WiFi Can Do More: Towards Ubiquitous Wireless Sensing

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***Abstract*—The next big deal for WiFi is not about communication and networking, but sensing. Wireless Sensing technology is turning a WiFi device into a ubiquitous sensor, which not only adds a brand new dimension to the functions, capabilities, and applications of all WiFi systems, but also revolutionizes how sensing, especially human-centric sensing, is practiced. WiFi Sensing utilizes ambient WiFi 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 WiFi 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 WiFi Sensing, and share our unique technologies that have been deployed for real-world applications. We foresee that WiFi 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 WiFi for the Internet only? You are missing a lot! Recently, the world's understanding of WiFi has been changed, from a pure communication platform to a ubiquitous sensing infrastructure. Because of its worldwide ubiquity, this sensing capability turns WiFi networks instantly into the world's ever largest "sensorless" sensing network, without any dedicated hardware sensors. Today, WiFi 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 WiFi 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 WiFi 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 WiFi 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 WiFi standard. It is scheduled to be finished in 2024. Beyond WiFi 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 WiFi's omnipresence and low cost and high sensing capabilities and accuracy, WiFi sensing promises to be a very attractive solution.

Repurposing WiFi 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 WiFi signals everywhere in our living and working space. Therefore, WiFi 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, WiFi 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 WiFi sensing, and will report our humble experience in commercializing WiFi sensing for real-world applications.

II. WiFi As A Sensor: The World's Largest Sensor Network

There are reportedly over 20 billion of WiFi devices worldwide connected via Wireless Local Area Network (WLAN).

Till today, the majority of these WiFi devices are merely for data networking. With wireless sensing, these WiFi devices will soon have a brand new functionality: sensing. WiFi 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 WiFi sensing. WiFi devices are everywhere, and so are WiFi 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 WiFi systems (e.g., Google WiFi, Amazon Eero, LinkSys Mesh WiFi, Huawei HarmonyOS Mesh, etc) are also increasingly deployed for whole-home coverage, leading to a relatively dense in-home network of WiFi devices. On the other hand, WiFi signals propagate everywhere due to the omnidirectional propagation property and obstacle-penetrating capability. As a result, (re)using WiFi 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, WiFi 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, WiFi 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 WiFi 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 WiFi 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 WiFi radio without any dedicated sensors or wearables.

Fig. 1. An illustration of multipath propagation of WiFi 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 WiFi sensing. For example, the solutions can be delivered as purely software-based services without extra hardware - only a pair of WiFi 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, WiFi 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 WiFi be (re)used for sensing?* WiFi sensing is complex, yet the basic principles are fundamental. WiFi signals are electromagnetic waves propagating in space. To intuitively understand how WiFi could serve as a sensor, one can imagine WiFi 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 WiFi 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. WiFi 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 undergoes 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 WiFi sensing, the

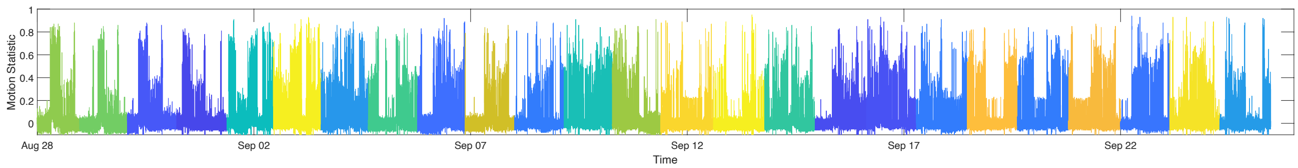

Fig. 2. Motion Statistics over a month for a one-bedroom apartment. Different days are marked in different colors.

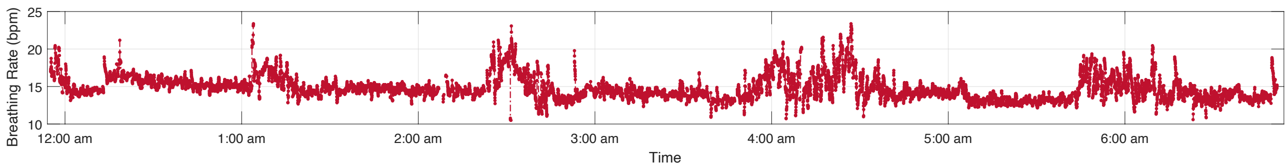

Fig. 3. Overnight breathing rates during sleep.

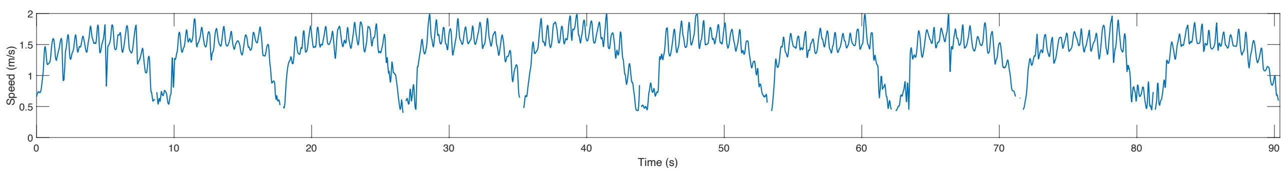

Fig. 4. Estimated speed of a user walking around a path for 10 rounds.

