WiEps: Measurement of Dielectric Property With Commodity WiFi Device—An Application to Ethanol/Water Mixture

Hang Song, Member, IEEE, Bo Wei, Member, IEEE, Qin Yu, Xia Xiao, Member, IEEE, and Takamaro Kikkawa, Life Fellow, IEEE

Abstract—WiFi signal has become accessible everywhere, providing high-speed data transmission experience. Besides the communication service, channel state information (CSI) of the WiFi signals is widely employed for numerous Internet-of-Things (IoT) applications. Recently, most of these applications are based on the analysis of the microwave reflections caused by the physical movement of the objective. In this article, a novel contactless wireless sensing technique named WiEps is developed to measure the dielectric properties of the material, exploiting the transmission characteristics of the WiFi signals. In WiEps, the material under test is placed between the transmitter antenna and receiver antenna. A theoretical model is proposed to quantitatively describe the relationship between CSI data and dielectric properties of the material. During the experiment, the phase and amplitude of the transmitted WiFi signals are extracted from the measured CSI data. The parameters of the theoretical model are calculated using measured data from the known materials. Then, WiEps is utilized to estimate the dielectric properties of unknown materials. The proposed technique is first applied to the ethanol/water mixtures. Then, additional liquids are measured for further verification. The estimated permittivities and conductivities show good agreement with the actual values, with the average error of 4.0% and 8.9%, respectively, indicating the efficacy of WiEps. By measuring the dielectric property, this technique is promising to be applied to new IoT applications using ubiquitous WiFi signals, such as food engineering, material manufacturing process monitoring, and security check.

Index Terms—Channel state information (CSI), dielectric property measurement, microwave propagation, WiFi signal, wireless sensing.

I. INTRODUCTION

RECENT years, with the rapid evolution of Internet of Things (IoT), wireless sensing using ubiquitous signals has been widely studied [1]–[4]. Compared with vision-based or sensor-based approaches, wireless sensing does not require any additional sensors deployed on the human body and it can operate without light. Therefore, it has gained extensive research attention worldwide. Owing to the fine-grained channel state information (CSI) [5], numerous human-centric applications have been proposed using off-the-shelf WiFi devices. Gu et al. [6] developed MoSense, a motion detection system which can identify human presence and activities. Liu et al. [7] proposed a sleep monitoring system which can recognize the postures and vital signs. Zhang et al. [8] developed BreathTrack, a system which can be used to accurately track the human breath status indoor. The emerging artificial intelligence techniques are also incorporated with the WiFi signals to improve the activity recognition accuracy [9], [10]. Wang et al. [11] proposed the LiFSS, a submeter position system which is low human effort and device-free. WiMorse, a Morse-code input system is proposed for people who have disease by tracking the finger movements [12]. Besides, other systems are proposed for specific use, such as emotion detection [13], noninvasive user identification [14], and vehicle speed estimation [15].

Although a lot of systems have been developed for different purposes with WiFi signals as mentioned above, the physical basis of these applications is similar. The variations of the signal amplitude and phase caused by physical movement are utilized. According to electromagnetic wave theory [16], when the emitted microwave encounters an interface with a different dielectric property, the wave will be partially reflected and partially transmitted through. The variations caused by the physical movement is related to reflected signals. Therefore, the majority of recent researches are concentrated on the reflection part of the microwave. In fact, the dielectric characteristics will also influence the transmission of the microwave signal, resulting in the change of signal amplitude and phase. There are a few works utilizing the change of signal caused by dielectric property for wheat moisture detection [17], fire event detection [18], and material classification [19]. However, these applications are mainly formulated as classification problems. The core techniques are feature extraction and classification methods. While the physical basis of these applications, which is dielectric property change, is not revealed and thoroughly analyzed. In this article, the transmitted WiFi signal through a material is theoretically analyzed and it is utilized to quantitatively measure the dielectric properties of the materials.

Manuscript received March 3, 2020; revised May 5, 2020; accepted May 28, 2020. Date of publication June 1, 2020; date of current version December 11, 2020. This work was supported in part by the Japan Society for the Promotion of Science KAKENHI under Grant 20K14740, and in part by NSFC under Grant 61271323. (Corresponding authors: Bo Wei; Hang Song.) Hang Song, Qin Yu, and Xia Xiao are with the Tianjin Key Laboratory of Imaging and Sensing Microelectronic Technology, School of Microelectronics, Tianjin University, Tianjin 300072, China (e-mail: songhang168@tju.edu.cn). Bo Wei is with the Department of Computer and Communication Engineering, Waseda University, Tokyo 169-8555, Japan (e-mail: weibo0504@fuji.waseda.jp). Takamaro Kikkawa is with the Research Institute for Nanodevice and Bio Systems, Hiroshima University, Hiroshima 739-8527, Japan.

Digital Object Identifier 10.1109/JIOT.2020.2999210
Measuring the dielectric property is essential in many applications since it reflects the physical and chemical characteristics of the materials [20]. When the components of a certain material change, the permittivity and conductivity will be influenced. Therefore, by knowing the dielectric properties of the materials, the constituents can be analyzed. Dielectric characterization has been widely applied to a variety of areas, such as monitoring the quality of the composite material during manufacturing [21], food engineering [22]–[24], analyzing the material chemical features [25], security check [26], and biomedical engineering [27]–[30]. However, most of the current measurement methods require the use of expensive commercial equipment, such as vector network analyzer (VNA). This limits the deployment in wider scenarios for small business or individual users at a low cost.

In this article, a new system named WiEps is developed for dielectric characterization with commodity WiFi devices. Eps stands for epsilon which is commonly utilized to note the permittivity. In WiEps system, two computers equipped with the Intel 5300 NICs are utilized to transmit and receive signals, respectively. On the transmitter side, one antenna is connected. While on the receiver side, two antennas are employed to receive the signal. The material to be tested is placed on the line of sight (LOS) between the transmitter and one of the receivers. The antennas used are also commercial goods for the WiFi communication system without any modification. During the experiment, the signals are emitted toward the material under test (MUT) and the transmitted signals are captured by the receiver antennas. CSI data are recorded by the NIC and then processed to extract the amplitude and phase information of the received signal. A theoretical model is proposed to quantitatively describe the relationship between transmitted signal characteristics and dielectric properties of the material. In this model, the influence of the multipath effect is incorporated.

