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WiFi for Sensorless Sensing: A Review

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ABSTRACT: The capability of PHY layer of WiFi has made it possible to utilize WiFi signals for both communication and sensing. Sensing via WiFi would help in remote sensing without any actual wearable sensors. Simultaneous perception and data transmission without extra communication infrastructure and contactless sensing are possible by using wifi signals. Ubiquitous deployment of WiFi networks and the growing popularity of wifi usage, if fully connected, they would potentially be ranked as one of the world's largest wireless sensor networks. The concept of this sensor less sensing requires more than a simple combination of WiFi and radar. To meet the rising demand for pervasive environment perception in everyday life this sensing combination of WiFi and radar seeks breakthrough from dedicated radar systems, and aims to bring balance between low cost and high accuracy. Despite increasing research interest, wireless sensing is still in a very early stage. Using the introductions on basic principles and working prototypes, a review on the feasibilities and limitations of wireless, sensor less, and contactless sensing via WiFi is presented. This article is an envision on wireless sensing concept for interested readers to explore this open and largely unexplored field and create next-generation wireless and mobile computing applications.

KEYWORDS: Channel State Information (CSI), sensor less sensing, WiFi; indoor localization, device-free human detection, activity recognition, wireless networks; ubiquitous computing.

I.INTRODUCTION

Developments in technology have extended the role of wireless signals from being a communication medium to a contactless sensing platform, especially indoors. In indoor environments, wireless signals often propagate via both the direct path and multiple reflection and scattering paths, resulting in multiple aliased signals superposing at the receiver. As the physical space constrains the propagation of wireless signals, the wireless signals in turn convey information that characterizes the environment they pass through. Herein the environment refers to the physical space where wireless signals propagate, which includes both ambient objects (e.g., walls and furniture) and humans (e.g., their locations and postures). As shown in Fig. 1, sensing the surrounding environment is done by analyzing the received WiFi signals, with increasing levels of sensing contexts. It is not a brand-new concept to exploit wireless signals for contactless environment sensing.

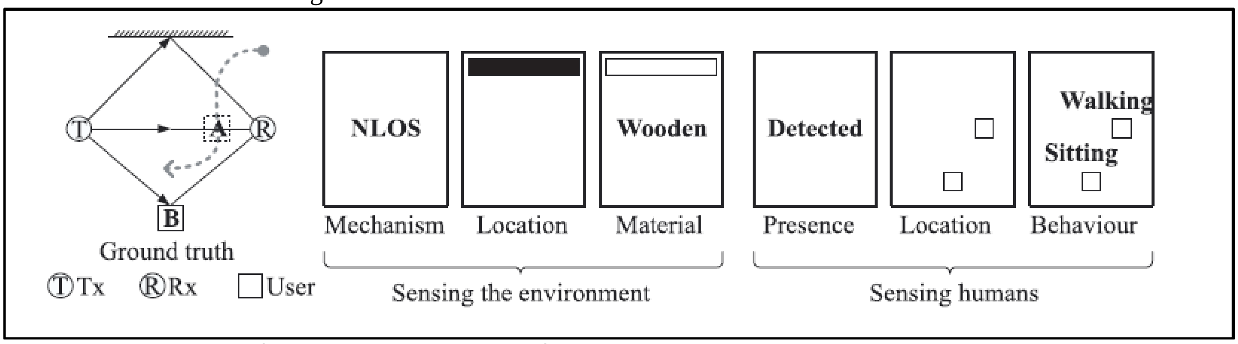

Fig 1 Illustration of setups and sensing tasks for wireless sensing in multipath propagation environments.