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 WiFi. There are at least three fundamental issues of commodity WiFi that we are facing: Firstly, WiFi transceivers are not synchronized, and therefore the measured channel information contains significant phase distortions. Secondly, commercial WiFi 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 WiFi signals, however, is greatly and fundamentally constrained, making traditional 2-ray reflection models and phased array signal processing techniques impractical for WiFi sensing.

Another great challenge, rarely discussed in academia, is how to deploy WiFi 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 WiFi 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 WiFi devices. And it damages the unique advantage of ubiquity if existing deployed WiFi devices could not be reused. Hence, to promote industrial-scale real-world adoption of WiFi sensing, we must develop purely software-based solutions running on top of legacy WiFi devices, which will then serve both networking and sensing concurrently, a true integrated communication and sensing solution.

IV. What WiFi Can 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 WiFi 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 WiFi sensing solutions, we investigate the problem of WiFi 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. 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.

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 WiFi packets, needing minimal software modifications of WiFi driver. Specifically, we look at the Auto-Correlation Function (ACF) of CSI, which embodies several unique spatial-temporal features:

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 WiFi 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. 2 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 WiFi 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. 3 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 0^{th}-order Bessel function of its first kind. We manage to draw an important theoretical conclusion that connects WiFi 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 0^{th}-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. 4 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.

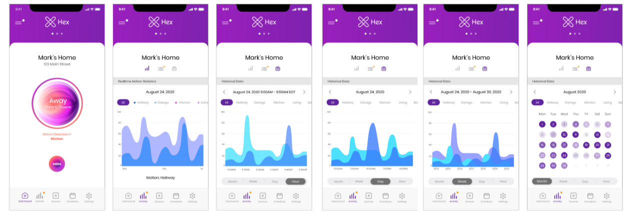

Fig. 5. Screenshots of HEX Home App, a home security application based on our WiFi motion sensing.[2]

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 WiFi devices (e.g., a home router plus a WiFi-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 WiFi, 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 WiFi - 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.

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

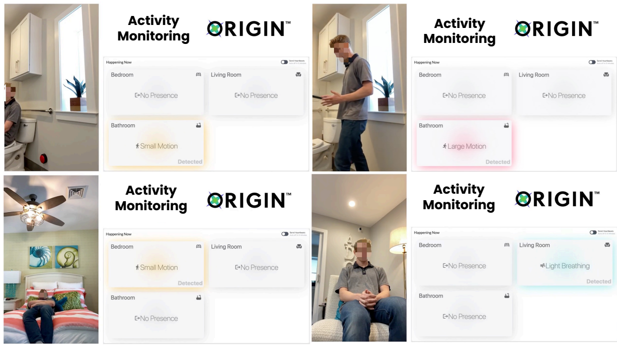

Fig. 6. Activities of Daily Living monitoring using WiFi.

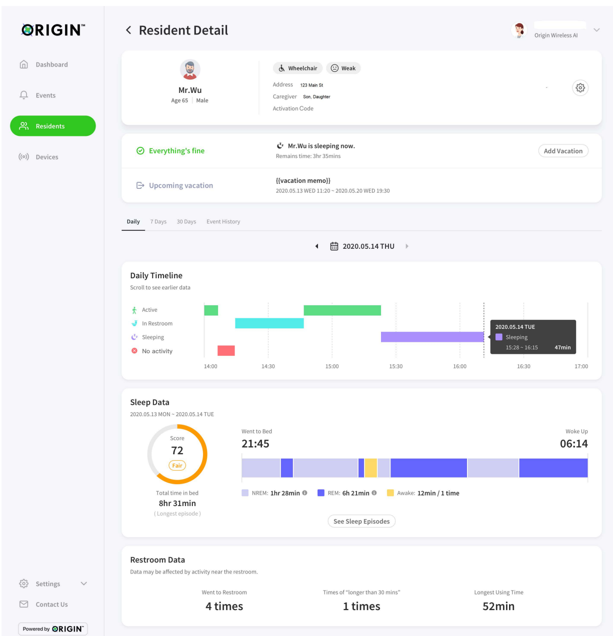

Fig. 7. Remote Patient Monitoring of elders using WiFi-based motion sensing and breathing estimation.

can be created that covers the area between and around them. Using WiFi 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 WiFi 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. 5), a DIY, camera-free home security system, which makes WiFi motion based security services available to beyond Linksys WiFi 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 WiFi radio with one single antenna and 20MHz bandwidth.

2) ADL Monitoring. Activities of Daily Living (ADL) monitoring (Fig. 6) 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.

3) 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 WiFi in real-time. Based on the accurate instantaneous breathing rate, a sleep monitoring application (Fig. 7) 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.

4) 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.