For evaluation, WiEps is first applied to measure the ethanol/water mixture. The ethanol/water solutions with different concentrations are prepared and put into a container in turn. Then, signal transmission experiments are conducted. In order to calculate the parameters of the theoretical model, the dielectric properties of the solutions are also measured using the standard open-ended coaxial probe method with VNA. For further validation, additional liquids are measured using WiEps. The estimated dielectric properties agree well with the actual values, with the average error of 4.0% and 8.9% across all materials for dielectric constant and conductivity, respectively. The results demonstrate that the proposed WiEps system is effective in measuring both the dielectric constant and conductivity of the material, and it is promising to be applied to new IoT applications using ubiquitous WiFi signals.

The main contributions of this article are as follows.

1) We investigate the transmitted signals through the material and analyze the influence of the dielectric properties on the channel state response.

2) We propose WiEps, a dielectric characterization system which can estimate the dielectric property of a material with ambient WiFi signals. To the best of our knowledge, this is the first work that theoretically analyzes the transmission characteristics of the WiFi signals and utilizes the CSI data for dielectric property measurement.

3) We propose a theoretical model which quantitatively describes the relationship between the dielectric properties and the transmitted WiFi signals. In this model, the influence of the multipath effect is taken into consideration. Therefore, it can work under indoor condition without any specific requirement.

4) We implement the WiEps using the commodity WiFi device and apply it to measure the dielectric properties of ethanol/water mixtures and other liquids. The experiment results demonstrate the efficacy of the proposed system.

The remainder of this article is organized as follows. Section II briefly reviews the methods for dielectric characterization. Section III depicts the detailed system design of WiEps. Section IV illustrates the theoretical model for measuring dielectric property using WiFi signals. Section V presents the experimental evaluation of the proposed system with ethanol/water mixtures and other liquids. Finally, the conclusion is given in Section VI.

II. RELATED WORK

Generally, there are two kinds of approaches to measure the dielectric properties, the resonant and nonresonant methods [31]. In the resonant method, customized cavity or resonator is designed and the perturbation principle is utilized to analyze the resonant shift with and without the existence of MUT. Rajab et al. [32] proposed a dielectric characterization technique using a resonant nonradiative dielectric waveguide structure. Zhu et al. [33] developed a hollow coaxial cable Fabry–Perot resonator for measuring the liquid dielectric constant and applied it to monitor the evaporation of ethanol in ethanol/water mixtures. Koirala et al. [34] measured the water/ethanol solution using a spiral-coupled passive microresonator sensor. Su et al. [35] developed a flexible complementary spiral resonator and attached it to robotic hand for measuring the objects grasped. Other devices, such as metamaterial-based sensors [36], [37] and microfluidic sensor [38] are developed for measuring the dielectric properties of chemicals and liquids.

In the nonresonant method, customized waveguide or transmission lines are fabricated and the lumped models are utilized to analyze the impedance change with the presence of MUT. Bois et al. [21] developed a plug-loaded two-port waveguide measurement technique for dielectric characterization of granular and liquid materials. Bobrov et al. [39] proposed a technique for measuring the dielectric property of soil in a wideband frequency using a single coaxial cell. Pantoja et al. [40] proposed a new model to estimate the complex permittivity of the soil using the two-port coaxial probe. Meaney et al. [41] developed a transmission-based open-ended coaxial probe for dielectric characterization in clinical use.

Besides the conventional methods which are based on VNA, there are other methods developed for dielectric measurement. Guo et al. [42] proposed an improved device based on the parallel-plate capacitance method for measuring the rocks
with the impedance analyzer or VNA. Gutierrez et al. [26] developed a field-deployable system to measure the complex permittivity of the improvised explosives using the M-sequence device. Bertling et al. [43] measured the ethanol content of liquid solution using the terahertz quantum cascade laser. Dheke et al. [44] developed a system using UWB signals to measure the permittivities of liquids.

### III. System Design

The system design and configuration of WiEps is shown in Fig. 1. In the WiEps system, two commodity WiFi devices and Intel 5300 NICs are installed on two separate personal computers. Three antennas are utilized to emit and receive signals. One emitter antenna Tx is connected to one NIC. The other two antennas Rx1 and Rx2 are connected to the other NIC and utilized as the receivers. The material to be measured is placed in between the Tx and Rx2 on the LOS. The thickness of the material is denoted as \( d \). In this article, an acrylics-made container is utilized to hold the water/ethanol mixture and other materials. Then, the thickness of the gap which contains the material is \( d \). The container is originally used for storing papers and it is sold on market. The antennas are also commercial goods for the WiFi communication system without any modification.

During the experiment, the communication is conducted between two computers. The modulated signal is emitted from Tx and received by Rx1 and Rx2. As shown in Fig. 1, the red dashed lines represent the wave propagation on LOS where the effect of the material is included. Since the experiment is assumed to be carried out in the indoor environment, there are multipath effects which influence the received signals by Rx antennas. The multipath waves are illustrated as purple dashed lines in Fig. 1. After being captured, the received signals are processed by NIC and CSI data are recorded.

WiFi standard 802.11n utilized the orthogonal frequency-division multiplexing (OFDM) technology for communication [45]. The recorded CSI reveals the channel response features of the subcarriers. Specifically, the utilized device measures the CSI data of a subgroup of 30 within the 64 subcarriers. When there is a material presenting at the propagation path in between Tx and Rx2, the received signal by Rx2 will be influenced and the channel state will change accordingly. Meanwhile, a consistent reference channel is utilized to synchronize the data. In order to quantitatively characterize the relationship between transmitted signal characteristics and dielectric properties of the material, a theoretical model is proposed. In the model, the influence of the multipath effect is incorporated. Therefore, there is no special requirement of the environment for deploying the WiEps system.

