THE COMMERCIAL MARKET VALUE FOR WI-FI SENSING

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INTRODUCTION

Wi-Fi Sensing is a nascent technology that leverages Radio Frequency (RF) signals from pre-existing Wi-Fi infrastructure to detect presence and motion. The technology has undergone rapid development, progressing from a mere academic theory a decade ago, to one of the most competitive positioning solutions currently on the market today. The final standardization of Wi-Fi Sensing (802.11bf) by the IEEE is on track for September 2024, at which time Wi-Fi will evolve from a communication-only standard to a dual-function technology that forms a fundamental component of the future of Integrated Sensing and Communication (ISAC). The enhanced capabilities of Wi-Fi, combining communication and sensing, will raise the overall value of Wi-Fi deployments and devices over the coming decade and lead to valuable new services being created across both consumer and enterprise Wi-Fi deployments.

The core drivers of Wi-Fi Sensing's development and commercialization are the several software vendors active in the market today, including Aerial, Cognitive, Origin, and nami, alongside their ecosystem partners, such as Plume for Cognitive and Verizon for Origin. Most Wi-Fi Sensing platforms are software-level applications that interpret Channel State Information (CSI) data extracted from chipsets, although Renesas/Celeno has also developed a unique hardware level implementation of Wi-Fi Sensing operating with full-duplex operation. Wi-Fi Sensing is still in the early stages of its development, with substantial untapped potential. Standardization will play a vital role in facilitating the maturity and scalability of the technology, as it will help resolve the technical challenges hindering widespread adoption, enable vendor interoperability, accelerate innovation, and boost awareness and confidence in the new technology.

Today, this low-cost, non-invasive form of activity monitoring can be used to gather contextual insights for a range of innovative residential applications, with the most promising being remote healthcare monitoring, security, and smart home automation. Over the coming years, there will be an increase in dedicated Wi-Fi Sensing equipment for critical applications like healthcare and security, as these devices can assist consumer acceptance of the technology, provide greater reliability, allow for optimized topology, and incorporate additional features specific to the application. Going forward, Wi-Fi Sensing's standardization and ecosystem maturity will drive further refinement and innovation of the technology, stimulating the creation of additional groundbreaking Wi-Fi Sensing applications in the enterprise and industrial domains, spanning everything from smart transportation to smart factories.

This whitepaper begins with an overview of the technological underpinnings of Wi-Fi Sensing, and then provides an update of the progress toward industry standardization. ABI Research then explores the key use cases and market opportunities of the technology, followed by an examination of the current market dynamics of Wi-Fi Sensing, profiling the key ecosystem vendors. We end the paper with an analysis of the core trends impacting Wi-Fi Sensing, projections of the technology's Total Addressable Market (TAM) through 2028, and strategic recommendations and guidance for the industry.

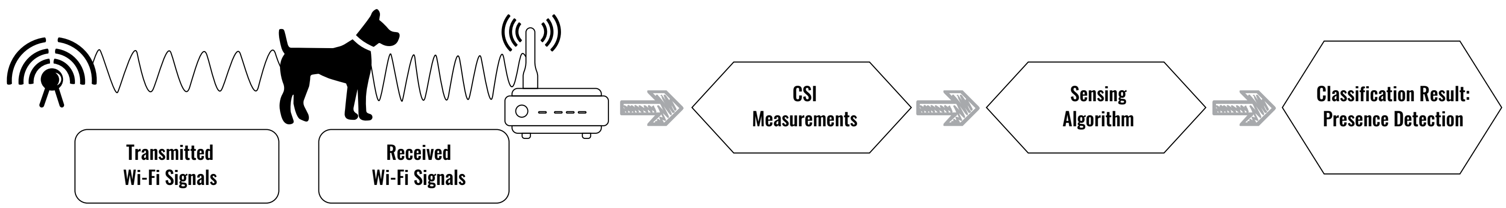
KEY APPLICATIONS AND MARKET OPPORTUNITIES

VALUE PROPOSITION OF WI-FI SENSING

Before delving into the numerous use cases of the technology, it is important to grasp why Wi-Fi Sensing is one of the most competitive positioning solutions currently on the market. The most common form of Wi-Fi Sensing involves an Access Point (AP) measuring the variations in the attenuation of received RF waves collected from one or more clients, and then through the application of statistical and Artificial Intelligence (AI) models the software can infer and contextualize presence or movement for a variety of use cases. Figure 1 illustrates this process.