Aircraft radar systems, as a representative, detect the presence of outdoor aircrafts and determine their range, type, and other information by analyzing either the wireless signals emitted by the aircrafts themselves or those broadcast by the radar transmitters and reflected by the aircrafts afterwards. Recent research has also explored Ultra-Wide Band (UWB) signals for indoor radar systems[1]. Primarily designed for military context, however, these techniques

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either rely on dedicated hardware or extremely wide bandwidth to obtain high time resolution and accurate range measurements, impeding their pervasive deployment in daily life. On the other hand, contactless sensing technology is of rising demand in our everyday world. For instance, extensive research is done in the area of human detection [2–5]. Where Passive refers to detecting users via wireless signals, while the users carry no radio-enabled devices[2]. Such privacy preserving modes can stimulate various applications like security surveillance, intrusion detection, elderly monitoring, remote health-care, and innovative human-computer interaction. Deploying extra sensors like UWB radar systems is one solution for passive human detection. Such WiFi-based sensing is challenging in two aspects: Standard WiFi signals have limited bandwidth and insufficient time resolution compared with dedicated radar signals; commercial WiFi hardware often fails to support sophisticated radar signal processing. It is thus urgent to break away from traditional radar systems and develop theory and technology for high-resolution wireless sensing with off-the-shelf WiFi infrastructure. Although neither WiFi nor radar alone yields new concepts, their combination sparks interesting innovations in mobile computing. This wide unexplored field has been termed as Wireless Sensing, Sensor less Sensing or Radio Tomography Imaging[3] by researchers, and we will use wireless sensing and sensorless sensing throughout this paper. In this paper, we reviewed the emergence of wireless, sensorless, and contactless sensing viaWiFi.We focus on the principles and the infrastructure advances that enable wireless and sensorless sensing on commodity devices. Although WiFi based sensing prototypes were designed over past few years but we expect wireless, sensorless, and contactless sensing technology to leap towards industrial products in the coming few years.

II. LITERATURE SURVEY

Environment information can be inferred from wireless signals. Generally, a weak WiFi signal strength may indicate the long distance from the access point. Though intuitive, Received Signal Strength is widely used to infer environment information such as propagation distances. We have witnessed various sensing applications using RSS, with RSS-based localization as the most representative.

2.1 Received signal strength

RSS acts as a common proxy for channel quality and is accessible in wireless communication technologies like RFID, GSM, WiFi, and Bluetooth. Researchers also utilize RSS for sensing such as passive human detection and indoor localization. In theory, it is possible to estimate propagation distance by substituting RSS into propagation models or take a set of RSS from multiple access points as fingerprints for each location or infer human motions from RSS fluctuations. However, in typical indoor environments, wireless signals often follow multiple paths which is called as multipath propagation. In presence of multipath propagation, RSS may no longer decrease monotonically with propagation distance, thus ranging accuracy is limited. Multipath propagation can also lead to unpredictable RSS fluctuations. Such fluctuations in RSS may cause false match in fingerprint-based localization.

However sensing with RSS is less reliable and robust due to single-valued nature hence it fails to depict multipath propagation. Hence to avoid the impact of multipath via redundancy[3] RSS-based sensing applications often resort to dense deployed wireless links.

2.2 Channel state information

Recent efforts have dived into the PHY layer to combat the impact of multipath since RSS is only a MAC layer feature. Multipath propagation can be implemented by Channel Impulse Response (CIR). Under the time-invariant assumption, CIR is modeled as a temporal linear filter:

$$h(\tau)=\sum_{i=0}^{N} ai\, e^{-j\theta i}\delta(\tau-\tau i) \qquad (1)$$

where ai, θi, and τi denote the amplitude, phase, and delay of the i^{th} path. N is the number of paths and δ(τ) is the Dirac delta function. Each impulse represents a propagation path resolvable by time delays. Multipath propagation also leads to constructive and destructive phase superposition, which exhibits frequency-selective fading. Therefore multipath propagation can also be featured by Channel Frequency Response (CFR), the Fourier transform of CIR given infinite bandwidth. Obtaining high-resolution CIR or CFR often involves dedicated channel sounders. Yet the physical layer of

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WiFi, especially Orthogonal Frequency Division Multiplex (OFDM) based WiFi standards (e.g., IEEE 802.11a/g/n), offers a sampled CFR at the granularity of subcarriers. With slight modifications in firmware and commercial WiFi network interface cards[12], these sampled versions of CFR measurements can be revealed to upper layers in the format of CSI. Each CSI estimates the amplitude and phase of one OFDM subcarrier

H(fk)= ǁH(fk)ǁkej<H (2)

where H(fk) is the CSI at the subcarrier of central frequency fk, amplitude ǁH(fk)ǁ, and phase H.