### IV. Theoretical Model

Define the received signal by the antenna Rx2 in complex form as \( A_{2} \cdot e^{j\theta_{2}} \), where \( A_{2} \) and \( \theta_{2} \) are the amplitude and phase of signal. Since the received signal is the superposition of multipath components, it can be expressed as follows:

\[
A_{2} \cdot e^{j\theta_{2}} = A_{LOS} \cdot e^{j\theta_{LOS}} + A_{m} \cdot e^{j\theta_{m}}
\]

where \( A_{LOS} \) and \( \theta_{LOS} \) are the amplitude and phase of signal transmitted on LOS where the material exists. While \( A_{m} \cdot e^{j\theta_{m}} \) represents the total effect of other multipath signals. When the microwave propagates in a dissipative medium, the amplitude is attenuated by a factor of \( e^{-kr_{2}d} \). Meanwhile, the phase change in the medium is calculated as \(-kr_{2} \cdot d\) [16]. \( d \) is the propagating distance which is equivalent to the thickness of the material as shown in Fig. 1. \( k_{R} \) and \( k_{I} \) are the coefficients calculated as follows:

\[
k_{R} = \omega \sqrt{\mu_{0} \varepsilon_{0} \varepsilon_{r}} \left[ \frac{1}{2} \left( \frac{1}{1 + \frac{\sigma^2}{(\varepsilon_{0} \varepsilon_{r} \omega)^2}} + 1 \right) \right]^{1/2}
\]

\[
k_{I} = \omega \sqrt{\mu_{0} \varepsilon_{0} \varepsilon_{r}} \left[ \frac{1}{2} \left( 1 + \frac{\sigma^2}{(\varepsilon_{0} \varepsilon_{r} \omega)^2} - 1 \right) \right]^{1/2}
\]

where \( \omega \) is the angular frequency of the wave, \( \mu_{0} \) and \( \varepsilon_{0} \) are the magnetic permeability and dielectric permittivity of vacuum, and \( \varepsilon_{r} \) and \( \sigma \) are the relative dielectric constant and conductivity of the medium. Considering the attenuation effect of the material, (1) can be rewritten as

\[
A_{2} \cdot e^{j\theta_{2}} = A'_{LOS} \cdot e^{j(k_{R} \cdot d)} \cdot e^{j(\theta'_{LOS} - k_{R} \cdot d)} + A_{m} \cdot e^{j\theta_{m}}
\]

where \( A'_{LOS} \cdot e^{j\theta'_{LOS}} \) implies the signal without the effect of the material.

The received signals can also be expressed as the multiplication of transmitted signal using the channel frequency response in the frequency domain

\[
R(f) = S(f) \cdot H(f)
\]

where \( S(f) \) and \( R(f) \) are the spectrums of the transmitted and received signal. \( H(f) \) is the channel response which is measured by the NIC and revealed as the CSI data. Then, the signals \( A_{2} \cdot e^{j\theta_{2}}, A_{m} \cdot e^{j\theta_{m}}, \) and \( A'_{LOS} \cdot e^{j\theta'_{LOS}} \) can be represented as

\[
A_{2} \cdot e^{j\theta_{2}} = S(f) \cdot \|H_{2}(f)\| \cdot e^{j\theta_{2}}
\]

\[
A_{m} \cdot e^{j\theta_{m}} = S(f) \cdot \|H_{m}(f)\| \cdot e^{j\theta_{m}}
\]

\[
A'_{LOS} \cdot e^{j\theta'_{LOS}} = S(f) \cdot \|H_{LOS}(f)\| \cdot e^{j\theta'_{LOS}}
\]

where \( H_{2}(f), H_{m}(f), \) and \( H_{LOS}(f) \) are the channel responses corresponding to the receiver Rx2, multipath, and LOS without

![Fig. 1. Schematic of the proposed WiEps system. (Red and purple dashed lines represent the wave propagation in the LOS and multipath effect, respectively.)](image-url)
material, respectively. Insert (6)–(8) into (4) and divide out relative to that of the reference channel 

data. (a) and (b) two independent measurement cases. (c) Adjust the phase relative to that of the reference channel \( H_{r1} \).

Fig. 2. Illustration of phase information revealed by the channel response data. (a) and (b) two independent measurement cases. (c) Adjust the phase relative to that of the reference channel \( H_{r1} \).

Introduce three variables \( \Delta \theta_{H_{r2}} = \theta_{H_{r2}} - \theta_{H_{r1}} \), \( \Delta \theta_{H_{l}} = \theta_{H_{l}} - \theta_{H_{r1}} \), and \( \Delta \theta_{H_{m}} = \theta_{H_{m}} - \theta_{H_{r1}} \). Insert \( \Delta \theta_{H_{r2}}, \Delta \theta_{H_{l}}, \) and \( \Delta \theta_{H_{m}} \) into (10), the equation can be rewritten as follows:

\[
\| H_{r2}(f) \| \cdot e^{j \Delta \theta_{H_{r2}}} = \| H_{l}(f) \| \cdot e^{j \Delta \theta_{H_{l}}} \cdot e^{-j k_{l} d - j k_{R} d} + \| H_{m}(f) \| \cdot e^{j \Delta \theta_{H_{m}}}. \tag{11}
\]

By using (11), the relationship between the material dielectric property and the measured CSI data is characterized with two complex coefficients to be determined, which are \( \| H_{l}(f) \| \cdot e^{j \Delta \theta_{H_{l}}} \) and \( \| H_{m}(f) \| \cdot e^{j \Delta \theta_{H_{m}}} \). The effects from other objects’ reflected signals are included in \( \| H_{m}(f) \| \cdot e^{j \Delta \theta_{H_{m}}} \). Since other objects are kept stationary during the whole experiment, \( \| H_{m}(f) \| \cdot e^{j \Delta \theta_{H_{m}}} \) is considered to be consistent. By using the materials whose dielectric properties are already known, the coefficients can be calculated.