Figure 1: Diagram of Wi-Fi Sensing Operation

(Source: ABI Research)



One of the key advantages of Wi-Fi Sensing is that it can leverage existing Wi-Fi infrastructure, such as an AP and numerous Internet of Things (IoT) devices dotted throughout the home, with the only change necessary being the addition of firmware on the AP for measurement coordination, extraction, and processing. These attributes mean that the technology can be deployed virtually instantaneously in consumer homes for a low cost and with minimal disruption, while still offering strong coverage. In contrast, all the alternative commercially-available positioning technologies on the market today require the installation of additional devices solely for the purpose of motion tracking, significantly adding to the cost and complexity of deployment. Compounding this are the shortcomings that each of the competing technologies have vis-à-vis Wi-Fi Sensing, as detailed in Table 1. The traditional Passive Infrared (PIR) sensors used for in-home detection require Line of Sight (LOS), are insensitive to slow-moving objects, and cannot function at high temperatures. The low-cost Bluetooth suffers from limited coverage, high interference, and low accuracy, while Radio Frequency Identification (RFID) is unfeasible given that each target requires an RFID tag. Ultrasound can offer high precision, but is power hungry, prone to high interference levels, and can be harmful to infants and pets. And the fledgling Ultra-Wide Band (UWB) can also offer high precision, but as a new technology, it lacks developed infrastructure and comes at a high price point.

Table 1: Attributes of Commercially Available Wireless Positioning Technologies

(Source: ABI Research)

SENSING TECHNOLOGY	WI-FI	BLUETOOTH	UWB	5G	RFID	ULTRASOUND	VISIBLE LIGHT POSITIONING (VLP)
Cost	Low	Moderate	High	High	Low	High	Moderate
Dedicated devices required	No	Yes	Yes	Yes	Yes	Yes	Yes
Main advantages	Can leverage existing infrastructure, meaning no need for new equipment and great coverage.	A low-cost solution that also consumes comparatively low amounts of energy.	Very high accuracy, passive sensing avoids multi-path interference for Time of Flight (ToF) measurements.	Very high accuracy.	Simple and low-cost technology.	High levels of accuracy.	Low power consumption.
Main disadvantages	Low precision with sub-7 Gigahertz (GHz) frequencies.	Limited coverage area, low accuracy, and high levels of interference as it relies on 2.4 GHz.	New technology lacking developed infrastructure, high cost, and requires line of sight for best results.	Costs driven up by equipment and spectrum licensing requirements.	High response times, low accuracy, targets need RFID tags.	Can be harmful to infants or pets, suffers high levels of interference, also consumes high power.	Coverage is poor, as it requires line of sight and has low precision.

CURRENT COMMERCIAL USE CASES

Currently, most Wi-Fi Sensing solutions on the market only provide simple presence detection abilities, i.e., both Plume Sense and Verizon's Home Awareness can alert consumers to a presence in their home, but not the specific location where the movement is occurring. There are several reasons for this low level of granularity, spanning the technical (restrictions of sub-7 GHz frequencies, sub-optimal topology of existing networks, limitations of current sensing algorithms) and the commercial (the business requirements of the partners of the software vendors going to market only require this level of localization).

There is consensus among all the Wi-Fi Sensing software vendors that the most promising Wi-Fi Sensing applications will be found within remote healthcare, home security, and home automation, with most resources currently being directed toward the first. For example, to enhance its healthcare abilities, Origin is planning to launch its fall detection, sleep analytics, and wander (alerting unexplained absences) capabilities over the next 12 months. Cognitive is concentrating its resources on improving the analytics that can be ascertained from the long-term data and analytics collected by Wi-Fi Sensing, the main use for which will be healthcare. In contrast, nami is focusing its resources on improving the sensing topology, which it believes is the most important for improving sensing performance and granularity. For example, the company is working to raise the Frames per Second (fps) of the sensing programs from the current 30 Hertz (Hz) up to 300 Hz, which will deliver considerable improvements to granularity.

