Commodity Hardware for Scalable RAN Infrastructure and Agricultural Sensing

Jian Ding
jian.ding@yale.edu
Yale University

Abstract

Next-generation wireless networks promise massive connectivity with higher data rates and lower latency, offering transformative potential for agriculture by enabling smarter, more efficient, and sustainable farming practices. However, the advancement of wireless infrastructure and precision agriculture is constrained by the need for specialized, costly hardware. Our research addresses this challenge by designing systems that leverage general-purpose commodity hardware for both radio-access network (RAN) infrastructure and soil monitoring. By utilizing existing servers at edge and cloud data centers, as well as ubiquitous Wi-Fi devices, we can eliminate the need for expensive, dedicated equipment, reducing costs and accelerating the evolution of wireless and agricultural sensing technologies.

CCS Concepts

• **Human-centered computing → Ubiquitous and mobile computing systems and tools**; • **Networks → Wireless access points, base stations and infrastructure**.

Keywords

Commodity hardware, precision agriculture, RAN infrastructure

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1 Introduction

The rapid evolution of next-generation wireless networks, with their promise of massive connectivity, ultra-low latency, and higher data rates, is crucial for supporting the diverse capacity needs in agriculture. These networks enable smarter, more efficient, and sustainable farming practices by facilitating real-time monitoring, automation, and data-driven decision-making. Agricultural sensing applications vary in their capacity requirements: some, like soil moisture monitoring and irrigation management, prioritize low-latency and reliable communication, while others, such as drone-based precision spraying and machine learning for crop disease detection, demand higher throughput and low latency. Addressing these varying demands requires scalable, high-performance connectivity that can support both low-latency applications and those requiring higher data rates, making next-generation wireless networks indispensable for modern agriculture.

However, both wireless communication systems and precision agriculture face significant challenges due to their reliance on costly, specialized hardware. In wireless communication, the current infrastructure for radio-access networks (RAN) often requires dedicated hardware, such as FPGAs, which limits scalability and increases operational expenses. Similarly, precision agriculture relies on expensive, custom sensors to monitor key soil properties like moisture, electrical conductivity (EC), and carbon content. The high cost and lack of scalability of these specialized systems hinder large-scale, real-time environmental monitoring, particularly in resource-constrained regions.

To address these challenges, our research focuses on developing systems that harness the power of general-purpose commodity hardware to perform complex tasks traditionally reliant on specialized equipment. By utilizing existing infrastructure, such as general purpose servers in edge and cloud data centers and commercially available Wi-Fi devices, we aim to eliminate the need for specialized, dedicated hardware. This approach significantly reduces costs and accelerates the evolution of both wireless and agricultural sensing systems. My work contributes to the design of scalable, efficient, and cost-effective solutions that make high-performance wireless communication and soil monitoring accessible for broader, more widespread use. This shift not only enables the practical deployment of next-generation networks, but also paves the way for smarter and more sustainable agricultural practices through real-time monitoring and data-driven decision-making.

2 RAN Infrastructure: Real-Time Massive MIMO Baseband on CPUs

The realization of cellular networks, particularly 5G, demands systems that can efficiently handle massive connectivity with low latency and high throughput. One of the core technologies driving 5G networks is massive multiple-input, multiple-output (MIMO), which significantly enhances spectral efficiency by using a large number of antennas at the base station. However, the computational demands of massive MIMO baseband processing have traditionally required specialized hardware, such as FPGAs or ASICs, which are expensive, inflexible, and difficult to program.

We propose an alternative solution that eliminates the reliance on specialized hardware utilizing general-purpose commodity hardware. The **Agora** system, described in [1], is the first public framework demonstrating that software-only real-time massive MIMO baseband processing is possible on a single many-core server. Agora is designed to handle the computational intensity of 5G baseband

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processing using a software-only system that prioritizes on parallelism across multiple CPU cores. Its key contributions include: exploiting data parallelism within a frame's processing to reduce latency, using a manager-worker threading model to efficiently schedule tasks across multiple cores, and optimizing cache and memory access to improve performance. Agora's design prioritizes efficient parallel computation through SIMD extensions and kernel-bypass packet I/O, while avoiding the pipeline-parallel bottleneck of prior systems. This approach makes Agora highly scalable and cost-effective, as it replaces the need for specialized hardware with commercial, general-purpose servers, demonstrating that it can meet the data rate and latency requirements of 5G NR in real-time while supporting up to 64 antennas and 16 data streams.

The realization of Agora's capabilities on commodity hardware represents a significant step toward making next-generation wireless networks more accessible, affordable, and scalable. It demonstrates that a shift to cloud-native, software-based baseband processing can meet the stringent performance requirements of 5G while eliminating the need for dedicated, specialized hardware.

3 Agricultural Sensing: Wi-Fi and Smartphones for Cost-Effective Soil Monitoring

Precision agriculture depends on real-time monitoring of soil properties like moisture, EC, and carbon content to optimize irrigation and support sustainable farming practices. However, existing soil sensing technologies are often costly and specialized, limiting access for small-holder farmers. Our research addresses this by using affordable commercial hardware, including Wi-Fi devices and smartphone cameras, to enable scalable soil sensing solutions that can integrate with next-generation wireless networks.