2.3 RSS vs. CSI

CSI shows multipath propagation to a certain extent when compared to RSS thus making it an upgrade for RSS. Like an Analogy, CSI is to RSS what a rainbow is to a sunbeam.

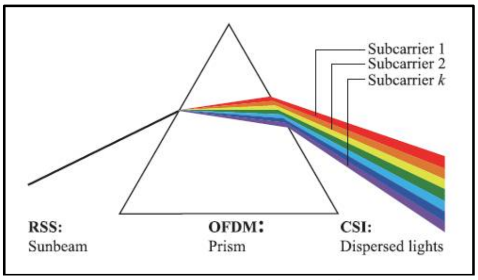

Fig 2 An analogous illustration of RSS and CSI.

As shown in Fig. 2, CSI separates signals of different wavelengths similar to light spectrum via OFDM, while RSS is a single-valued amplitude of superposed paths. As physical layer information, CSI carries channel information invisibly in MAC layer. CSI estimates the value of CFR on various multiple subcarriers, thus depicting the frequency selective fading of WiFi channels.CSI measures amplitude and phase of each subcarrier. Thus CSI provides richer channel information in the frequency domain. Since CIR is the inverse Fourier transform of CFR, CSI also enables the distinction in the time domain coarse-grained path. With proper processing, while retaining stable overall structure in the same environment. Hence we may extract finer-grained and more robust signal features from CSI via machine learning and signal processing, rather than obtain only a single value by simply adding up the amplitudes over subcarriers (a similar processing approach as RSS). Although currently CSI is only accessible on certain platforms, the continuing popularity of WiFi and its ubiquitous deployment still make CSI a relatively pervasive signal feature. However, the resolution of CSI is limited by the operating bandwidth of WiFi. Even with a bandwidth of 40MHz (IEEE 802.11n with channel bounding), its time resolution still fails to distinguish individual paths. We envision WiFi standards with increasingly wider bandwidth (e.g., IEEE 802.11ac) would provide finer-grained multipath propagation information in future.

III.METHODOLOGY

3.1Sensorless Sensing via WiFi

CSI can benefit wireless sensing. As an upgrade to RSS, CSI boosts the performance of RSS-based sensing applications. For instance, in RSS-based localization, RSS can be used as either a location-specific fingerprint or to calculate the distance between the mobile client and the access point. Similarly, CSI can be employed as a fine grained fingerprint as it carries both amplitude and phase information across subcarriers; or for more accurate ranging by accounting for frequency-selective fading. Here we refer interested readers to Ref. [13] for a more comprehensive overview on CSI-based indoor localization. Since RSS is unable to resolve multipath propagation and has unpredictable fluctuation in dense multipath propagation RSS-based applications often consider multipath harmful. In contrast, CSI manages to resolve this multipath effect at subcarrier level itself. Though it is coarse-grained, CSI offers more opportunities to harness multipath in various wireless sensing applications.

3.1 Sensing the environment

In multipath environments, propagation paths are broadly classified into Line-Of-Sight (LOS) and Non- Line-Of-Sight (NLOS) paths, where NLOS paths often pose major challenges in wireless communication and mobile computing applications. Severe NLOS propagation may degrade communication quality and deteriorate theoretical signal propagation models. To avoid the impact of NLOS propagation the availability of LOS path must be identified. As CSI always depicts multipath at the granularity of subcarriers, researchers have explored CSI for LOS identification[14, 15]. Zhou et al.[14] extracted statistical features from CSI amplitudes in both the time and frequency domains, and leveraged receiver mobility to distinguish LOS and NLOS paths based on their difference in spatial stability. Wu et al[15] utilized CSI phases of multiple antennas for real time LOS identification for both static and mobile scenarios[15]. Phase information offers an orthogonal dimension to traditional amplitude-based features, and has been successfully adopted in a range of applications, e.g., millimeter-level localization[16]. Another important characteristic in the environment is the shape and the size of rooms and corridors, which make up part of the floor plan. Floor plan is often assumed to be offered by service providers and researchers have shown increasing interest to draw floor plans by combining wireless and inertial sensing. Some works also demonstrated the feasibility of using wireless sensing alone to recover part of the floor plan information. For instance, by analyzing the difference of CSI changing rates when the WiFi device moves Wang et al.[17]distinguished straight pathways, right-angle, and arc corners. With channel measurements on multiple receiving antennas, the authors in Ref. [18] developed a space scanning scheme by calculating the angle-of-arrivals of multiple propagation paths and inferring the locations of the reflecting walls. Despite its bulky size, the working prototype holds promise for scanning the physical space wirelessly and contactless.