There are more applications under commercialization and to be commercialized, such as proximity detection, child presence detection, gait recognition, all using WiFi. 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 [10]–[12]. It uses only a single arbitrarily placed WiFi 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 WiFi standards do not (yet) have the support for WiFi sensing. Recognizing the increasing interests and the great potential of WiFi sensing, IEEE has formed a Task Group, with preparation efforts started in 2019, to standardize the specifications for WiFi sensing. The new standard is called IEEE 802.11bf, formally called WLAN Sensing, which is backward compatible with existing and soon-to-appear WiFi 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 WiFi 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 WiFi 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 WiFi 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, WiFi 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 WiFi sensing in several aspects as follows.

(1) Advanced WiFi Sensing. With the growing interests, WiFi sensing will undoubtedly continue to improve and expand. In particular, there are two arising opportunities, thanks to the emerging 802.11ax (WiFi 6) and 802.11ay/ad (WiGig) protocols. WiFi 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 [13], [14]. An important challenge would be how to best use these characteristics to address sensing needs. With potentially all WiFi devices becoming empowered for WiFi sensing, cooperative sensing among a set of co-existed devices would become another challenge.

(2) Integrated WiFi Sensing and Communications. Integrated Sensing and Communication (ISAC) has recently been widely discussed, mainly because the rise of WiFi sensing has changed the role of traditional communications devices. Our WiFi Sensing solutions measure desired sensing data from regular WiFi packets and run as an add-on service on top of existing WiFi 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 the sensing and networking, and how to combat inter-radio interference between neighboring WiFi devices.

(3) Wireless Sensing Data Analytics. In WiFi 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 WiFi 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.

(4) Privacy and Security Concerns. WiFi 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., WiFi 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 WiFi sensing. More systematic privacy protection efforts are desirable when WiFi 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. WiFi communication is definitely one of such technologies, and we believe WiFi sensing is yet another one arising. With Wireless AI, we redefined WiFi, 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 WiFi can do more, more even beyond our imagination today.

References

[1] "LinkSys Aware," https://www.ces.tech/Innovation-Awards/Honorees/2020/Honorees/L/Linksys-Aware.aspx, accessed 2021.

[2] "HEX Home," https://www.ces.tech/Innovation-Awards/Honorees/2021/Honorees/H/Hex-Home.aspx, accessed 2021.

[3] "Remote Patient Monitoring," https://www.ces.tech/Innovation-Awards/Honorees/2021/Best-Of/O/Origin-Health-Remote-Patient-Monitoring.aspx, accessed 2021.

[4] K. J. R. Liu and B. Wang, *Wireless AI: Wireless Sensing, Positioning, IoT, and Communications*. Cambridge University Press, 2019.

[5] B. Wang, Q. Xu, C. Chen, F. Zhang, and K. R. Liu, "The promise of radio analytics: A future paradigm of wireless positioning, tracking, and sensing," *IEEE Signal Processing Magazine*, vol. 35, no. 3, pp. 59–80, 2018.

[6] F. Zhang, C. Wu, B. Wang, H.-Q. Lai, Y. Han, and K. R. Liu, "Widetect: Robust motion detection with a statistical electromagnetic model," *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*, vol. 3, no. 3, pp. 1–24, 2019.

[7] F. Zhang, C. Wu, B. Wang, M. Wu, D. Bugos, H. Zhang, and K. R. Liu, "Smars: Sleep monitoring via ambient radio signals," *IEEE Transactions on Mobile Computing*, vol. 20, no. 1, pp. 217–231, 2019.

[8] F. Zhang, C. Chen, B. Wang, and K. R. Liu, "Wispeed: A statistical electromagnetic approach for device-free indoor speed estimation," *IEEE Internet of Things Journal*, vol. 5, no. 3, pp. 2163–2177, 2018.

[9] C. Wu, F. Zhang, Y. Hu, and K. R. Liu, "Gaitway: Monitoring and recognizing gait speed through the walls," *IEEE Transactions on Mobile Computing*, vol. 20, no. 6, pp. 2186–2199, 2020.

[10] F. Zhang, C. Chen, B. Wang, H.-Q. Lai, Y. Han, and K. R. Liu, "Wiball: A time-reversal focusing ball method for decimeter-accuracy indoor tracking," *IEEE Internet of Things Journal*, vol. 5, no. 5, pp. 4031–4041, 2018.

[11] C. Wu, F. Zhang, Y. Fan, and K. R. Liu, "RF-based inertial measurement," in *Proceedings of the ACM Special Interest Group on Data Communication*, 2019, pp. 117–129.

[12] C. Wu, F. Zhang, B. Wang, and K. R. Liu, "Easitrack: Decimeter-level indoor tracking with graph-based particle filtering," *IEEE Internet of Things Journal*, vol. 7, no. 3, pp. 2397–2411, 2019.

[13] F. Zhang, C. Wu, B. Wang, and K. R. Liu, "mmeye: Super-resolution millimeter wave imaging," *IEEE Internet of Things Journal*, vol. 8, no. 8, pp. 6995–7008, 2020.

[14] S. D. Regani, C. Wu, B. Wang, M. Wu, and K. R. Liu, "mmwrite: Passive handwriting tracking using a single millimeter wave radio," *IEEE Internet of Things Journal*, 2021.