Wi-Fi Can Do More: Towards Ubiquitous Wireless Sensing

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***Abstract*—The next big deal for Wi-Fi is not about communication and networking, but sensing. Wireless Sensing technology is turning a Wi-Fi device into a ubiquitous sensor, which not only adds a brand new dimension to the functions, capabilities, and applications of all Wi-Fi systems, but also revolutionizes how sensing, especially human-centric sensing, is practiced. Wi-Fi Sensing utilizes ambient Wi-Fi signals to analyze and interpret human and object movements, underpinning many sensing applications such as motion sensing, sleep monitoring, fall detection, etc. These new sensing functionalities can benefit the global Wi-Fi ecosystem including integrated circuit manufacturers, device manufacturers, system integrators, application developers, and ultimately end users. In this article, we introduce the concepts, principles, challenges of Wi-Fi Sensing, and share our unique technologies that have been deployed for real-world applications. We foresee that Wi-Fi Sensing will enter billions of devices and millions of homes, creating a smarter space for a smarter life. Today is just the beginning of this revolution.**

I. INTRODUCTION

Still use Wi-Fi for the Internet only? You are missing a lot! Recently, the world's understanding of Wi-Fi has been changed, from a pure communication platform to a ubiquitous sensing infrastructure. Because of its worldwide ubiquity, this sensing capability turns Wi-Fi networks instantly into the world's ever largest "sensorless" sensing network, without any dedicated hardware sensors. Today, Wi-Fi sensing is revolutionizing many applications, including motion detection, home security, sleep monitoring, fall detection, gait recognition, gesture control, activities of daily living monitoring, lighting control, and energy management, just to name a few.

After years of effort predominantly in academia, there are now emerging and significant contributions from the industry. For example, Belkin released an award-winning Wi-Fi integrated communication and motion sensing product LinkSys Aware [1] in 2019 in partnership with Origin Wireless. Origin Wireless has also released award-winning products such as HEX Home [2] for home security, Remote Patient Monitoring [3], etc. Realizing the new possibilities and the huge implied market, mainstream chipset manufacturers, such as Qualcomm, NXP, Broadcom, Intel, MediaTek, and Cypress have also started to support Wi-Fi sensing in their current and/or next-generation chipsets. More and more companies, from the security industry to consumer electronics to healthcare, are eager to integrate Wi-Fi sensing services into their existing and upcoming IoT products. Since 2019, a Task Group of IEEE Standards has been formed, with huge enthusiasm and participation across a wide spectrum of industries, to establish a new standard called IEEE 802.11bf on WLAN sensing which will be an amendment to the ubiquitous IEEE 802.11 standards. It is scheduled to be finished in 2024. Beyond Wi-Fi sensing, other wireless signals like UWB signals and millimeter-wave signals are also exploited for sensing. Wireless sensing, in general, is becoming an increasingly hot topic that is attracting huge attention from both industry and academia. Due to Wi-Fi's omnipresence and low cost and high sensing capabilities and accuracy, Wi-Fi sensing promises to be a very attractive solution.

Repurposing Wi-Fi for sensing involves great challenges, yet the very basic idea is intuitively simple. Similar to radar signals, the wireless signals propagating in the air are affected or influenced by the environment. Amazingly, such a process can capture or "encode" certain environmental information in the received signals, which in turn, if properly done, allows deciphering the encoded environmental information and monitoring of our activities with no need of any contact sensors. Just like Computer Vision enables machines to perceive visual signals and speech recognition allows machines to understand sound signals, we generally term wireless sensing as *Wireless AI* [4], which allows IoT devices to perceive the physical environments via our everyday ambient wireless signals.

In today's world, we are immersed in Wi-Fi signals everywhere in our living and working space. Therefore, Wi-Fi sensing can be done in a ubiquitous, wireless, contactless, and sensorless way, without attaching any devices to the target or instrumenting the environment with extra sensing hardware such as invasive cameras. This could enable a wide range of revolutionary applications. For example, it can secure our home by seamlessly detecting an intruder, with no need to install security cameras or contact sensors everywhere inside the home. It can monitor one's activity of daily living as well as sleep quality overnight, without the need to wear any devices or be watched by a camera. It can detect an accidental fall, which can be dangerous and even fatal. There are many more application potentials to be explored and imagined. In essence, Wi-Fi sensing is not only revolutionizing how sensing is being practiced, but also making possible many applications that were impossible before.