People counting is an implementation that all vendors are currently working on, which has a broad range of applications spanning residential to enterprise (*e.g.*, building managers who need people counting for climate control). While enterprise and industrial use cases beyond this are currently limited, the standardization of Wi-Fi Sensing in 2024 will change this, as the low hanging fruit in these markets is plentiful (healthcare and security can leverage the same technology as residential), with the challenge then being finding the correct partners to bring these solutions to market. Another area of active development is within the usage of Wi-Fi chipsets prevalent in modern vehicles to alert vehicle owners that a child has been left in the vehicle, with the main purpose of avoiding child hot car deaths. The alert could be made by honking the car horn, for example, or if the automobile has a cellular connection, through a mobile notification. The development of this application is being expedited by national regulations (*e.g.*, the Hot Cars Act of 2021 in the United States), which is forcing car manufacturers to act. Figure 2 provides a snapshot of the current and future Wi-Fi Sensing applications on vendors' roadmaps.

Figure 2: Current and Future Wi-Fi Sensing Abilities

(Source: ABI Research)

Below, ABI Research discusses the three most promising Wi-Fi Sensing use cases today, alongside a range of additional opportunities for the future.

ELDERLY HEALTHCARE MONITORING

The global elderly population will increase rapidly over the coming decades, with the United Nations (UN) projecting a 40% expansion between 2020 and 2030. This will further drive the need for low-cost, easily accessible remote healthcare technologies, a demand that Wi-Fi Sensing will be perfectly positioned to fulfill once the technological advancements scheduled for the next 12 months (notably fall detection and sleep analytics) are launched. The technology will be used by consumers to detect falls, unexpected absences, or abnormal adjustments in typical daily routines, and can immediately alert family, caregivers, or emergency responders if necessary. Family members will be able to remotely check on an elderly relative's status, and can monitor and review activity insights, such as sleeping patterns, idle times, or the number of trips to the bathroom, which could reveal concerning behavioral changes.

Wi-Fi Sensing is being viewed as a preferable alternative to other remote care technologies for several reasons. First, unlike video surveillance, Wi-Fi Sensing is neither intrusive, nor stigmatizing. Second, because the solution does not require any additional hardware and, therefore, has an extremely low cost, it is extremely accessible. Third, Wi-Fi Sensing does not require adjustments to the target's daily routine in any way, as the technology can operate discreetly in the background without interfering with the occupant's way of life. This contrasts with healthcare wearables, such as bracelets or pendants, which many elderly owners do not wear (80% by one estimate). Furthermore, according to one report, only 17% actually activated the emergency button after a fall. In contrast, Wi-Fi Sensing could automatically alert the relevant individual/organization without any necessary manual input. Finally, the technological advancements scheduled over the coming 12 months will provide Wi-Fi Sensing with healthcare abilities not available with other solutions, making it one of the most competitive options in the market.

There are several go-to-market strategies for this application. First, software developers can work directly with Internet Service Providers (ISPs) that can bundle the application into their service packages either to increase competitiveness or raise extra revenue. This route may face low consumer confidence given that ISPs have not traditionally served this area, so an alternative strategy is to work directly with healthcare providers, either to incorporate Wi-Fi Sensing into their existing equipment, or to work with third-party Original Equipment Manufacturers (OEMs) to devise a dedicated device for this purpose. Healthcare providers and dedicated devices will aid consumer acceptance of the solution and raise device reliability and network topology. Furthermore, dedicated devices can also incorporate additional features of use for healthcare, such as two-way radios, further increasing their value proposition.