3.2 Sensing humans

Humans, a part of the environment where wireless signal propagate within, are of utmost interest in wireless sensing. In passive human detection, CSI can detect tiny human variations from both LOS and NLOS paths, thereby enhancing detection sensitivity and expanding sensing coverage. Zhou et al.[4] utilized CSI as finer-grained fingerprints to achieve omnidirectional passive human detection on a single transmitter-receiver link, where the user approaching the receiver from all directions can be detected. With fusion of multiple links, CSI also facilitates fine-grained passive human localization[19]. Xi et al.[5] extended human detection to multi-user scenarios by correlating the variation of CSI to the number of humans nearby for device-free crowd counting. Pioneer research has marched beyond detecting simply the presence of humans. On the one hand, CSI-based wireless sensing shifts from locating users in the physical coordinates to offering more context-aware information. Some work demonstrated the feasibility of general-purposed daily activity recognition by using CSI as fingerprints for the hybrid of locations and activity patterns[7]. Others targeted at more concrete scenarios, e.g., fall detection[20], adopting similar principles with scenario-tailored optimization. On the other hand, ambitious CSI-based sensing applications strive to detect micro body-part motions at increasingly finer granularity. Some reported over 90% accuracy of distinguishing multiple whole-body[6] and bodypart gestures[9], while others claimed accurate breath detection[10] or even lips reading[8]. Nevertheless, researchers have reached to on to what extent of motion granularity and variety is CSI capable of performing in practice.

IV. FUTURE SCOPE

4.1One leap further: WiFi radar

Over the past five years, CSI has spawned various applications and its application scenarios continue to expand. As an upgrade for RSS, it is natural to improve performance of some applications simply by replacing RSS with CSI. CSI also enables various applications with RSS alone, such as gesture detection, breath sensing, and complex environment analysis. Nevertheless, CSI is not a panacea, and its improvement in sensing granularity is still incomparable with radar signals. Some envisioned applications might have already gone beyond the capability of CSI. Apart from further exploring and exploiting the frequency diversity and the phase information of CSI, researchers also began to identify its limitations in practice, as well as seek other techniques to extend CSI-based sensing to general WiFi-based sensorless sensing or WiFi radar. In Ref. [21], researchers pointed out via ambiguity function analysis that the range resolution of WiFi-compatible passive bistatic radars can only reach meters, which is fundamentally constrained by the bandwidth of WiFi signals. To overcome this intrinsic constraint, researchers alternatively incorporate Multi-Input-Multi- Output (MIMO) technology. Researchers in Ref. [22] exploited antenna cancellation techniques to eliminate the impact of static clutters to enable through-wall sensing of human movements. In Ref. [23], the authors achieved computational imaging using WiFi, and built a MIMO-based prototype on software defined radio platforms. They experimentally demonstrated that the size, material, and orientation of the target objects can significantly affect the performance of WiFi imaging, and a one-fit-all solution is still to be explored.

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V. CONCLUSION

Wireless and sensorless sensing seek breakthroughs while having contraction among the limitations of various wireless communications applications. There is growing demand for environment perception in people's daily life. This wifi application seeks a balance between low cost and high accuracy and explores the solutions via frequency diversity and spatial diversity, and also creates various applications that were previously infeasible with wireless communications and mobile computing. The technological advances would boost the capability of wireless sensing too much finer granularity and higher sensitivity, which will in turn develop new applications. This article serves as a mere introduction to the concept of wireless and sensor less sensing. If WiFi is considered as a side sensor, thenWiFi-based sensorless sensing can be regarded as one of the world's largest wireless sensor networks, spreading over office buildings, shopping malls, other public places and homes, and silently watching the activities of humans therein. This kind of secured network contributes a lot in the field of security and monitoring fields. Living inside such a network, every individual in the physical world has been bestowed with unique being in the digital world.

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