In this article, we will give a high-level overview of the vision, principles, and challenges of Wi-Fi sensing, and will report our humble experience in commercializing Wi-Fi sensing for real-world applications.

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II. WI-FI AS A SENSOR: THE WORLD'S LARGEST SENSOR NETWORK

There are reportedly over 20 billion of Wi-Fi devices worldwide connected via Wireless Local Area Network (WLAN). Till today, the majority of these Wi-Fi devices are merely for data networking. With wireless sensing, these Wi-Fi devices will soon have a brand new functionality: sensing. Wi-Fi devices are evolving to become ubiquitous sensing interfaces for perceiving various environmental information. Such a huge amount of connected devices, when enabled by wireless sensing, immediately form the world's ever largest sensor network - a ubiquitous, multi-purposed, and non-intrusive sensor network.

Ubiquity is perhaps one of the biggest advantages of Wi-Fi sensing. Wi-Fi devices are everywhere, and so are Wi-Fi signals. They have been massively and ubiquitously deployed in buildings and homes. As of 2020, there are reported, on average, over 10 connected devices in a US household. A variety of IoT devices, such as smart speakers, smart TVs, smart phones, smart pads, smart plugs, smart lights, smart doorbells, and other smart appliances have entered our homes, and meanwhile, mesh Wi-Fi systems (e.g., Google Wi-Fi, Amazon Eero, LinkSys Mesh Wi-Fi, Huawei HarmonyOS Mesh, etc) are also increasingly deployed for whole-home coverage, leading to a relatively dense in-home network of Wi-Fi devices. On the other hand, Wi-Fi signals propagate everywhere due to the omnidirectional propagation property and obstacle-penetrating capability. As a result, (re)using Wi-Fi for sensing offers a whole-home, through-the-wall, no-blind-spot solution, which is readily available worldwide including developing and undeveloped countries and regions.

Also, because of the nature of wireless signals, Wi-Fi sensing is inherently a distinct non-contact and unobtrusive solution. In contrast, traditional techniques for human-centric sensing, such as smartphones, wearables, cameras, and low-power radars tend to be intrusive, inconvenient, and/or inaccurate. For example, wearables may be popular but tend to be intrusive. The adherence issues of wearables are especially problematic among older adults and may be too challenging for those with neurodegenerative diseases. Cameras are too privacy-intrusive, and people do not like to be watched while staying at home. On the contrary, Wi-Fi sensing presents a contactless solution with no wearables or cameras to intrude into the end users' daily routine, and no adherence issues. Take sleep monitoring as an example. We simply extract information from the ambient Wi-Fi signals, which are most likely already there, and do not need to instrument the bed or the user body with any extra hardware. In fact, sleep monitoring could be done when one is not even aware of the service. The end users would not be burdened by special equipment or wearables or be worried about potentially privacy-intrusion by devices such as a camera or a microphone.

Another unique advantage of wireless sensing, compared to traditional sensors, is a potentially all-in-one multi-purposed sensing solution. Classical sensors typically only sense one particular type of sensing information, for example, the temperature only for temperature sensors, the pressure only for pressure sensors, acceleration only for accelerometers, etc. Consequently, to sense multiple dimensions of sensing information, one needs to deploy an array of different traditional sensors. In contrast, with Wi-Fi sensing, a connected device can serve as a multi-purposed sensor, via different analytics, that can capture multiple dimensions of information, such as locations, motion, vital signs, activities, and so on, all using the built-in Wi-Fi radio without any dedicated sensors or wearables.

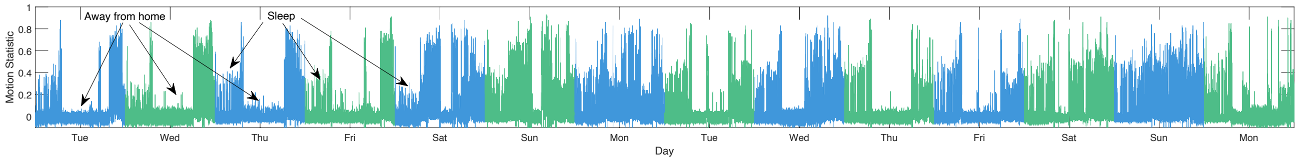
Fig. 1. An illustration of multipath propagation of Wi-Fi signals in indoor space. Human activities at different locations altering the propagation can be sensed from the received signals.

