AI-Enabled WiFi Sensing: Creating an Intelligent, Connected Ecosystem

Abstract—The next revolution in WiFi technology is not about communication and networking but sensing. Wireless sensing technology turns 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 transforms how sensing—especially sensing that focuses on detecting and analyzing human presence—is practiced. The integration of this technology with advanced AI models and algorithms further enhances the accuracy of these systems. AI-enabled 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 sensing functionalities benefit the global WiFi ecosystem, including integrated circuit manufacturers, device manufacturers, system integrators, application developers, and end users. In this white paper, we introduce the concepts, principles, challenges, evolution, and growth potential of AI-enabled WiFi Sensing and share Origin AI's unique technologies and innovations that have been deployed for real-world applications and are currently impacting consumers and businesses. We are at the forefront of AI-enabled WiFi Sensing innovation. In the coming years, we expect the technology to enter billions of devices and millions of homes, enhancing consumers' safety, health, and well-being.

Introduction: WiFi Sensing's Revolutionary Evolution

Many people still believe that WiFi's only purpose is to connect us to the internet, but the technology has vast potential that, up until recently, was untapped. In the past decade, the world's understanding of WiFi has changed from a pure communication platform to a ubiquitous sensing infrastructure. Because of its worldwide ubiquity, this sensing capability instantly turns WiFi networks into the world's largest "sensorless" sensing network, not requiring any dedicated hardware sensors.

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 the commercial technology industry and academia. Due to WiFi's omnipresence, low cost, and high sensing capabilities and accuracy, WiFi Sensing promises to be a very attractive solution.

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. The largest real-world impact, directly improving consumer safety, is in the home security space.

After years of effort in developing WiFi Sensing predominantly in academia, significant contributions from the WiFi Sensing industry have emerged. Origin AI's uniquely powerful, accurate, and seamless approach to WiFi Sensing is called AI Sensing^{SM}.

Realizing the new possibilities and the huge implied market, the broader technology and connected device industry has taken significant strides to develop and integrate WiFi Sensing support into their devices. 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. Mainstream chipset manufacturers—such as Qualcomm, NXP, Broadcom, Realtek, Intel, MediaTek, and Cypress—have started to support WiFi Sensing in their current and/or next-generation chipsets.

In 2019, a task group of Institute of Electrical and Electronics Engineers (IEEE) Standards 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.

Although there was a slight delay, the development of IEEE 802.11bf is approaching completion as of January 2025.

With the standardization of 802.11bf close to formal approval in IEEE, the next key undertaking within the WiFi Sensing sector will be turning attention toward commercialization, productization, and interoperability. To this end, many companies, including Origin AI, are turning to another organization, Wi-Fi Alliance® (WFA), to develop essential testing programs to ensure interoperability. We expect that the development and approval of the relevant WFA testing programs will receive strong industry-wide participation and likely take two to three years. Already in place are preliminary commitments from key industry players to independently develop 802.11bf chipsets and modules necessary for the interoperability work.

For now, we patiently await the arrival of 802.11bf chipsets, modules, and systems. They will be tested and approved by authorized test labs to ensure interoperability. And then, the age of ubiquitous WiFi Sensing will commence.

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 for 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,[1] 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 spaces. 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 activities 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 potential applications to be explored and imagined. In essence, WiFi Sensing is not only revolutionizing how sensing is being practiced but also making many applications that were impossible before possible.

In this white paper, we will give a high-level overview of the vision, principles, and challenges of WiFi Sensing and report our experience in commercializing AI-enabled WiFi Sensing/AI Sensing℠ for real-world applications.

WiFi as a Sensor: The World's Largest Sensor Network

There are reportedly over 20 billion WiFi devices worldwide connected via wireless local area network (WLAN).

