Towards Accurate Wi-Fi 6E-based Liquid Sensing in a Static Environment

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***Abstract*—With the emergence of Integrated Sensing and Communication (ISAC) into the 6G standardization roadmap, there is growing interest in using wireless communication technologies for various sensing applications. Although technologies such as mmWave, UWB have been explored for this purpose, Wi-Fi stands out as a cost-effective and widely deployed technology. While previous studies have primarily utilized Wi-Fi 4 and 5, this work investigates the feasibility of liquid sensing using the latest Wi-Fi 6E standard. We use Channel State Information (CSI) to distinguish between different liquids placed along the Line-of-Sight (LoS) path, and address challenges specific to Wi-Fi 6E equipped with Intel Ax210. Our proposed method improves sensing classification performance by utilizing CSI amplitude for receiver CSI order alignment. Experimental results demonstrate the potential of Wi-Fi 6E for accurate, low-cost liquid sensing in a static environment.**

***Index Terms*—CSI, Wi-Fi, ISAC, Wireless Sensing, Liquid Sensing**

I. Introduction

With the emergence of Integrated Sensing and Communication (ISAC) as a core feature of 6G, wireless communication technologies have gained renewed attention for their potential in environmental and object sensing. Various technologies, including mmWave, UWB, and Wi-Fi, have been explored for sensing applications. Among these, Wi-Fi offers notable advantages due to its availability and low cost.

One particular application of wireless sensing involves identifying and distinguishing different liquids. When electromagnetic waves pass through dielectric materials, they undergo attenuation. Since different liquids have distinct permittivity values, their interaction with radio signals varies accordingly. These physical differences enable the use of wireless sensing to classify liquid substances.

While many existing studies have focused on Wi-Fi 4 and 5, recent advances in Channel State Information (CSI) extraction tools (e.g. PicoScenes, AX-CSI) have made it feasible to perform fine-grained sensing with the newer Wi-Fi 6E standard [1], [2]. However, Wi-Fi 6E introduces new challenges that have to be considered. In this work, we leverage Wi-Fi 6E for static liquid sensing and propose a method that compensates for CSI ambiguity issue to enhance the sensing accuracy.

II. Background

A. Channel State Information (CSI)

We consider a scenario in which a liquid object is placed along the Line-of-Sight (LoS) path between the transmitter (Tx) and receiver (Rx). In Wi-Fi systems, known preambles in the transmitted signal allow the estimation of the wireless channel. The relationship between the transmitted and received signals can be expressed as:

$$Y = HX + N, \tag{1}$$

where Y is the received signal, X is the transmitted signal, and H is the CSI.

CSI consists of the LoS and non-Line-of-Sight (NLoS) components as:

$$H = H_{\text{LoS}} + H_{\text{NLoS}}. \tag{2}$$

Wi-Fi 6E standard utilizes Orthogonal Frequency Division Multiplexing (OFDM), resulting in different subcarriers occupying different frequencies. The frequency-selective attenuation occurs when signal blocked by a liquid in LoS path due to the dielectric properties of liquid, which can affect both the amplitude and phase of CSI.

To reduce multipath effects, we adopt a strategy used in WiMi [3]. Subcarrier with minimal phase variance difference between two receive antennas is selected, assuming that LoS propagation dominates in the corresponding frequency.

B. CSI Amplitude Ratio and CSI Phase Difference

CSI is represented as a complex value, consisting of amplitude and phase components. Although both are affected by the liquid, raw amplitude and phase often suffer from noise and fluctuations. In particular, CSI amplitude typically exhibits high variance, which hinders robust classification. To mitigate this, we compute the amplitude ratio between two Rx antennas on the same device, significantly reducing variance.

For CSI phase, hardware-induced distortions such as Carrier Frequency Offset (CFO) and Sampling Frequency Offset (SFO) make raw CSI phase resemble random noise. Since such distortions similarly affect antennas on the same Rx, taking the phase difference between them partially reduces these offsets. CSI amplitude ratio and phase difference can offer robust features with improved stability.