There are more benefits of this largest sensor network of the world enabled by Wi-Fi sensing. For example, the solutions can be delivered as purely software-based services without extra hardware - only a pair of Wi-Fi devices (such as a home router, a laptop, a smartphone, a smart speaker, or an IoT device) is minimally needed - promising an affordable solution for everyday usage even for low-income families and in less developed regions. Also, Wi-Fi sensing is much easier to deploy than traditional sensors, requiring only amateur (DIY) installation instead of professional installation typically needed for traditional sensors.

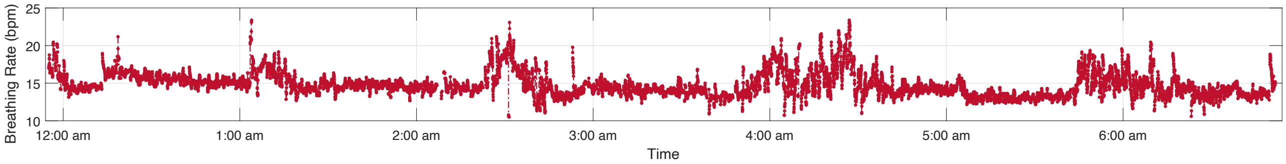
III. PRINCIPLES AND CHALLENGES

An important and challenging question is then, *why and how can Wi-Fi be (re)used for sensing?* Wi-Fi sensing is complex, yet the basic principles are fundamental. Wi-Fi signals are electromagnetic waves propagating in space. To intuitively understand how Wi-Fi could serve as a sensor, one can imagine Wi-Fi signals in a home as water ripples in a pool. As illustrated in Fig. 1, wireless signals are waves bouncing back and forth among objects, walls, ceilings, furniture, and, certainly, humans. In other words, there is not only a direct Line-Of-Sight (LOS) path between a Wi-Fi transmitter (e.g., a home router) and receiver (e.g., a smartphone, laptop, a smart speaker, among other IoT devices) but also many Non-LOS (NLOS) multipaths - a well-known phenomenon in wireless communication. So a home is like a wave pool and when one moves through it, she/he will disrupt all these waves. Wi-Fi sensing leverages these multipath disturbance/distortions to perform sensing, without cameras, wearables, or any dedicated sensors.

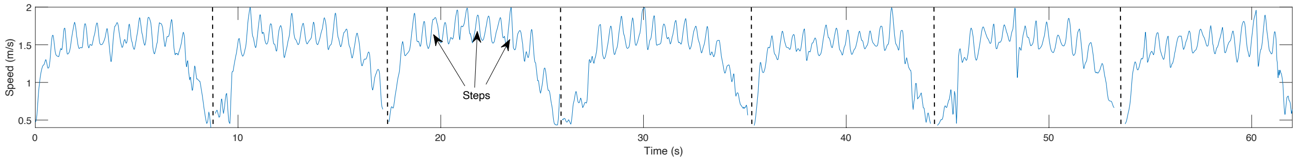
The above phenomenon is generally termed as *multipath propagation*. A transmitted signal propagating in the air un-



(a) Motion Statistics over two weeks for a one-bedroom apartment. Different days are marked in different colors. The reliable and responsive motion detection underpins applications like intruder detection, presence detection, home automation, etc. By accumulating long-term data, the repeated/changing activity patterns can be inferred, which can support applications like daily activity monitoring, home liveness, personalized healthcare, etc.



(b) Overnight breathing rates during sleep. Our approach nicely captures the instantaneous changes in breathing rates. This provides an unprecedented opportunity for non-contact, non-intrusive sleep monitoring.



(c) Estimated speed of a user walking around a path for 6 rounds. The speed variances during each step cycle are precisely preserved. With the accurate and robust speed estimation, we can perform fall detection (based on the speed pattern during a fall), step counting, person identification (using gait as a biometric marker), wellness monitoring (by assessing the walking patterns and trend), etc.

