Ubiquitous Computational Spectroscopy: Bridging Lab-grade Spectroscopy to Everyday Devices

Haiyan Hu
csehaiyanhu@ust.hk
The Hong Kong University of Science and Technology
Hong Kong, China

Abstract

High-fidelity chemical sensing has long been restricted to laboratory settings, leaving a critical information void in ubiquitous mobile computing. To eliminate this barrier, we introduce ubiquitous computational spectroscopy, a paradigm that redefines sensing by shifting the burden from hardware precision to algorithmic intelligence. The core innovation lies in the systematic exploitation of spectral redundancy and physics-domain priors to reconstruct high-dimensional chemical fingerprints from sparse, low-SNR responses. By integrating active illumination coding with task-driven feature extraction, my researches dismantle the physical limits of commodity hardware, ultimately realizing the vision of laboratory-grade molecular intelligence on everyday device.

CCS Concepts

• **Human-centered computing** → **Mobile devices**; • **Computing methodologies** → *Machine learning*.

Keywords

Near-infrared Light; Computational Spectroscopy

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1 Introduction

As a non-invasive technique for extracting chemical fingerprints, spectral analysis plays an indispensable role in safeguarding human health, ensuring food safety, and facilitating environmental monitoring. By analyzing the reflection or absorption characteristics of substances in response to light signals within specific wavebands, we can precisely quantify key biochemical indicators, such as proteins, fats, and sugars, and even detect trace amounts of harmful adulterants [2].

However, current paradigms in spectral sensing face a severe dichotomy. While professional laboratory-grade spectrometers boast exceptionally high resolution and signal-to-noise ratios, their prohibitive costs (often tens of thousands of dollars) [6], bulky dimensions, and stringent operational requirements confine them to lab settings. In contrast, ubiquitous consumer devices (e.g., smartphones and wearables) offer only coarse, broad-spectrum measurements with sparse sampling and low signal quality [5], making them are ill-equipped for high-precision biochemical analysis tasks.

Challenges. To bridge this gap and enable laboratory-grade sensing on consumer-level hardware, we must overcome three hierarchical scientific challenges. First, consumer-level sensors lack fine-grained dispersive elements, resulting in a loss of spectral dimensionality at the source. Second, while spectral data is highly redundant, extracting weak signals of low-concentration substances from high-noise, low-quality readings remains a fundamental bottleneck. Lastly, transitioning from "one-shot" laboratory identification to continuous, closed-loop monitoring in dynamic clinical or domestic environments requires extreme system robustness.

Contributions. We summarize an evolutionary paradigm of ubiquitous computational spectroscopy, utilizing algorithmic intelligence to compensate for physical hardware deficiencies. Our research is structured across three pillars (Figure 1). **First,** we address the loss of spectral dimensionality by shifting the sensing burden from the detector to the light source through active illumination coding on commodity hardware. **Second,** to overcome high-noise and low-quality bottlenecks, we exploit spectral redundancy and latent manifolds for physics-informed reconstruction, enabling laboratory-grade sensitivity and high-fidelity chemical fingerprinting for complex food safety analysis. **Lastly,** we ensure system robustness via generalized frameworks and closed-loop monitoring, maintaining consistent performance across heterogeneous samples to enable real-time nutritional intervention in the real world.

2 Active and low-cost spectral acquisition

The fundamental limitation of ubiquitous spectroscopy lies in the absence of high-resolution dispersive elements in consumer electronics. To bridge this information gap at the source, we propose a shift from passive sensing to active illumination coding. In NIRSCam [4], we designed a time-multiplexed LED-array modulation scheme that shifts the spectral separation burden from the detector to the light source, enabling calorie estimation on mobile devices. We further extended this concept in FruitPhone [5], where we repurposed the unmodified smartphone screen as a programmable scanning light source, simulating a laboratory-grade monochromator to excite specific biochemical responses for sugar content detection.