Until recently, the majority of these WiFi devices have been merely for data networking. With AI-enabled sensing, these WiFi devices now have a brand-new functionality. WiFi devices are evolving to become ubiquitous sensing interfaces for perceiving various environmental information. When enabled by wireless sensing, this huge number of connected devices immediately forms the world's largest-ever sensor network—a ubiquitous, multipurpose, and nonintrusive 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, smartphones, smart pads, smart plugs, smart lights, smart doorbells, and other smart appliances—have entered our homes. 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 in developing and undeveloped countries and regions.

Also, because of the nature of wireless signals, WiFi Sensing is inherently a distinctly noncontact 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 user's 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 potential 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 multipurposed 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 multipurpose 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. 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.

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.

Principles and Challenges

An important and challenging question is this: 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, smart speaker, etc.) but also many non-line-of-sight (NLOS) multipaths—a well-known phenomenon in wireless communication. So, a home is like a wave pool, and when one moves through it, it will disrupt all these waves. WiFi Sensing leverages these multipath disturbances/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 role of multipath propagation has completely changed 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. 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.

Translating the above principle into practical solutions involves grand technical challenges, especially using commodity WiFi. There are at least three fundamental issues of commodity WiFi that we are facing: Firstly, WiFi transceivers are not synchronized; 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 antennae, 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 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, implicitly assume 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 truly integrated communication and sensing solution.

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, the auto industry, etc.

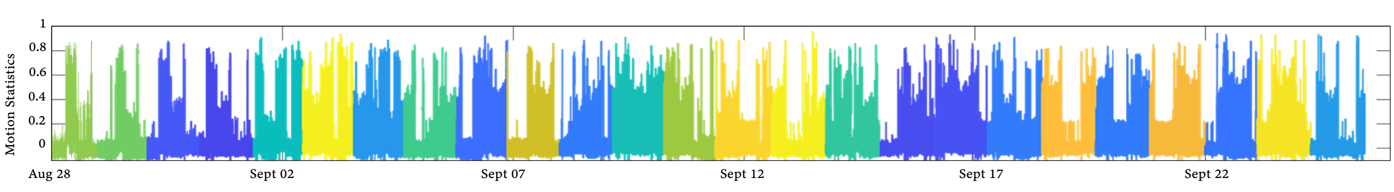
To overcome the above challenges and deliver practical WiFi Sensing solutions, we investigate the problem of WiFi Sensing from the first principle of electromagnetic (EM) waves and manage to develop a set of statistical approaches under a statistical EM field model, circumventing the need to resolve individual multipaths. The model was inspired by the principle of time-reversal,[2] 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 autocorrelation function

(ACF) of CSI, which embodies several unique spatial-temporal features:

1) Motion[3]**:** 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 a 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 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[4]**:** 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 in an unfavorable situation, e.g., far away from the link, behind the wall, or covering a thick blanket, etc. Using

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



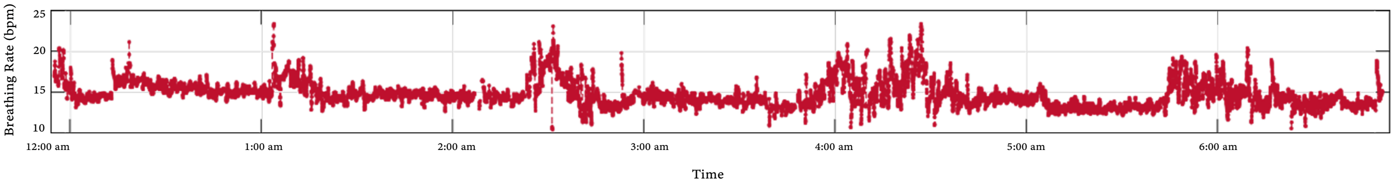


Fig. 3. Overnight breathing rates during sleep.