Fig. 2. Sensing motion, breathing, and speed via Wi-Fi signals.

dergoes reflection, refraction, and/or penetration before finally arriving at the receiver as a superimposed signal. Interestingly, multipath propagation has been a long-standing enemy in classical wireless communication. Numerous efforts have been devoted to combat (or undo) multipaths to ensure high data communication quality. Yet in the context of Wi-Fi sensing, the role of multipath propagation has completely changed and, in fact, from being a nuisance to a key enabler for practical and robust sensing. Because of multipath propagation, the signal travel spans the whole space (e.g., the whole home or office), be it via LOS or NLOS paths, and thus the sensing provides full coverage of the space being able to detect even tiny motions or changes at any corner of the space. Basically, an object's movements in the space will alter the propagation of at least a subset of the multipath components, which in principle can be observed from the received signals. As such, we can decipher the movements of the object and further interpret the corresponding activities and behaviors from the received signals.

It involves grand technical challenges to translate the above principle into practical solutions, especially using commodity Wi-Fi. There are at least three fundamental issues of commodity Wi-Fi that we are facing: Firstly, Wi-Fi transceivers are not synchronized, and therefore the measured channel information contains significant phase distortions. Secondly, commercial Wi-Fi has limited channel bandwidths, e.g., only 20MHz~80MHz (the emerging 802.11ax provides 160MHz), rendering an insufficient time/range resolution to distinguish multipath signals arriving at slightly different times. Thirdly, there are usually only a small number of antennas, e.g., typically one to three on IoT devices, producing a poor spatial resolution to differentiate multipath signals arriving from different angles. These limitations together lead to a stringent situation: While there is a considerable number (e.g., several hundred or more) of multipaths in the complex indoor environments, the multipath resolvability of Wi-Fi signals, however, is greatly and fundamentally constrained, making traditional ray tracing models and phased array signal processing techniques impractical for Wi-Fi sensing.

Another great challenge, rarely discussed in academia, is how to deploy Wi-Fi sensing solutions by integrating on top of commodity devices without affecting the primary networking functionality? Research works could, and frequently do assume implicitly a set of Wi-Fi devices dedicated for sensing purposes only. In the real world, however, this assumption turns out to be unfavorable and unrealistic because of many reasons. It increases the cost as users need to purchase additional devices, which may significantly prevent the wide adoption of the technologies. It also violates users' expectation that sensing is enabled using their (existing) in-home Wi-Fi devices. And it damages the unique advantage of ubiquity if existing deployed Wi-Fi devices could not be reused. Hence, to promote industrial-scale real-world adoption of Wi-Fi sensing, we must develop purely software-based solutions running on top of legacy Wi-Fi devices, which will then serve both networking and sensing concurrently, a true integrated communication and sensing solution.

IV. WHAT CAN WI-FI SENSE, TODAY?

As of today, based on our version of Wireless AI, we have been able to measure at least three types of physical characteristics using commodity Wi-Fi devices: motion, periodicity (and thus vital signs such as breathing rate), and speed, which together can spawn a wide range of applications in security, healthcare, smart homes, auto industry, etc.

To overcome the above challenges and deliver practical Wi-Fi sensing solutions, we investigate the problem of Wi-Fi sensing from the first principle of electromagnetic (EM) waves and manage to develop a set of statistical approaches under a statistical EM field model, circumventing the need of resolving individual multipaths and estimating their geometric parameters. The model was inspired by the principle of Time-Reversal [5], which creates a spatial-temporal focusing effect of the signal energy. Our approaches leverage *all the multipaths* and analyze their statistical behaviors. Rather than avoiding or tolerating multipaths, our approaches truly embrace multipaths and utilize all of them. Given the fact that there are many multipaths in complex indoor environments, our approaches turn out to be highly accurate and robust in the real world, underpinning the commercialization of different applications. As will be shown later, our approaches overcome all the challenges aforementioned and enable various sensing applications on commodity Wi-Fi devices that tend to suffer from limitations in synchronization, bandwidths, and antennas, without affecting the networking function.