Soil Moisture and EC. In **Strobe** [2], we introduce a novel technique for measuring soil moisture and EC using RF propagation in the unlicensed 2.4 GHz Wi-Fi spectrum. Traditional soil moisture and EC sensors can be expensive, and even moderately priced sensors (US$100s) often suffer from inaccuracies. Strobe overcomes this limitation by being the first to use the widely available Wi-Fi signals, significantly lowering costs and making soil monitoring more accessible and cost-effective. The system uses an aboveground transmitter paired with an underground multi-antenna array to measure the propagation time and signal amplitude differences across antennas placed at different depths in the soil. These measurements are then used to calculate soil permittivity and EC, which directly correlate with soil moisture and salinity.

A key innovation of Strobe is its use of relative time-of-flight (ToF) measurements between underground receiver antennas buried at different depths, enabling accurate soil property estimation without the need for wide bandwidth. Unlike prior RF-based systems that rely on absolute ToF (i.e., the ToF between the transmitter and receiver), which demands broader bandwidths in the GHz range, Strobe uses only 70 MHz of the 2.4 GHz spectrum. This approach, previously unexplored in Wi-Fi-based sensing systems, delivers superior ToF resolution and provides a low-cost, high-precision solution for soil moisture and EC estimation.

Soil Carbon Content. Expanding on Strobe, we propose **Scarf** [3], a cost-effective solution for soil carbon sensing. Soil carbon sequestration is crucial for soil health, crop yields, and climate change mitigation, but current measurement methods are costly and time-consuming, often requiring dry combustion or expensive techniques like laser-induced spectroscopy and neutron scattering.

Scarf addresses these challenges by combining Wi-Fi signals with smartphone images. The Wi-Fi signals measure soil permittivity, which is influenced by both soil carbon content and moisture, while the optical images capture soil lightness, which is also correlated with carbon and moisture levels. By integrating the two signal modalities—RF signals and images—Scarf can jointly estimate soil moisture and carbon content without the need for time-consuming sample preparation or expensive equipment. Scarf uses a hybrid modeling approach that combines physics-based equations with machine learning. First, a mathematical model generates a preliminary carbon estimate by leveraging both RF and visual features. To account for the nonlinear and interdependent effects of moisture, carbon, permittivity, and lightness on signal behavior, a ResNet model is trained to predict the residual error between the mathematical model estimate and the ground truth. The final carbon prediction is computed by adding this learned correction back to the initial estimate. Scarf achieves high accuracy, with a coefficient of determination (R^2) of 0.911 on sand-compost mixtures—comparable to state-of-the-art methods that cost $1000s USD.

Both Strobe and Scarf showcase how commodity hardware can solve key agricultural sensing challenges while leveraging the connectivity and data throughput of next-generation wireless networks. By using readily available, low-cost Wi-Fi devices and smartphone cameras, these systems lower the barrier to entry for soil monitoring, enabling broader adoption of precision agriculture at a fraction of the cost of traditional methods. This approach supports the vision of democratizing data-driven agriculture [4], making it more accessible for farmers in resource-constrained regions. Additionally, their ability to integrate with next-generation wireless infrastructures ensures that they contribute to the broader shift toward smarter, more connected agriculture.

4 Closing Remarks

In conclusion, this research illustrates the transformative potential of commodity hardware in solving complex challenges across wireless communication and agricultural sensing. By utilizing general-purpose CPUs and widely available Wi-Fi devices, these innovations enable scalable and cost-effective solutions that integrate seamlessly with next-generation wireless networks to enhance precision agriculture. As wireless infrastructure advances and the demand for sustainable agricultural practices increases, these systems provide a path forward for real-time, data-driven insights that enhance productivity, sustainability, and climate resilience globally.

References

[1] Jian Ding, Rahman Doost-Mohammady, Anuj Kalia, and Lin Zhong. Agora: Real-time massive mimo baseband processing in software. In *Proc. ACM Int. Conf. emerging Networking EXperiments and Technologies (CoNEXT)*. ACM, 2020.

[2] Jian Ding and Ranveer Chandra. Towards low cost soil sensing using Wi-Fi. In *Proc. of ACM Int. Conf. Mobile Computing and Networking (MobiCom)*. ACM, 2019.

[3] Jian Ding, Ranveer Chandra, Rattan Lal, and Leandros Tassiulas. Cost-effective soil carbon sensing with wi-fi and optical signals. In *Proc. of ACM Int. Conf. Mobile Computing and Networking (MobiCom)*. ACM, 2024.

[4] Ranveer Chandra, Manohar Swaminathan, Tusher Chakraborty, Jian Ding, Zerina Kapetanovic, Peeyush Kumar, and Deepak Vasisht. Democratizing data-driven agriculture using affordable hardware. *IEEE Micro*, 42(1):69–77, 2022.