Rewrite (11) as the following:

\[
e^{-j k_{l} d - j k_{R} d} = \frac{\| H_{r2}(f) \| \cdot e^{j \Delta \theta_{H_{r2}}} - \| H_{l}(f) \| \cdot e^{j \Delta \theta_{H_{l}}}}{\| H_{l}(f) \| \cdot e^{j \Delta \theta_{H_{l}}}}. \tag{12}
\]

Denote the result of the right-hand side of (12) as \( B \cdot e^{j \theta_{R}} \). Then, the following can be obtained:

\[
k_{l} = - \frac{\ln B}{d}, \tag{13}
\]

\[
k_{R} = - \frac{\theta_{R}}{d}. \tag{14}
\]

Divide \( k_{R} \) by \( k_{l} \) using (3) and (2), the following equation can be obtained:

\[
\left( \frac{k_{R}}{k_{l}} \right)^{2} = \sqrt{\frac{1 + \frac{\sigma^{2}}{(\varepsilon_{r} \varepsilon_{0})^{2}}} {1 + \frac{\sigma^{2}}{(\varepsilon_{r} \varepsilon_{0})^{2}}}} + 1. \tag{15}
\]

Introduce \( n = \sigma / \varepsilon_{r} \) to (15), thus (15) can be rewritten as

\[
\left[ \frac{k_{R}}{k_{l}} \right]^{2} = 1 + \frac{n^{2}}{(\varepsilon_{r} \varepsilon_{0})^{2}} - 1. \tag{16}
\]

By using (16), \( n \) can be calculated as

\[
n = \varepsilon_{r} \varepsilon_{0} \sqrt{\frac{1 + \frac{k_{R}^{2}}{k_{l}^{2}}}{\frac{k_{R}^{2}}{k_{l}^{2}} - 1}} - 1. \tag{17}
\]

Substitute \( \sigma / \varepsilon_{r} \) with \( n \) in (2), the relative dielectric constant can be calculated as

\[
\varepsilon_{r} = \frac{2k_{R}^{2}}{\omega^{2} \varepsilon_{0} \varepsilon_{0}} \left[ \frac{1 + \frac{n^{2}}{(\varepsilon_{r} \varepsilon_{0})^{2}}} {1 + \frac{n^{2}}{(\varepsilon_{r} \varepsilon_{0})^{2}}} + 1 \right]. \tag{18}
\]

Subsequently, the conductivity can be obtained by

\[
\sigma = n \cdot \varepsilon_{r}. \tag{19}
\]

With the derivation above, the dielectric constant \( \varepsilon_{r} \) and conductivity \( \sigma \) of a material can be obtained from the measured channel response data.

Fig. 3 summarizes the flowchart of the WiEps system for the dielectric characterization. The operation is divided into two stages, which are the calibration stage and estimation
stage. In the calibration stage, the measurements are conducted using materials with known dielectric properties. Then, the coefficients which determine the current WiEps system are calculated using the phase adjusted CSI data and the factors $k_I$ and $k_R$ as described in (11). In the estimation stage, the measurements are carried out using the materials whose dielectric properties are unknown. Subsequently, the factors $k_I$ and $k_R$ are calculated using the phase adjusted CSI data and the coefficients as depicted in (12)–(14). Finally, the dielectric constant and conductivity of the material are estimated as described in (17)–(19).

V. EXPERIMENT EVALUATION

The performance of the proposed WiEps system is first evaluated by applying to the measurement of ethanol/water mixtures. In the evaluation, the solutions with different ABVs are prepared. The ABVs are from 0% to 90% at a step of 10%. The Chinese liquor (Baijiu) with the ABV of 46% and 56% are utilized to assess the system. Besides, additional liquids are tested for further validation of the system.

A. Dielectric Property Measurement With Standard Technique

In order to calibrate the WiEps system and evaluate the correctness of the results by the proposed method, the dielectric properties of the materials are measured in advance by the standard technique with VNA and open-ended coaxial probe [27]–[29], [46]. Fig. 4 shows the measurement setup. The ROHDE & SCHWARZ ZVA40 VNA with the frequency range of 10 MHz–40 GHz and SPEAG DAK-3.5 probe with the frequency range of 200 MHz–20 GHz are utilized. The cables and the probe are fixed carefully. They are not touched through the whole process. The calibration is carried out before measurement using the Open/Short/Load (OSL) technique. The ethanol/water solutions with different ABVs and other materials are stored in separate bottles. During the measurement, the cushion is first moved away and the probe is immersed into the solution by moving the bottle. The probe is kept static and it is ensured that there are no air bubbles attaching on the probe. Then, the cushion is set under the bottle to keep the measurement system stable. After the measurement, the cushion and bottle are moved away and the head of the probe is dried by tissue. The bottle is changed in turn and the measurement is repeated for all materials. The measured data are sent to the PC connected to the VNA and processed by the DAK software to get the dielectric constant and conductivity values.

The dielectric properties measured in a wide frequency range by the standard technique are shown in Fig. 5. It can be observed that the dielectric constant decreases with the frequency increasing. While the conductivity is increasing when the frequency increases. The conductivity implies the dissipation effect of electromagnetic energy in the materials. The increasing conductivity indicates that the energy of the
microwave is absorbed more at higher frequencies. Regarding to different ABVs, the dielectric constant increases monotonically with the reduction of alcohol volume. While the conductivity does not show such monotonic behavior with the change of ABV. The relationship between the ABV rate and wideband dielectric properties has been studied mathematically in [46] and [47] using dispersive models. While in this article, the frequency range of the microwave is narrow. Therefore, the dielectric properties at a single frequency are considered. The dashed line shows the values at 5.32 GHz, which is the chosen operation frequency of the WiEps system in the evaluation. The dielectric properties at 5.32 GHz will be utilized for calibrating WiEps and comparing the results.

B. Measurement With the WiEps System

The experiment configuration of the WiEps system in operation is shown in Fig. 6. The antennas and the container are fixed on the table. Tx1 is connected to port A of the NIC on the transmitter side. Rx1 and Rx2 are connected to port A and B of the NIC on the receiver side. The size of the container is A5 standard with the length of 210 mm and the height of 148 mm. The gap of the container is 2 mm. The communication channel 64 with the center frequency of 5.32 GHz and the bandwidth of 20 MHz is chosen in the experiment [45]. Tx1 is set to transmit signals every 0.05 s and each measurement lasts 20 s. It should be noted that the physical movement of human affects the received signals significantly. Therefore, during the experiment, after loading the material, the operator starts the measurement and gets away from the system immediately to avoid the influence of human on the final experiment results.