Like many others, we utilize Channel State Information (CSI), standard information in the physical layer of wireless communications systems used to characterize the signal propagation channel. CSI is also commonly represented as Channel Frequency Response (CFR) in the frequency domain or Channel Impulse Response (CIR) in the time domain. CSI can be conveniently estimated from regular Wi-Fi packets, needing minimal software modifications of Wi-Fi driver. Specifically, we look at the Auto-Correlation Function (ACF) of CSI, which embodies several fundamental spatial-temporal characteristics:

1) **Motion** [6]: The ACF contains at least one precise and sensitive motion indicator, such as the value of the first sample of the ACF. We term this indicator as *motion statistic* and use it for motion detection, which yields whole-home coverage and almost zero false alarms using a single pair of Wi-Fi devices. In theory, the motion statistics should produce *zero false alarm rate* for motion detection. In practice, due to device noises and hardware imperfections, some false alarms might be observed, yet still at a false alarm rate as low as 10^{-6}, according to our real-world experiments and our field testing in partnership with a security company. Fig. 2a depicts the motion statistics over a month in a one-bedroom apartment in which a couple lives.

2) **Periodicity** [7]: ACF can be used in a time-domain approach to detect and estimate signal periodicity. We use it to estimate the breathing rate, i.e., the period of human breathing, which is a predominantly periodic chest movement. As a time-domain approach, ACF promises faster responsiveness compared to frequency-domain approaches such as Fourier Transform. The challenge, however, is that breathing signals are very weak, especially when the subject is under an unfavorable situation, e.g., far away from the link, behind the wall, or covering a thick blanket, etc. Using our approach, breathing rates can be estimated with a high accuracy better than one breathe per minute (BPM) and basically instantaneously with a delay at the millisecond level, even when the subject is far away from the Wi-Fi link (e.g., over 10 meters) and/or behind the wall. And it works robustly for continuous breathing monitoring during sleep, regardless of the user's sleeping posture and blanket-covering conditions. We achieve remarkable performance by optimally combining all subcarriers to leverage frequency diversity, which significantly boosts the coverage and robustness of periodicity estimation for weak signals like breathing. Fig. 2b shows a one-night example of our real-world sleep monitoring applications. As seen, the subject's breathing rates are continuously and responsively monitored throughout the night.

3) **Speed** [8], [9]: Further, by investigating the properties of the ACF of EM waves in the space domain, we surprisingly find that the ACF embodies the moving speed of the scattering objects. Specifically, the ACF turns out to be a function of the target's moving speed, in the form of the 0th-order Bessel function of its first kind. We manage to draw an important theoretical conclusion that connects Wi-Fi signals with moving speed in an elegant and concise representation: $\rho(\tau) = \alpha J_0(kv\tau)$, where ρ is the ACF of CSI, α is the channel gain, J_0 is the 0th-order Bessel function of its first kind, k is a constant denoting the wavenumber, and v is the desired moving speed. With this, we can effectively estimate a target's moving speed, regardless of the target's moving direction and specific location. It significantly outperforms conventional methods based on the Doppler Effect, which heavily depends on the moving direction, target location, and LOS conditions. Fig. 2c illustrates the estimated speed when a user is walking around an office space, where the Tx and Rx are placed at over 10 meters away from each other without LOS between them.

The three physical characteristics, i.e., motion, periodicity, and speed, their variants, and their combinations can enable many different applications, as discussed next. In practice, as shown in the above examples, we can measure these physical characteristics in both LOS and NLOS areas using only a single link, i.e., a single pair of Wi-Fi devices (e.g., a home router plus a Wi-Fi enabled smart speaker).

In the literature, many sophisticated approaches have been proposed to estimate other channel parameters such as Angle of Arrival (AoA), Time of Flight (ToF), Doppler Frequency Shift (DFS), etc. Due to the inherent limitations of commercial Wi-Fi, however, there is seemingly a considerable gap between the reported results obtained under controlled conditions in the laboratories and practical applications in the real world. Thus we omit further discussions on these approaches.

V. REAL-WORLD APPLICATIONS

Based on the three types of physical characteristics measured using commodity Wi-Fi - motion, periodicity (breathing rate), and speed - wireless AI has advanced new applications in security, healthcare, smart homes, etc., and has made them a reality today for real-world users, as detailed below.