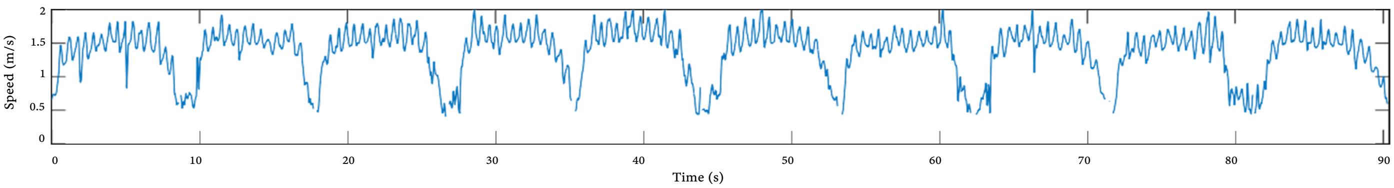


Fig. 4. Estimated speed of a user walking around a path for 10 rounds.

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[5,6]**:** 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 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 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. 4 illustrates the estimated speed when a user is walking around an office space, where the Tx and Rx are placed 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 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.

Origin AI's Advanced and Differentiated WiFi Sensing Solution

The past decade has witnessed great efforts from industry in commercializing WiFi Sensing for real-world applications, most of which are not successful due to practical challenges in a multipath-rich indoor environment. By treating plentiful multipath reflections as massive virtual antennae and exploiting the statistical theory of electromagnetic (EM) waves, Origin Research (the lauded research arm of Origin AI) discovered a universal relationship between the WiFi physical layer channel state information (CSI) and the intensity, speed, and periodicity of motion, enabling a wide range of unobtrusive, accurate, and robust WiFi Sensing applications, which have been successfully deployed on various types of IoT devices in millions of families. Such a discovery laid the foundation of Origin AI's technology, which offers accurate and robust performance, outperforming and differentiating from other solutions.

Origin AI's technology and approach advances and evolves traditional applications and understandings of WiFi Sensing. Due to the company's evolution of the technology, driven by AI, Origin's WiFi Sensing solution is called AI Sensing℠. Origin AI's Human Presence℠ detection engine is the defining feature of AI Sensing℠ and TruShield technology. The engine first detects motion caused by a moving object by using the CSI as input to calculate the average motion statistics, which reflect the strength or intensity of motion present in a given environment. To distinguish between human and nonhuman motion and minimize false alarms, Origin AI developed an advanced algorithm that filters out nonhuman movement by feeding relevant features into an ML-based classifier. Deep neural networks are further developed to improve the robustness of classification, which can achieve >99% classification accuracy with 20 seconds of CSI. This level of advanced motion classification offers unmatched verification, reducing false alarms and delivering superior intrusion detection accuracy.

Meanwhile, more practical challenges arise. The diversity in frequency, device types/locations, environments, and users' daily routines require specific parameter tuning in WiFi Sensing applications based on conventional signal processing (SP). Pushing the performance limits, machine/deep learning (DL) techniques have become a promising alternative and received increasing attention. However, most existing learning-based methods heavily rely on features directly extracted from raw CSI and are thus susceptible to environmental changes and performance degradation without retraining. Origin Research proved that the autocorrelation function (ACF) of the CSI, the key feature of Origin AI's first-generation sensing algorithms, can very effectively and solely reflect the movement/motion of moving subjects, invariant to environment changes, agnostic to subjects/devices' location/orientation/etc., and designed a suite of learning-based algorithms for next-generation sensing applications.

WiFi operating at higher frequency with a larger bandwidth (e.g., 802.11ay) offers better spatial resolution and enables more fine-grained motion/vibration sensing. Origin's pioneering introduction of radio-modality microphones (RadioMic) opened up a new frontier of the next generation of radio sensors, transforming the acoustic/audio research landscape. RadioMic not only introduced methods to capture raw vibration signals from the sources and ambient objects showing high-quality speech recovery but also paved the way for integrating DL systems in audio-radio sound sensing and introduced many revenues for future research, including speech enhancement and separation (RadioSES), enhancing noisy mixture speeches and voice activity detection (RadioVAD) ideal for automatic microphone mute/unmute without user intervention. Combining the power of SP and DL, Origin Research has also proposed a high-accuracy CNN-based gait recognition system with minimal training and a CGAN-based high-resolution human silhouette imaging network enabling people identification.