After measurement, both the coarse-grained received signal strength indicator (RSSI) and the fine-grained CSI data are recorded. RSSI indicates the whole received power by the receiver antenna and CSI reveals the channel response by each subcarrier. However, the values of RSSI and CSI are relative to some internal references. The raw data cannot be utilized for quantitative calculation. In the theoretical derivation, the amplitude of the channel response, such as \( \| H_{22}(f) \| \) in (11) is expected to be in voltage. Therefore, the CSI data need pre-processing to rescale the unit. The total received power can be calculated by

\[
P_{\text{total}} = 10^{\frac{\text{RSSI}_a}{10}} + 10^{\frac{\text{RSSI}_b}{10}} + 10^{\frac{\text{RSSI}_c}{10}} - \text{AGC} - C
\]

(20)

where RSSI\(_a\), RSSI\(_b\), and RSSI\(_c\) are the recorded RSSI at three antenna ports, respectively. AGC is the automatic gain control factor which is implemented in the hardware to amplify the received signal adaptively before sampling. \( C \) is a constant which implies the internal reference. Subsequently, a rescale factor can be obtained by

\[
\alpha = \frac{\sum \text{CSI}_a \cdot \text{CSI}_a^H + \sum \text{CSI}_b \cdot \text{CSI}_b^H + \sum \text{CSI}_c \cdot \text{CSI}_c^H}{30}
\]

(21)

where CSI\(_a\), CSI\(_b\), and CSI\(_c\) are the CSI data recorded at three ports, respectively. CSI\(_a^H\), CSI\(_b^H\), and CSI\(_c^H\) are the corresponding conjugates. Then, all the CSI data are multiplied by \( \sqrt{\alpha} \) and the units are in voltage.

Fig. 7 shows an example of the amplitude \( \| H_{22}(f) \| \) and adjusted phase \( \Delta \phi_{H_{22}} \) for all recorded 30 subcarriers at Rx2 in time dimension. It can be observed that there are large variations at the first 5 s (red box in Fig. 7) both in phase and amplitude. This is caused by human activity where the operator leaves from the system after measurement starts. The signals become relatively stable after 5 s. As for a single carrier, there are still some random noise in the data. The time-averaging method is used to mitigate the noise. To ensure that the system is completely stable and the influence of human is avoided, the averaging range is chosen from 10 to 20 s. The averaged values are employed for calculation of the dielectric property.

Fig. 8 shows the averaged amplitudes and adjusted phases of all the ethanol/water mixtures with respect to the subcarrier number. Generally, microwave signals propagate slower in materials with larger dielectric constant. Thus, the phase will be lagged more. It can be observed that with the increase of ABV, the phase becomes larger at all subcarrier frequencies as shown in Fig. 8(a). The results coincide with the dielectric properties measured in Section V-A. As for the amplitude, the microwave attenuates more quickly in materials with higher...
conductivity. However, the values for 0% and 90% at higher frequencies tend to be similar while the conductivities of the two ABVs are quite different. This is caused by the multipath effect. Meanwhile, the difference of amplitude is relatively smaller for various ABVs and no monotonic relationship is found between the amplitude and ABV. In order to quantitatively characterize the relationship between the CSI data and dielectric property, the model proposed in Section IV is employed.

C. Dielectric Characterization Using the Theoretical Model

In the calibration stage as shown in Fig. 3, the measured dielectric properties at 5.32 GHz and the CSI data of the 16th subcarrier which is adjacent to the center frequency are utilized. The Levenberg–Marquardt method is applied to fit the complex-valued equation [48]. Then, using the estimated coefficients, the dielectric properties are calculated according to the workflow in the estimation stage. The relative errors \( \delta_{\varepsilon_r} \) and \( \delta_{\sigma} \) are used to assess the accuracy

\[
\delta_{\varepsilon_r} = \frac{|\varepsilon_r - \hat{\varepsilon}_r|}{\varepsilon_r} \quad (22)
\]

\[
\delta_{\sigma} = \frac{|\sigma - \hat{\sigma}|}{\sigma} \quad (23)
\]

where \( \varepsilon_r \) and \( \sigma \) are the dielectric properties measured by the standard method. \( \hat{\varepsilon}_r \) and \( \hat{\sigma} \) are the corresponding estimated values using the proposed WiEps system.

The WiEps is first calibrated using the known ethanol/water mixtures. Then, the calibrated system is used to measure the unknown materials which are the Baijiu liquors. The estimated results and the comparison with the standard method are shown in Table I. It can be observed that the relative errors of dielectric constant are lower than 8% and the average error across 12 materials is approximately 4.3%. This demonstrates that the proposed model effectively characterizes the dielectric constant using the CSI data. While the corresponding errors of conductivity are within 15% and the average error across 12 materials is about 7.1%, which is relatively larger compared with that of dielectric constant. These results indicate that the proposed WiEps can be used for the measurement of dielectric properties. Especially, the quantitative quality check of liquors is possible with WiEps. The ABV can be estimated using a preprepared table which lists different ABVs and the corresponding dielectric properties.

D. Estimation Results With Other Subcarriers

The bandwidth of the WiFi signal is 20 MHz and the frequency range of the operating channel is from 5310 to 5330 MHz. Within the operating frequency range, the dielectric properties of the ethanol/water solutions are almost the same. If the values at the center frequency are chosen as the baseline, the variation range for \( \varepsilon_r \) is \([-0.17\%, 0.18\%]\) and that for \( \sigma \) is \([-0.44\%, 0.51\%]\). Therefore, the dielectric properties can be regarded constant within the bandwidth range.