Home Security. Partnered with Belkin, we have launched Linksys Aware in 2019, the first-of-its-kind Wi-Fi motion sensing product. Linksys Aware is a software-based subscription service that uses one's existing Intelligent Mesh Wi-Fi

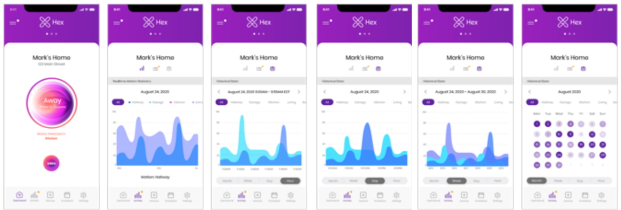


Fig. 3. Screenshots of HEX Home App, a home security application based on our Wi-Fi motion sensing.[2]

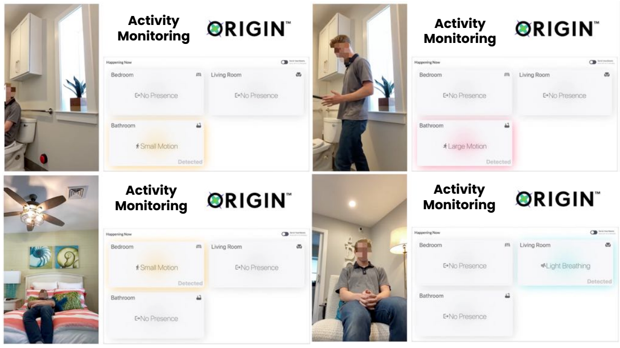


Fig. 4. Activities of Daily Living monitoring using Wi-Fi.

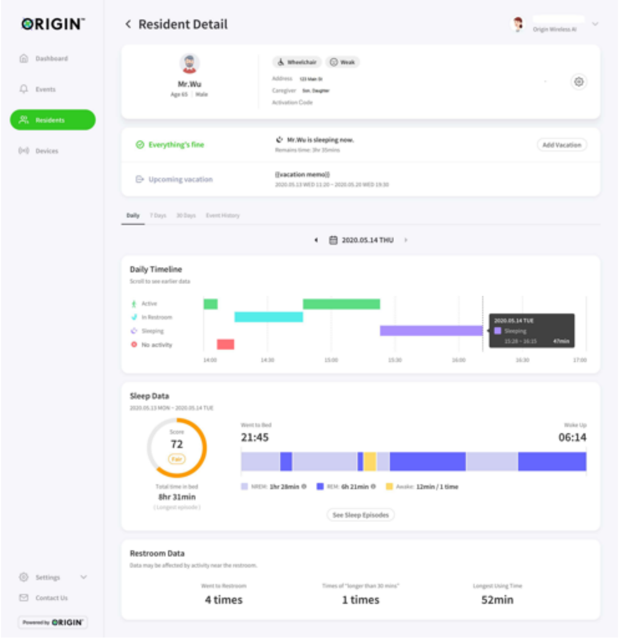


Fig. 5. Remote Patient Monitoring of elders using Wi-Fi-based motion sensing and sleep monitoring.

network to sense motion without the use of cameras or additional hardware, ensuring privacy and convenience throughout his/her home. For every pair of mesh Wi-Fi devices, a sensing bubble can be created that covers the area between and around them. Using Wi-Fi waves to monitor movement in the user's home, this bubble wraps around corners, sees through walls, and stretches or shrinks based on the strategic placement of the devices. As people move through these Wi-Fi waves, they bounce, break, and bend around them. Linksys Aware then calculates how the waves change and informs users when meaningful motion is detected. With the accompanying app, users can view real-time and historical motion levels in their home, change system modes, adjust sensitivity levels, and more. In June 2021, we further launched Hex Home (Fig. 3), a DIY, camera-free home security system, which makes Wi-Fi motion based security services available to beyond Linksys Wi-Fi users. Both Linksys Aware and HEX Home support simultaneous sensing and communication functionalities, i.e., an integrated communication and sensing solution. In addition, our solutions work well on extremely low-cost IoT devices that only have a 2.4GHz Wi-Fi radio with one single antenna and 20MHz bandwidth.

ADL Monitoring. Activities of Daily Living (ADL) monitoring (Fig. 4) not only can detect instantaneous motion and its strength, but also the motion location, and thus enables a user to know where the loved ones are in their homes in real-time or track activity patterns with historical data, and know how much time a loved one has spent in each room in the home. If some abnormal activity is detected, e.g. "mom has been in the bathroom for an hour", it can set alerts to notify caregivers.

Sleep Monitoring. Understanding breathing patterns is one of the key factors for sleep monitoring and respiratory rate variability. Our breathing monitoring application enables capturing of the slightest chest movements using standard Wi-Fi in real-time. Based on the accurate instantaneous breathing rate, a sleep monitoring application (Fig. 5) can provide information such as time to bed, awake time, wake up, Rapid Eye Movement (REM), and non-REM (NREM) monitoring, informs caregivers of average breathing rate and breathing rate variability, and calculate some sleep score, so that the caregivers can know how the loved one slept, track any improvement or deterioration, and look for anomalies from historical sleep data.

