) in Wi-Fi backscatter for capacity and concurrency enhancement. The design is compatible with standard Wi-Fi and provides 1.45-5× capacity and 48× concurrency compared to the state-of-the-art.

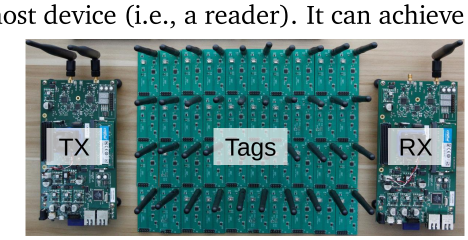

Figure 1: OFDMA-BS reader and tags.

Asymmetric communication for ultra-low-power IoT. To communicate with existing wireless infrastructures such as Wi-Fi, an IoT device needs to adopt a compatible PHY layer which entails sophisticated hardware and high power consumption. To break the tension, I designed SlimWiFi [5], a system that adopts a novel *asymmetric communication* scheme to realize Wi-Fi-compatible ULP radio. Through a careful codesign of the signal modulation scheme and reverse processing of the Wi-Fi data, SlimWiFi enables existing Wi-Fi access points to modulate/demodulate on-off keying (OOK) waveform sent by an extremely low-power IoT tag. With this measure, SlimWiFi radically simplifies the IoT radio architecture, evading power-hungry components such as data converters and high-stability carrier generators. Through collaboration with RFIC experts, we taped out the integrated chip version of SlimWiFi radio and verified it can perform active data transmission at sub-100 μW power, 3 orders of magnitude lower than standard IoT radios!

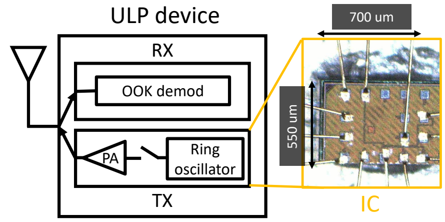

Figure 2: SlimWiFi ULP device.

2 High reliability communication and sensing

Ultra-high frequency (UHF) RFID, a widely deployed passive IoT technology, has been carrying the vision of automating item tracking across a logistic network. However, RFID is known to be unreliable for both object identification and localization due to the low signal strength and narrow bandwidth. For example, UHF RFID systems suffer from two long-standing problems: (1) miss-reading non-line-of-sight or misoriented tags and (2) cross-reading undesired, distant tags due to multi-path reflections. These hindrances lead to unacceptable loss, especially in large-scale supply chains and logistic networks as shown in Fig. 3. My research tackled the challenge of highly reliable RFID for industry IoT in three ways.

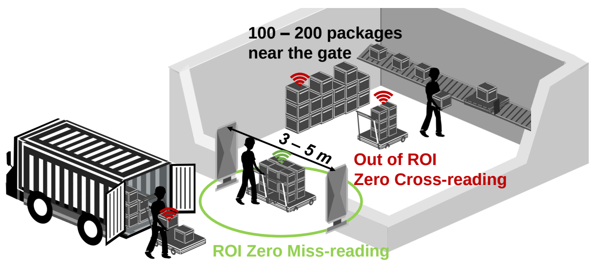

Figure 3: Package identification in logistic networks.

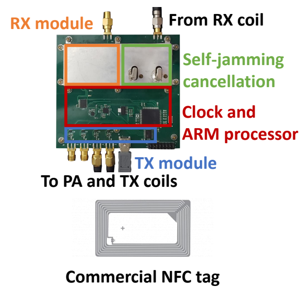

Figure 4: NFC+ reader and commercial NFC tag.

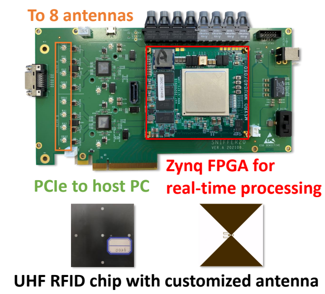

Figure 5: RF-Chord reader and UHF RFID tag.