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: Powered by AI-enabled WiFi Sensing and made available to consumers, internet security providers (ISPs), security providers, and other relevant businesses in 2024, TruShield Security^{SM} is Origin AI's next-generation do-it-yourself (DIY) security system. In an era where homeowners and renters demand user-friendly and affordable security solutions that protect their loved ones, residences, and property, DIY security companies face the challenge of providing reliable systems that can reduce false alarms, are simple to support, and that customers can easily set up on their own. Origin AI's TruShield is a cutting-edge DIY security system that monitors a home with just a home router and common IoT devices, such as smart light bulbs, smart speaker, security cameras, etc., offering a simple plug-and-play solution designed to enhance user-friendliness and reduce false alarms with the end goal of increasing customer satisfaction, combating attrition, and reducing cost-to-serve. Since broadband WiFi can be found in every home nowadays, ISPs are in an excellent position to offer WiFi Sensing-based security services.

TruShield Security empowers ISPs and security providers to offer their customers unparalleled security that integrates seamlessly with current setups, creating new revenue-generating products without requiring additional equipment or installations.

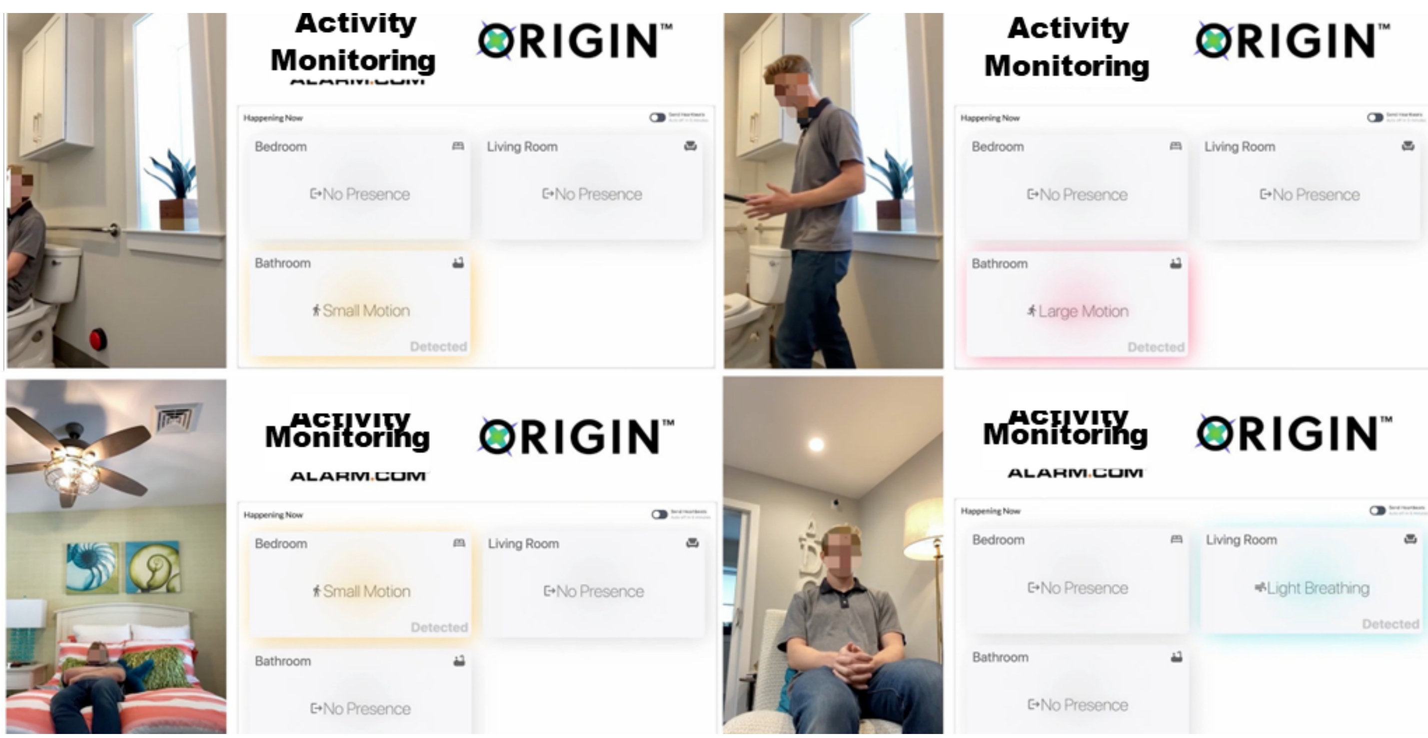
With Origin AI's TruShield, ISPs and security companies transform smart devices into advanced virtual sensors, creating an intelligent home ecosystem to enhance security, connectivity, and convenience. The TruShield platform features the most advanced intrusion-detection solution, utilizing AI to verify human presence in a space. By intelligently filtering out nonhuman motion—such as pets, fans, and mechanical motion—we achieve the lowest false alarm rates in the industry.