The bandwidth is divided into 64 subcarriers with a frequency interval of 312.5 kHz and only 56 of them are used to transmit data and pilots. The recorded CSI data include a subgroup of 30 subcarriers from No. −28 to No. 28 [45]. The CSI data from other subcarriers are also applied to calibrate the WiEps system and to characterize the Baijiu liquors. The estimation errors are shown in Fig. 9. Each group of the bar plots represents the results for a certain material. The subcarrier is sorted in the ascending order from left to right within the group. It can be observed that as for dielectric constant, the estimation errors are below 8% which is at the same level of the 16th subcarrier except for the 90% solution. The estimation errors with different subcarriers vary a lot in some materials, such as the 90% solution and 46% Baijiu. The difference in error is larger than 5%. Meanwhile, some subcarriers perform better than the 16th one in some materials, such as 30% and 70% solutions, and both 46% and 56% Baijiu. A similar observation is also obtained for the conductivity error. Except for the data of 80% solution, the estimation errors are below 15% which is at the same level of the 16th subcarrier. The estimation results are quite similar for 0%, 10%, 20%, and 30% of conductivity.
solutions. While those for 40%, 50%, and 60% have larger variation. There is no significant evidence to imply which subcarrier performs best consistently. However, it is found that in most cases where the estimation error changes a lot, the error value is almost ascending or descending with respect to the subcarrier number. Therefore, the subcarrier which is adjacent to center frequency is considered to be a moderate choice for estimating the dielectric property.

E. Validation With Other Liquids

In order to further validate the efficacy of the proposed WiEps, it is applied to more liquids. Besides, the experiment with no material inside the container (air) is also carried out. During the experiment, the distances between the object and Tx/Rx antenna are set as 10 cm, and the distance between Tx and Rx antennas is 20 cm. The additional liquids include two other kinds of liquors (Jinro Soju and Grape Soju), saline with different concentrations (0.9%, 3.5%, and 7%), and glucose/water mixtures (5%, 10%, and 25%). For each material, the measurement is conducted five times and the order of the measurement is shuffled. Totally, 105 measurements are carried out with 21 materials (including air).

Fig. 10(a) and (b) shows the amplitudes and phases of all the measurement of the materials with respect to the subcarrier number. By averaging the data from multiple measurements, the averaged values at the 16th subcarrier are shown in Fig. 10(c). It can be observed that the amplitude of air is the largest and those of the saline are small. This is because the conductivity of saline is relatively high. The WiEps is calibrated with known ethanol/water mixtures using the averaged data from multiple measurements. Then, the dielectric properties of other materials are estimated using the averaged data as well. The measurement results for all materials are shown in Table II. The dielectric properties of the air are estimated with absolute errors of 0.38 and 0.39 for $\varepsilon_r$ and $\sigma$. Since the actual dielectric properties for air is small, the relative errors can be a large number even when the absolute value is small. Therefore, when referring to the average relative error, the air is excluded. The average relative errors of dielectric constant and conductivity across all materials except...
Fig. 11. Amplitude, adjusted phase, and averaged phase/amplitude at the 16th subcarrier from multiple measurements of CSI data for all measurements when the distances between Tx and Rx are (a)–(c) 40 cm, (d) and (e) 60 cm, and (g)–(i) 100 cm, respectively.

are better than those of 40 and 60 cm. The reason is considered to be the effect of multipath. When the distances are 40 and 60 cm, the phase spans are only 40° and 78°, respectively. For comparison, those of 20 and 100 cm are 130° and 203°, respectively. When the multipath signals are strong, the change in the LOS component which caused by the materials have less influence on the total received signal. Therefore, the phase span is smaller. Since the data are converted from analog signals, the accuracy is degraded by the quantum error and small values may not be precisely sampled. The data accuracy is worse if the value range is small. In the proposed theoretical model, the effect of multipath signals is included. However, if the data accuracy is low, the performance of the model will be impaired. Thus, the performance when the distances are 40 and 60 cm is worse than that of 100 cm. Comparing the results for the cases of 20 and 100 cm, it can be found that the smaller distance has better estimation accuracy because the amplitude of the received signal is larger and the data accuracy can be improved. Therefore, to get an optimal performance of WiEps with the commodity WiFi device, the distance between the object and the antennas should be configured relatively small. Meanwhile, weaker multipath signals with the configuration can help improve the measurement accuracy.

VI. Conclusion
A dielectric property measurement system, WiEps is developed which is composed of the commodity WiFi devices. The proposed system utilizes the transmission features of the microwave caused by dielectric property change. The transmitted WiFi signal through the material is theoretically analyzed and it is utilized to quantitatively measure the dielectric properties of the materials. A theoretical model is proposed to characterize the wave propagation behavior through the material in the WiEps system and to quantitatively describe the relationship between the material dielectric property and CSI data. The system is first applied to measure the ethanol/water mixtures. Then, additional liquids are tested for further verification. In the experiment, WiEps is deployed under the indoor condition where the multipath effect exists. Using the WiEps, the average errors across all materials are 4.0% and 8.9% for dielectric constant and conductivity, respectively. These results demonstrate the efficacy of the proposed WiEps system for dielectric property measurement.

By quantitatively estimating the dielectric properties of the material, this method can be applied to food engineering, such as quality check of liquors and identification of liquids. Besides, this method is also promising to be applied in security check, water contamination detection, and monitoring the dielectric property of material during the manufacturing process. More applications will be considered and investigated in the future work.

REFERENCES
[1] J. Wang, L. Zhang, Q. Gao, M. Pan, and H. Wang, “Device-free wireless sensing in complex scenarios using spatial structural information,” *IEEE Trans. Wireless Commun.*, vol. 17, no. 4, pp. 2432–2442, Apr. 2018.
[2] L. Zhang and H. Wang, “3D-WiFi: 3D localization with commodity WiFi,” IEEE Sens. J., vol. 19, no. 13, pp. 5414–5412, Jul. 2019.

[3] X. Yang et al., “Freezing of gait detection considering leaky wave cable,” IEEE Trans. Antennas Propag., vol. 67, no. 1, pp. 544–541, Jan. 2019.

[4] H. Yan, Y. Zhang, Y. Wang, and K. Xu, “WiAct: A passive WiFi-based human activity recognition system,” IEEE J. Sel. Top. Antennas Propag., vol. 20, no. 1, pp. 296–305, Jan. 2020.