Long range magnetic RFID for reliable object identification: Through collaboration with field workers and engineers in Alibaba, I found the root cause of the reliability issue lies in the UHF signal properties. The high carrier frequency electromagnetic signal will be inevitably blocked by RF-unfriendly items like water/metal containers (which leads to miss-reading), and will experience strong reflections in the indoor environment (which leads to cross-reading). Therefore, I designed a novel system called NFC+ [3] which makes use of the lower carrier frequency magnetic waves of near-field communication (NFC) systems. Traditional NFC systems work in a very short range, which has hampered their deployment in practice. In contrast, NFC+ is a new NFC reader hardware architecture, leveraging resonance engineering and MIMO techniques to reach commercial NFC tags at a long range. Compared to UHF RFID, NFC+ can reduce the miss-reading rate from 23% to 0.03%, and the cross-reading rate from 42% to 0, for randomly oriented objects within a range of 3 meters. NFC+ works even in RF-adverse settings, e.g., tracking water bottles and objects shielded by metal. NFC+ is in the process of being integrated into Alibaba's latest logistic network for online shopping, grocery delivery and local life services.

Multi-antenna wideband UHF RFID for reliable localization: Due to lower tag cost and higher reading speed, standard UHF RFID is preferable when the target objects are RF-friendly (i.e., miss-reading is not severe). To improve the reliability of UHF RFID, my research investigates the question: can we filter out the cross-read distant tag through UHF RFID localization? Although many UHF RFID localization techniques are proposed, they are not reliable enough for industry settings, due to RFID's narrow bandwidth and hence coarse time/distance resolution. In RF-CHORD [4], my co-authors and I designed our own UHF RFID sniffer hardware which can capture the tag signal across multiple antennas and wide bandwidth. We further incorporated FPGA and GPU acceleration to process the signal in real time. Combined with a multipath-suppression algorithm, RF-CHORD can determine whether the tag is in the range of interest with extremely high confidence. It can localize up to 180 tags 6 m away from a reader within 1 second and with a 99th long tail error of 0.786 m. RF-CHORD was demonstrated at Alibaba Apsara Conference 2021 and received lots of interest from the attendees in the supply chain industry.

Ultra-wideband backscatter for reliable passive IoT localization: To further push the limit of RFID sensing latency and location resolution, I have designed UWB2 [7, 8]. Observing that the power consumption of the backscatter tag is unaffected by the interrogating signal bandwidth, UWB2 can generate a wideband signal on the reader device while keeping the tag passive and battery-free. Since no power-hungry active components need to be added to the tag, the UWB2 tag can harvest RF energy just like typical RFID, whereas the reader can achieve high localization accuracy and sensing resolution owing to the ultra-wide bandwidth.

3 Programmable experimental platforms for IoT

To explore future IoT systems, it is crucial to have a flexible experimental platform well before the IoT communication or sensing technology is standardized. In the course of my Ph.D. study, I developed several novel and impactful programmable experimental platforms to support research in the intersections of IoT, 5G, and neuroscience.

Millimeter-wave massive MIMO software radio. Millimeter-wave (mmWave) technologies represent a cornerstone for emerging wireless network infrastructure, and for RF sensing systems in security, health, and automotive domains. Despite the huge potential, it is extremely challenging to conduct experimental research in mmWave, due to the lack of a powerful and affordable experimental platform which supports both multiple RF chains and reconfigurable phased arrays.

My research filled this gap through M-Cube [2], the first massive MIMO mmWave software radio. As shown in Fig. 6, M-Cube is equipped with eight 32-element phased-arrays (a hybrid beamforming array with up to 256 antenna elements), at a cost that is an order of magnitude lower than existing commercial mmWave software radios. M-Cube builds on a novel software-radio architecture, which hijacks the RF front-end and phased array of a commercial 802.11ad radio, to enable arbitrary waveform transmission and real-time phased array reconfiguration. The M-Cube design entails a comprehensive understanding of the wireless system design, high-frequency RF circuit design to bridge the mmWave phased array and the software radio at baseband, FPGA programming for real-time operation and software programming on the Wi-Fi driver to repurpose the commercial mmWave radio. We have open-sourced M-Cube `http://m3.ucsd.edu/sdr/` and distributed replicas to ***more than 15*** research institutions in the US and EU. M-Cube has been serving as a versatile platform to enable experimental research in mmWave networking/sensing.