3 Computational spectroscopy

Spectral Reconstruction. Beyond hardware modulation, we developed physics informed reconstruction models to decode high-dimensional chemical information from these sparse, non-linear

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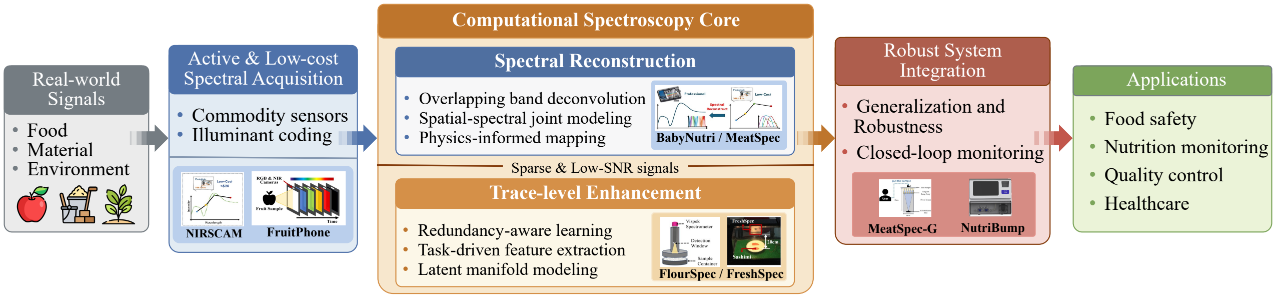

Figure 1: Ubiquitous Computational Spectroscopy Framework.

responses. In BabyNutri [2], we modeled the overlapping spectral sensitivities of low-cost sensors to reconstruct continuous absorption curves, achieving precise macronutrient analysis for infant safety. For more complex organic structures, MeatSpec [6] leverages spatial-spectral correlations within multispectral images (MSI) to suppress environmental noise, transforming $20 off-the-shelf modules into robust tools for ubiquitous food fraud inspection. **Trace-level Enhancement.** While established reconstruction methods focus on recovering the full-spectrum profile, they often struggle with high-noise floors when targeting low-concentration substances. We identified that spectral data is inherently redundant and physically correlated, offering a "less-is-more" opportunity for sensitivity enhancement. In FlourSpec [1], we introduced a task-specific encoder that skips redundant reconstruction and directly extracts features sensitive to trace-level adulterants. By concentrating on these high-entropy spectral regions, we achieved a limit of detection (LOD) that rivals professional bench-top instruments while using orders-of-magnitude cheaper hardware. Furthermore, in FreshSpec [7], we monitored sashimi freshness by employing a self-supervised learning paradigm to isolate the weak spectral signatures of volatile compounds from dominant background noise. By identifying the latent manifold of spectral variations during food degradation, our system achieves high-precision quality assessment in unconstrained domestic environments.

4 Robust System Integration

We transition these computational foundations into resilient systems capable of handling real-world heterogeneity and high-stakes clinical requirements. We developed generalized learning frameworks in MeatSpec-G [8] to ensure robust performance across numerous adulteration conditions in real-world. Furthermore, in NutriBump [3], we implemented the first closed-loop nutritional monitoring system for nasogastric tube patients. By integrating real-time spectral sensing with automated delivery, we demonstrated the clinical viability of ubiquitous spectroscopy for personalized healthcare and long-term patient intervention.

5 Conclusion and Future Direction

These researches establish the foundational framework for ubiquitous computational spectroscopy, dismantling the physical barriers that once confined chemical analysis to the laboratory. By synergizing active hardware modulation with physics-informed intelligence, this body of work proves that high-fidelity biochemical insights are extractable even from the sparse, noisy signals of commodity electronics. Moving forward, my research program is focused on the development of spectral foundation models to achieve robust generalization across heterogeneous hardware and unconstrained environments. Besides, we are extending this computational sensing paradigm to a broader spectrum of high-impact domains, including continuous physiological monitoring and precision agriculture, ensuring that the invisible wisdom of the molecular world is accessible to all.

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