[5] D. Halperin, W. Hu, A. Sheth, and D. Wetherall, “Tool release: Gathering 802.11 traces with channel state information,” SIGCOMM Comput. Commun. Rev., vol. 41, no. 1, p. 53, 2011.

[6] Y. Gu, J. Zhan, Y. J. Li, F. Ren, and S. Gao, MoSense: An RF-based motion detection system via off-the-shelf WiFi devices,” IEEE Internet Things J., vol. 4, no. 6, pp. 2326–2341, Dec. 2017.

[7] J. Liu, Y. Chen, Y. Wang, X. Chen, J. Cheng, and J. Yang, “Monitoring vital signs and postures during sleep using WiFi signals,” IEEE Internet Things J., vol. 5, no. 3, pp. 2071–2084, Jun. 2018.

[8] D. Zhang, Y. Hu, Y. Chen, and B. Zeng, “BreathTrack: Tracking indoor human breath status via commodity WiFi,” IEEE Internet Things J., vol. 6, no. 2, pp. 3899–3911, Apr. 2019.

[9] C. Xiao, D. Han, Y. Ma, and Z. Qin, “CiGaN: Robust channel state information-based activity recognition with GANs,” IEEE Internet Things J., vol. 6, no. 6, pp. 10191–10204, Dec. 2019.

[10] F. Wang, W. Gong, and J. Liu, “On spatial diversity in WiFi-based human activity recognition,” IEEE Access, vol. 8, no. 40503, Apr. 2019.

[11] J. Wang et al., “Low-human-effort, device-free localization with fine-grained subscriber information,” IEEE Trans. Mobile Comput., vol. 17, no. 11, pp. 2550–2563, Nov. 2018.

[12] K. Niu et al., “WiMorse: A contactless morse code text input system using ambient WiFi signals,” IEEE Internet Things J., vol. 6, no. 6, pp. 9993–10008, Dec. 2019.

[13] Y. Gu et al., “EmoSense: Computational intelligence driven emotion sensing via wireless channel data,” IEEE Trans. Emerg. Topics Comput. Intell., vol. 4, no. 3, pp. 216–226, Jun. 2020.

[14] L. Cheng and J. Wang, “Walls have no ears: A non-intrusive WiFi-based user identification system for mobile devices,” IEEE/ACM Trans. Netw., vol. 27, no. 1, pp. 245–257, Feb. 2019.

[15] J. Wang, J. Tong, Q. Gao, Z. Wu, S. Bi, and H. Wang, “Device-free vehicle speed estimation with WiFi,” IEEE Trans. Veh. Technol., vol. 67, no. 9, pp. 8205–8214, Sep. 2018.

[16] J. A. Kong, Electromagnetic Wave Theory. Cambridge, MA, USA: EMW, 2008.

[17] W. Yang, X. Wang, A. Song, and S. Mao, “Wi-Wheat: Contact-free wheat moisture detection with commodity WiFi,” in Proc. IEEE Int. Conf. Commun. (ICC), Kansas City, MO, USA, 2018, pp. 1–6.

[18] S. Zhong, Y. Huang, R. Ruby, L. Wang, Y. Qiu, and K. Wu, “Wi-Fire: Device-free fire detection using WiFi networks,” in Proc. IEEE Int. Conf. Commun. (ICC), Paris, France, 2017, pp. 1–6.

[19] C. Feng et al., “WiMi: Target material identification with commodity Wi-Fi devices,” in Proc. IEEE 39th Int. Conf. Distrib. Comput. Syst. (ICDCS), Dallas, TX, USA, 2019, pp. 700–710.

[20] O. Wolfbeis, Fiber-optic chemical sensors and biosensors. Anal. Chem., vol. 76, pp. 3269–3284, Apr. 2004.

[21] K. J. Bois, L. F. Handjojo, A. D. Benally, K. Mubarak, and R. Zoughi, “Comparison of different methods for dielectric property measurements in liquid sample media,” Int. J. RF Microw. Comput.-Aided Eng., vol. 28, no. 3, 2017, Art. no. e21215.

[22] J. Sheen, “Comparisons of microwave dielectric property measurements by transmission/reflection techniques and resonance techniques,” Meas. Sci. Technol., vol. 20, no. 4, pp. 1–12, 2009.

[23] K. Z. Rajab, K. Fuh, R. Mittra, and M. Lanagan, “Dielectric property measurement using a resonant nonradiative dielectric waveguide structure,” IEEE Microw. Wireless Compon. Lett., vol. 15, no. 2, pp. 104–106, Feb. 2005.

[24] C. Zhu, Y. Zhuang, Y. Chen, and J. Huang, “A hollow coaxial cable Fabry–Perot resonator for liquid dielectric constant measurement,” Rev. Sci. Instrum., vol. 80, no. 4, 2009.

[25] G. R. Koirala, R. Dhakal, E. Kim, Z. Yao, and N. Kim, “Radio frequency detection and characterization of water-ethanol solution through spiral-coupled passive micro-resonator sensor,” Sensors, vol. 18, no. 4, p. 1075, 2018.

[26] L. Xu, W. Huang, G. Wu, and H. Wu, “A flexible microwave sensor based on complementary spiral resonator for material dielectric characterization,” IEEE Sens. J., vol. 20, no. 4, pp. 1893–1903, Feb. 2020.

[27] W. Liu, H. Sun, and L. Xu, “A microwave method for dielectric characterization measurement of small liquids using a metamaterial-based sensor,” Sensors, vol. 18, no. 5, p. 1438, 2018.

[28] A. Soffiati, Y. Max, S. G. Silva, and L. M. de Mendonça, “Waveform metamaterial-based sensor for dielectric characterization of liquids,” Sensors, vol. 18, no. 5, p. 1513, 2018.

[29] Z. Wei, “A high-sensitivity microfluidic sensor based on a substrate integrated waveguide re-entrant cavity for complex permittivity measurement of liquids,” Sensors, vol. 18, no. 11, p. 4005, 2018.