We further extended the platform to realize a high-resolution imaging RADAR with a massive number of "pixels" (i.e., antenna elements) targeting automotive perception. Combining with Xilinx's RFSoC FPGA processor, we can generate arbitrary RADAR waveforms with up to 4 GHz bandwidth and hence high time/range resolution. The feasibility of the software-defined RADAR design is demonstrated in [10]. Furthermore, we explored how to extend the spatial resolution of mmWave RADAR by adopting a hybrid MIMO phased array architecture [11].

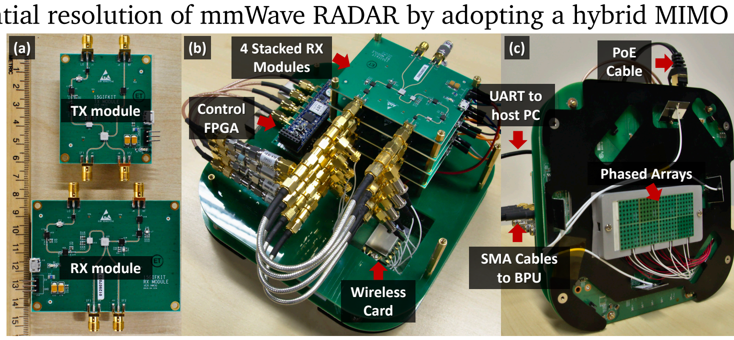

Figure 6: M-Cube platform.

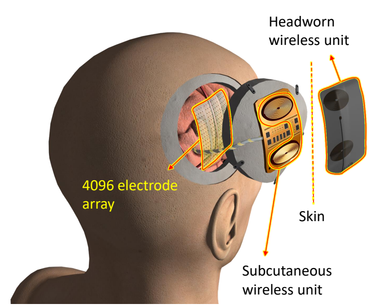

Figure 7: Neuron monitoring.

High-capacity, low-power wireless link for brain implant. Brain monitoring through the wireless link is becoming a game changer in the field of neuroscience. The wireless link enables long-term monitoring since it avoids the high risks of infection, bleeding, tissue or even brain damage due to tissue exposure with wire connection. However, cutting the wires entails several challenges: (1) Due to the extremely high complexity of the brain's neuron network, a high-density large-scale electrode array is needed for high-resolution neuron monitoring. Collecting the data from the electrode array will require ***extremely high throughput***. For example, the 4096-electrode array designed by my collaborators requires a throughput of more than 200 Mbps. (2) The implanted subcutaneous device should have ***low power consumption*** to avoid tissue injury by heat. (3) ***Wireless powering and batteryless operation*** are needed to avoid battery replacement through surgical operations.

As the leader of the wireless link design of the UG3 project, I collaborated with researchers, neurologists, neurosurgeons, and neurophysiologists from UCSD, OHSU, MGH and designed the two-stage wireless link shown in Fig. 7 to address the challenges at the same time. To support the high throughput, a custom-built magnetic link optimized for high throughput is adopted between the subcutaneous unit and the headworn unit. The wireless link between the headworn unit and the off-person monitoring station is supported by a high-throughput Wi-Fi link. Meanwhile, the subcutaneous unit is powered through magnetic power transfer for battery-free operation. With the wireless design, the platform can support long-term real-time neuron monitoring which can further support the research for a better understanding of brain activities.

4 Future Plans

Based on my research experience and expertise, I plan to continue working in an interdisciplinary and collaborative environment to explore new techniques for wireless IoT. My immediate research agenda will span three directions.