C. CSI Ambiguity and Rx alignment

Previous studies have reported ambiguity in CSI information in commercial off-the-shelf Wi-Fi network interface cards caused by the Phase-Locked Loop (PLL) [4]. In Wi-Fi 6E devices using Intel Ax210, a four-way phase ambiguity has

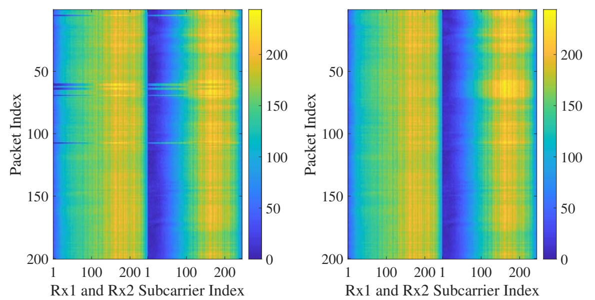

Fig. 1. Spectrogram of CSI amplitude in Rx1, Rx2.

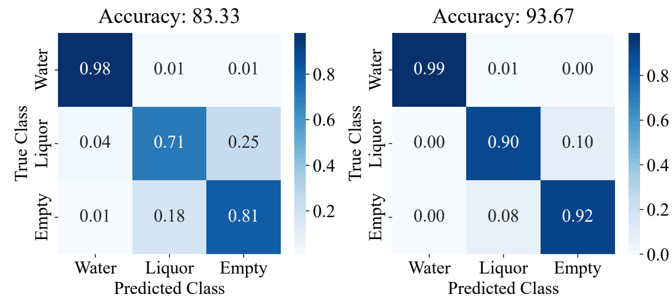

Fig. 2. Classification accuracy before and after Rx alignment using SVM.

been observed, due to PLL and inconsistent antenna mapping influenced by Received Signal Strength (RSS) [5].

While histogram-based approaches have been proposed to resolve this issue, we propose a method using CSI amplitude to infer consistent antenna ordering. Under the assumption of static liquid objects, amplitude patterns across frames should remain consistent for each antenna.

We measure cosine similarity between amplitude vectors across frames to identify the most consistent antenna ordering. The Rx indices are reassigned to minimize inter-frame dissimilarity, effectively correcting the Rx antenna mismatch without relying on statistical priors.

An example spectrogram before and after amplitude-based Rx alignment is shown in Fig. 1, where CSI coherence improves visibly. Finally, to account for possible π-level phase shifts caused by PLL, we apply modulo normalization before classification.

III. Experiment

A. Experimental Setup

We conducted experiments using two ThinkPad E15 laptops, each equipped with an Intel Ax210 Wi-Fi 6E chipset. One laptop acted as the Tx and the other as the Rx. The Tx used a single antenna, while the Rx used two antennas in a Single Input, Multiple Output (SIMO) configuration.

We used the 6 GHz band of Wi-Fi 6E, transmitting packets every 100 ms over a 20 MHz bandwidth, and CSI data were collected at the Rx using the PicoScenes framework. The distance between the Tx and Rx was fixed, and container including liquids or empty container were placed between them. The tested liquids include water and a type of Korean liquor (soju), along with an empty container for baseline comparison.

B. Classification and Results

To demonstrate the feasibility of liquid classification, we tested three classes: water, liquor, and empty container.

First, we selected subcarriers with low phase difference variance across the two Rx antennas, assuming these are dominated by LoS propagation and minimally affected by multipath fading.

We extracted CSI between the two antennas for the selected subcarrier and used material feature proposed in WiMi as features for classification [3]. Material feature is defined by CSI phase difference and CSI amplitude ratio to extract each material's property. A Support Vector Machine (SVM) with a radial basis function (RBF) kernel was used as the classifier. Due to the limited dataset size, we employed 5-fold cross-validation to evaluate classification accuracy.

Without correcting the CSI ambiguity, the classification accuracy was 83.33%. By applying the proposed amplitude-based Rx alignment technique, we observed an improvement in classification accuracy, increasing from 83.33% to 93.67%, as shown in Fig. 2.

IV. Conclusion

In this paper, we investigated the feasibility of static liquid sensing using Wi-Fi CSI that is attenuated by different liquids. Our work addresses challenges in Wi-Fi 6E, such as the CSI ambiguity caused by hardware-internal mechanisms. To mitigate these issues, we proposed a CSI amplitude-based Rx alignment technique that estimates consistent antenna indices based on signal similarity across frames. Experimental results show that our proposed method improves classification accuracy from 83.33% to 93.67%. For future work, we plan to further exploit the unique characteristics of Wi-Fi 6E, such as larger bandwidth and higher spatial resolution, to improve resolution and robustness in dynamic environments.

Acknowledgment

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