[30] P. P. Bobrov, A. V. Repin, and O. V. Rodionova, “Wideband frequency domain method of soil dielectric property measurements,” IEEE Trans. Geosci. Remote Sens., vol. 53, no. 5, pp. 2366–2372, May 2015.

[31] J. V. Pantoja, S. Gutierrez, E. Pineda, D. Martinez, C. Baer, and F. Vega, “Modeling and measurement of complex permittivity of soils in UHF,” IEEE Geosci. Remote Sens. Lett., early access, Oct. 8, 2019, doi: 10.1109/LGRS.2019.2942181.

[32] P. Meany, T. Ryholm, and H. Brisby, “A transmission-based dielectric property probe for clinical applications,” Sensors, vol. 18, no. 10, p. 3484, 2018.

[33] C. Guo, R. Liu, X. Chen, G. Mavko, and Z. He, “An ultra-wideband measurement method for the dielectric property of rocks,” IEEE Geosci. Remote Sens. Lett., vol. 16, no. 6, pp. 674–678, Jun. 2019.

[34] K. Berling et al., “Determining ethanol content of liquid solutions using laser feedback interferometry with a terahertz quantum cascade laser,” IEEE Sensors Lett., vol. 2, no. 3, pp. 1–4, Sep. 2018.

[35] A. Dhake, M. Gouda, Y. Zhao, H. Hassanieh, and R. R. Choudhury, “LiquID: A wireless liquid identifier,” in Proc. 16th ACM Int. Conf. Mobile Syst. (MobiSys), Munich, Germany, 2018, pp. 442–454.

[36] IEEE Standard for Information Technology—Local and Metropolitan Area Networks—Specific Requirements—Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 5: Enhancements for Higher Throughput, IEEE Standard 802.11n-2009, Oct 2009.

[37] J. Bao et al., “Microwave dielectric characterization of binary mixture of water, methanol, and ethanol,” J. Chem. Phys., vol. 104, no. 12, pp. 4441–4450, 1996.

[38] S. Mashimo, T. Umehara, and H. Reddin, “Structures of water and primary alcohol studied by microwave dielectric analyses,” J. Chem. Phys., vol. 95, no. 25, pp. 6257–6260, 1991.

[39] J. J. Moré, “The Levenberg–Marquardt algorithm: Implementation and theory,” Numerical Analysis (Lecture Notes in Mathematics), vol. 630, G. A. Watson, Ed. Berlin, Germany: Springer, 1978, pp. 105–116. [Online]. Available: https://link.springer.com/10.1007/BFb0067700#citeas
Hang Song (Member, IEEE) received the B.S. and M.S. degrees in electronic science and technology from Tianjin University, Tianjin, China, in 2012 and 2015, respectively, and the Ph.D. degree from Hiroshima University, Hiroshima, Japan, in 2018. He was a Visiting Researcher with the Research Institute for Nanodevice and Bio Systems, Hiroshima University. He is currently an Assistant Professor with the Tianjin Key Laboratory of Imaging and Sensing Microelectronic Technology, School of Microelectronics, Tianjin University. His research interests are wireless sensing, microwave imaging, signal processing, complex permittivity measurement for biomedical engineering, microwave detection system development, and antenna design.

Bo Wei (Member, IEEE) received the B.E. and M.E. degrees from Tianjin University, Tianjin, China, in 2012 and 2015, respectively, and the Ph.D. degree from Waseda University, Tokyo, Japan, in 2019. She is currently an Assistant Professor with the Graduate School of Fundamental Science and Engineering, Waseda University. Her research interests include wireless communication, machine learning, adaptive video transmission, computer networking, and Internet of Things. Dr. Wei is a member of IEICE.

Qun Yu received the B.S. degree in electronic science and technology from Tianjin University, Tianjin, China, in 2018, where he is currently pursuing the master’s degree with microelectronics and solid electronics. His research interests include microwave detection system and machine learning.

Xia Xiao (Member, IEEE) received the B.S. degree in physics and the M.S. degree in condensed physics from Tianjin Normal University, Tianjin, China, in 1993 and 1996, respectively, and the Ph.D. degree in electronic and information technology from the Technical University of Chemnitz, Chemnitz, Germany, in 2002. From 2002 to 2003, she contributed to the “MIRAI Project” with the National Institute of Industrial Science and Technology, Tokyo, Japan, where she worked in ULSI low-\(k\)/Cu interconnect technology as a Key Researcher. In 2003, she joined the School of Electronic Information Engineering, Tianjin University, Tianjin, where she is currently a Professor. From 2006 to 2007, she was a Visiting Professor with Hiroshima University, Hiroshima, Japan, where she worked in developing algorithms for UWB imaging for early breast cancer detection. Her research interests include advanced algorithms for early breast cancer detection by UWB and nondestructive characterization of film properties by surface acoustic waves.

Takamaro Kikkawa (Life Fellow, IEEE) received the B.S. and M.S. degrees in electronic engineering from Shizuoka University, Shizuoka, Japan, in 1974 and 1976, respectively, and the Ph.D. degree in electronic system from Tokyo Institute of Technology, Tokyo, Japan, in 1994. In 1976, he joined NEC Corporation, Tokyo, where he conducted research and development on interconnect technologies for large-scale integrated circuits and dynamic random access memories. From 1983 to 1984, he was a Visiting Scientist with the Massachusetts Institute of Technology, Cambridge, MA, USA, where he conducted research on SOI transistors. In 1998, he joined the Faculty of Hiroshima University, Hiroshima, Japan, where he is a Professor with the Graduate School of Advanced Sciences of Matter and the Director of the Research Institute for Nanodevice and Bio Systems. He is also a Councilor of Hiroshima University. From 2001 to 2008, he was appointed the Senior Research Scientist with the National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan, and the Group Leader of low-\(k\)/Cu interconnect technology of Japan’s “MIRAI Project.” His research interests include wireless and wired interconnect technologies, impulse-radio-CMOS transceiver circuits with on-chip antennas, and impulse-radar-based CMOS breast cancer detection systems. Prof. Kikkawa is a Fellow of the Japan Society of Applied Physics.