TruShield also introduces the first-ever human presence solution to accurately detect whether a person is in a space or not, enabling tremendous improvements in energy efficiency for HVAC, smart automations, and lighting controls in homes and businesses.

TruShield Security responds to evolving end-user customer demands and the home industry's shift toward integrated, intelligent solutions. End users can manage security through an app, which ISPs can tailor to their customers with customizable notifications and real-time updates. Users' phones will also act as a key, autodisarming the system on arrival. Additionally, TruShield Security complements outdoor cameras and video doorbells to bring seamless coverage indoors. By using existing IoT devices like smart speakers and plugs as sensors, TruShield eliminates blind spots and extends protection throughout the home.

2) ADL Monitoring: Activities of daily living (ADL) monitoring (Fig. 5) can detect not only instantaneous motion and its strength but also its location, thus enabling 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.

Fig. 5. Activities of daily living monitoring using WiFi.



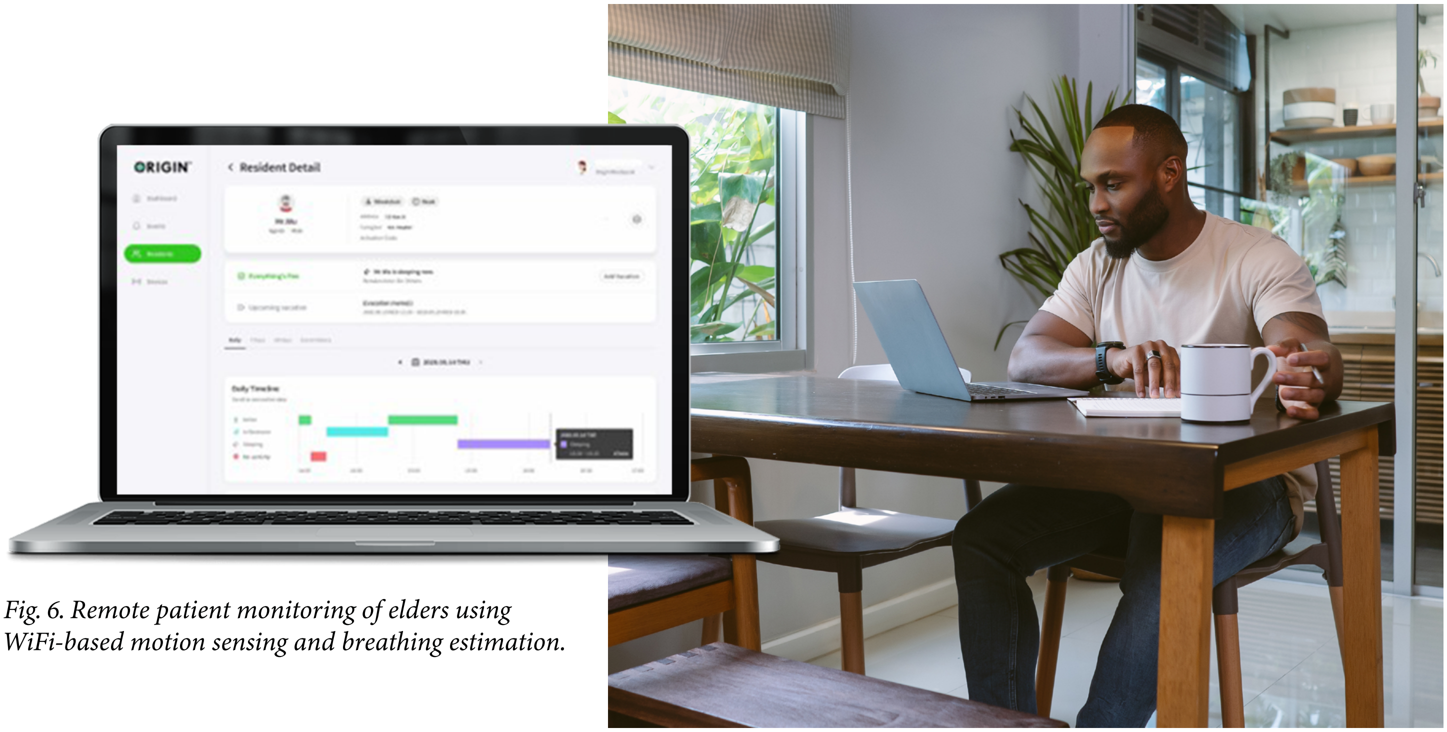


Fig. 6. Remote patient monitoring of elders using WiFi-based motion sensing and breathing estimation.

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. 6) can provide information such as time to bed, awake time, wake up, rapid eye movement (REM), and non-rapid eye movement (NREM) monitoring; inform caregivers of average breathing rate and breathing rate variability; calculate a sleep score so that caregivers can know how a loved one slept; track improvement or deterioration; and look for anomalies from historical sleep data.

4) Fall Detection: WHO estimates that there are typically 37 million severe falls and 646,000 fatal falls each year, making falls 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 have designed 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, and 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, and yet no 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.[7, 8, 9] 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 in massive buildings with very low cost. To the best of our knowledge, this is the first and only system to achieve this despite decades of effort worldwide. The prototype system attracts numerous interests from the industry and has been invited for demo at the headquarters of many major companies.