Passive IoT for hyperscale IoT networks. The vision of connecting everything in the physical world along with the digital world requires hyperscale IoT networks, consisting of trillions of IoT devices. However, the existing tethered or even battery-powered design is not feasible for IoT at scale due to the unaffordable maintenance cost and environmental hazards. Self-powered passive IoT is the ultimate means of attaining hyperscale IoT. With the advances in RFIC fabrication, low-power communication, and wireless energy harvesting, we are now at an important juncture to explore the system-level challenges of passive IoT. My previous work has shown the potential of radical system architectures to approach extremely low power without overhauling the existing infrastructure. My future research will further explore radical system architectures such as crystal-less design through accurate wireless clocking, ULP joint communication and sensing through UWB signals, highly efficient wireless energy harvesting through TX-RX co-design, etc. This research agenda aspires to build a fully passive IoT system for the next-generation hyperscale IoT network which is scalable, reliable, and multi-functional. I will continue to collaborate with researchers in the field of RFIC design, printable electronics, power storage, and data science, to bring the vision to reality.

The Internet of Human Things. Recently, computers are beginning to "walk" inside the human body. The Internet of Human Things (IoHT) wirelessly connect such implanted computers and enable a leap forward in health monitoring, disease treatment, new human-machine interaction, etc. I am interested in tackling the new challenge pertaining to this field. Examples include miniaturizing the radio devices without compromising radiation efficiency, combating the high signal loss through tissue, efficiently and safely powering the implanted devices, etc. My experience in ultra-reliable IoT communications (e.g., NFC+) and the neuron monitoring system (e.g., UG3) has equipped me with the sophisticated skill sets needed for IoHT. I will also seek collaboration with other researchers on solving interdisciplinary challenges such as brain-machine interfaces, neuromorphic AI chips for efficient IoHT data processing, remote control and powering of implanted micro-robots, etc.

Experimental research infrastructures for next generation wireless networks. Building mid-scale research infrastructures is among the top 10 grand ideas that the US National Science Foundation is targeting. Multiple experimental research testbeds have been built recently, under the support of NSF, DARPA, and the industry, to investigate emerging challenges in 5G, 6G, and the IoT in general. Based on my experiences in developing the M-Cube testbed and engaging with the user community, I will continue to explore projects along this line, such as (1) How to dual-use the same hardware for communication and sensing? Joint communication and sensing is a candidate 6G technology that enables environment awareness and highly efficient connectivity. But the lack of an experimental platform, especially on the mmWave band, has been impeding progress on this front. Built on my M-Cube platform, my future research will continue to explore innovative architectures for software-defined radio-radar devices. The new resulting experimental platforms will enable a reality check on the forthcoming 6G technologies, and potentially inspire new hardware, software, and algorithmic advances. (2) How to enable and leverage fully software-defined wireless infrastructures? 6G-era research, such as embedded machine learning techniques, site-specific adaptability, advanced signal design for joint communication and sensing, and scalable network automation, requires fully software-defined research infrastructures which provide flexibility on all layers of the protocol stack. Existing research platforms are built with a predefined physical layer and thus cannot satisfy the research requirements. I would like to build fully software-defined wireless infrastructures and work with other researchers to bring the 6G-era research to real deployment. There will be a lot of challenges to be addressed, such as how to implement the machine-learning based PHY layer in real-time, whether the layer slicing of the O-RAN paradigm is still feasible when adopting a new physical layer design, etc. (3) How to make use of the new spectrum such as mid-band, sub-THz, and THz? The new spectrum provides wider bandwidth which can support higher data rates and higher sensing accuracy, but it also introduces challenging problems, e.g., how to access the spectrum, how to schedule the packets with multiple bands, how to manage the coverage with beamforming, etc. To date, no versatile and affordable experimental platform is available to support such research. I plan to first fill the gap by integrating the M-Cube design with O-RAN to tackle the problems in the mmWave band and then collaborate with researchers on RF antenna array design, communication theory, and computer networks to address the challenges in other frequency bands.

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