Fall Detection. WHO estimates that there are typically 37M severe falls and 646K fatal falls each year, making it the second leading cause of accidental or unintentional injury deaths worldwide. Based on our accurate speed estimation method, we notice that falls exhibit unique speed variation patterns, different from most daily activities such as walking, sitting, standing, typing, etc. Inspired by this observation, we design a practical fall detection solution to detect trip-and-fall scenarios within the home and inform caregivers if a fall has taken place and in which room. Together with motion and breathing detection, it can track movement and breathing rate after a fall has occurred to help caregivers respond accordingly.

Child Presence Detection. On average, around 40 children die from hot cars each year (about one every 10 days), leading to over 900 deaths on record since 1998 in the US alone. Serious injuries or heatstroke deaths can happen to children left inside a closed car because the temperature can rise rapidly inside a car, especially in hot months. All these deaths could have been prevented, if the car can detect the unattended child timely and take prompt actions. Governments and the auto industry are taking initiatives to make Child Presence Detection (CPD) a compulsory feature for future cars. Our

Wi-Fi sensing technology achieved a pervasive solution with whole-car coverage and high accuracy, requiring no extra hardware than the existing in-car Wi-Fi [10]. The solution detects a child present anywhere inside a car quickly (within seconds) by sensing the child's tiny motion and/or breathing via Wi-Fi signals. Responsive actions, such as alerting car owners/parents via messages or horn alarms, and/or turning on air conditioner automatically, can then be taken to prevent the tragedies.

There are more applications under commercialization and to be commercialized, such as home automation, proximity detection, wander detection, gait recognition, all using Wi-Fi. Beyond these, we are also building ubiquitous solutions for location sensing, or the more commonly noted indoor localization/tracking. Pervasive indoor positioning is a long-standing problem that has attracted over 30 years of research effort, despite which no such system exists today that is accurate, scalable, low cost, and easy to deploy. We have developed Origin Tracking, the world's first indoor tracking technology with centimeter accuracy even under NLOS conditions [11]–[13]. It uses only a single arbitrarily placed Wi-Fi Access Point without knowing its location, offers large coverage including NLOS areas, supports a large number of users, and can be deployed at massive buildings with very low cost. To the best of our knowledge, this is the first and only system to achieve so, despite decades of efforts worldwide. The prototype system attracts numerous interests from the industry and has been invited for demo at the headquarters of many major companies.

VI. IEEE STANDARD AND FUTURE TRENDS

Not surprisingly, current IEEE 802.11 standards do not (yet) have the support for Wi-Fi sensing. Recognizing the increasing interests and the great potential of Wi-Fi sensing, IEEE has formed a Task Group, with preparation efforts started in 2019, to standardize the specifications for Wi-Fi sensing. The new standard is called IEEE 802.11bf, formally called WLAN Sensing, which is backward compatible with existing and soon-to-appear Wi-Fi devices. A particular goal of IEEE 802.11bf is to define specifications at both the MAC and PHY layers, with targeted frequency bands between 1 GHz and 7.125 GHz and above 45 GHz, which will enable sensing at millimeter frequencies. To ensure backward compatibility, the PHY layer will not be changed.

Our team was among the first to envision such a WLAN sensing standard and has been involved with the IEEE 802.11bf Wireless Sensing Project from the beginning (2019) to promote, advocate, monitor, and shape the development of Wi-Fi sensing in the context of the IEEE 802.11 standard. Since the early brainstorming sessions, we have strongly advocated for the potential value, feasibility, and use cases of Wi-Fi Sensing. We worked together with like-minded experts in the industry and formed the WLAN Sensing Technical Interest Group (TIG) in September 2019, then the WLAN Sensing Study Group (SG) in November 2019, and then a WLAN Sensing Task Group (TG) in March 2020. We worked intensely on the Project Authorization Request (PAR) and Criteria for Standards Development (CSD) of 802.11bf. In September 2020, the CSD and PAR were formally approved. The 802.11bf Task Group was established, and its work began. Many technical proposals have been presented and vetted. Many straw polls and motions have been voted upon. The TG is seeking to produce the first draft of the 802.11bf standards (Draft 0.1) in January 2022, the second draft (Draft 1.0) in July 2022, the third draft (Draft 2.0) in January 2023, and the final standard in September 2024.