IEEE Standard and Future Trends

Current WiFi standards do not yet support WiFi Sensing, but that will change imminently. Recognizing the increasing interest in and the great potential of WiFi Sensing, IEEE formed a task group. 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.

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. 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.

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.

As of January 2025, IEEE 802.11bf is approaching completion. Once implemented, the industry's next focus will be to ensure interoperability through testing programs with WFA and the development of 802.11bf chipsets, modules, and systems. This will pave the way for the widespread commercialization and productization of WiFi Sensing. Along the way, we envision many opportunities and challenges for the future development of WiFi Sensing in several aspects.

(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 this: 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, and multitarget sensing.[10, 11] 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 coexisting 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.

Conclusion

“The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it,” Mark Weiser visioned in 1991. WiFi communication is undeniably one such technology, and WiFi Sensing is yet another, rapidly ascending to enhance lives globally.

With AI Sensing℠, we have redefined WiFi from pure communication to omnipresent sensing capable of accurately distinguishing between human and nonhuman motion. We’ve also redefined what most consumers think of when they hear the word “sensing.” Our technology moves them from hardware/sensor-based to sensorless systems, with no additional equipment required.

Many unprecedented AI Sensing℠ applications have already been made a reality worldwide. Looking toward the future, we see boundless potential for the technology and its deployment and commercialization worldwide. There is no doubt that WiFi can and will do more—even beyond our imagination today.

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