Standardization is important because it enables compatibility and interoperability, allowing Wi-Fi sensing to become a standardized, legitimate, widespread feature on standard-compliant devices made by different vendors. One day when IEEE 802.11bf is finalized as a standard, Wi-Fi sensing will become a software service to be massively deployed on many devices and thus widely adopted by users, and will eventually become something people cannot live without. Along the way, we envision many opportunities, and challenges too, of the future development of Wi-Fi sensing in several aspects as follows.

Advanced Wi-Fi Sensing. With the growing interests, Wi-Fi sensing will undoubtedly continue to improve and expand. In particular, there are two arising opportunities, thanks to the emerging 802.11ax (Wi-Fi 6) and 802.11ay/ad (WiGig) protocols. Wi-Fi 6 offers a larger bandwidth of 160MHz for a single channel, and thus sheds a light on addressing several difficult problems such as accurate and robust fall detection. A challenge is - what would be the best way is to utilize the larger bandwidth to solve the problems. Besides having large bandwidths of a few gigahertz, WiGig further possesses short wavelengths at millimeter level and high directionality, together enabling high-resolution sensing applications such as heart rate monitoring, imaging, as well as multi-target sensing [14], [15]. An important challenge would be how to best use these characteristics to address sensing needs. With potentially all Wi-Fi devices becoming empowered for Wi-Fi sensing, cooperative sensing among a set of co-existed devices would become another challenge.

Integrated Wi-Fi Sensing and Communications. Integrated Sensing and Communication (ISAC) has recently been widely discussed, mainly because the rise of Wi-Fi sensing has changed the role of traditional communications devices. Our Wi-Fi Sensing solutions measure desired sensing data from regular Wi-Fi packets and run as an add-on service on top of existing Wi-Fi communication systems. Ideally, it is desirable that the added sensing capability of a device will not affect the original networking functionality of the device, and the networking traffics to and from nearby devices will not interfere with the sensing performance. A challenge is how to handle the intra-radio interference between sensing and networking, and how to combat inter-radio interference between neighboring Wi-Fi devices.

Wi-Fi Sensing Data Analytics. In Wi-Fi sensing, numerous data are collected accurately, conveniently, and continuously, which was previously difficult, if possible/affordable. In-depth analysis of these valuable data will open doors to study known and unknown facts of human activities, sleep behaviors, building/home efficiency, etc. With Wi-Fi Sensing becoming an everyday service on more and more consumer electronics, lots of such data will be accumulated, underpinning exciting research directions and commercial opportunities.

Privacy and Security Concerns. Wi-Fi sensing is usually argued as privacy-preserving, particularly when compared to other non-contact sensors such as cameras or microphones. However, when it becomes a ubiquitous service in our everyday life continuously collecting life-related data, privacy and security inevitably become a concern. As RF signals propagate with no clear physical boundaries (e.g., Wi-Fi can easily penetrate drywalls), malicious users could sniff CSI without authorization, from which the legitimate end users' sensitive information may be leaked. There have been some pioneering works on identifying potential security and privacy issues and developing solutions to protect end users' privacy from malicious Wi-Fi sensing. More systematic privacy protection efforts are desirable when Wi-Fi sensing becomes a standard sensing service.

VII. CONCLUSION

"The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it", as visioned by Mark Weiser in 1991. Wi-Fi communication is definitely one of such technologies, and we believe Wi-Fi sensing is yet another one arising. With Wireless AI, we redefined Wi-Fi, from pure communication to omnipresent sensing, as well as "sensing", from sensor-based to sensorless. Many unprecedented applications have already been made a reality to users worldwide today. Looking forward, there is no doubt that Wi-Fi can do more, more even beyond our imagination today.

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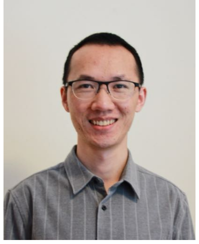

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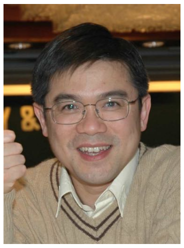

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