HOME SECURITY

Current home security systems can be expensive, with large upfront costs required to install additional dedicated hardware being prohibitive for many. They can also be unreliable, as the PIR sensors often used for the systems are prone to false alarms, and devices like security cameras can be hacked. And for some, the invasive nature of security cameras, especially those covering indoor environments, make them uncomfortable. Wi-Fi Sensing addresses all these concerns. As discussed before, Wi-Fi Sensing is low-cost and easy to implement; it is reliable because the number and scope of Wi-Fi signals ensure coverage is broad, and the devices are protected by Wi-Fi Protected Access (WPA) security; and because Wi-Fi Sensing only captures movement patterns, and processes all the data at the edge, the technology can protect consumer privacy.

Another key advantage of Wi-Fi Sensing security over traditional systems is that it expands the serviceable market. The technologies' low-cost nature has the potential to make home security accessible to customers such as renters, who previously would not have installed an expensive system if they were only going to remain in the property temporarily. As for bringing the solution to market, there are several strategies. First, software developers can work with Managed Service Providers (MSPs) so that they can offer not just digital security, but also physical security. This could be provided in tiers, such as by offering an entry-level service with basic functionality that uses existing Wi-Fi infrastructure, and an advanced tier service through which they can deploy dedicated Wi-Fi Sensing smart home equipment. Furthermore, the simple presence detection capabilities of today will become further augmented alongside the greater maturity of the technology over the coming decade. For example, within 36 months, it will be possible to track traits, such as height and gait, to discern whether the person who has entered the network area is a verified or unverified person, or to have custom AI algorithms trained through data from an individual user's environment. This will unlock further tiering possibilities of Wi-Fi Sensing home security subscriptions, with the possibility that access to advanced functions can constitute a premium tier. Another strategy is to work directly with security OEMs, which could augment their existing security technology or potentially replace it altogether with Wi-Fi Sensing. These dedicated security devices will likely prefer monostatic configurations (a co-located transmitter and receiver), as this will still operate when the network is down or the pair is unavailable.

SMART HOME

Wi-Fi Sensing is ideal for smart home automation, as unlike other non-invasive sensing technologies, it can discern presence if the human is obscured behind walls or objects, or if they were to remain inactive (i.e., stand or sit still). Connected appliances can then be activated/deactivated accordingly, helping to make the smart home more responsive and efficient, increasing their value proposition to consumers. Furthermore, Wi-Fi Sensing-powered automation can aid energy conservation, and long-term platform insights could be used to further optimize smart home usage. The potential market for this application is huge, spanning homeowners and businesses looking to reduce energy usage for monetary or carbon neutral purposes. Hospitality establishments could leverage Wi-Fi Sensing to save on energy costs without impairing service quality, and utility companies, potentially in partnership with Wi-Fi ecosystem vendors or service providers, could offer the technology as a cost-cutting service.

Given that Wi-Fi Sensing-powered smart home automation is already at a late stage of maturity and requires few complex algorithms, it is perhaps the simplest Wi-Fi Sensing algorithm to bring to market. Currently available examples, such as the smart lightbulbs from Signify, are designed to be deployed in pairs, with the attenuation of the RF waves between the two measured to detect presence. Over the coming decade, other consumer electronics manufacturers will increasingly adopt this technology to differentiate their products from the competition, but unlike for lightbulbs, a bistatic configuration will not be suited for single devices like smart TVs or smart speakers. For this reason, manufacturers of standalone devices will likely favor monostatic, hardware-level forms of Wi-Fi Sensing, where the transmitter and receiver are co-located on one chipset (*e.g.*, on Intel's Raptor Lake chipsets). This will allow their devices to "wake" when a human presence is detected without the need for a device pair or Internet connection. The route-to-market for such devices is either directly through retail, with the technology pre-installed on the smart home device, or through a subscription model where the devices and sensing functionality are leased to the consumer for a monthly fee.

FUTURE OPPORTUNITIES

Applications possible with sub-7 GHz frequencies include:

- **People Counting**: Non-invasive method of counting the approximate number of people in a location, potentially spanning multiple rooms or entire buildings. Users could include building managers for the purposes of climate control, companies leasing out properties wishing to track whether large events (*e.g.*, a party) are being held without permission, or stores wanting to know customer numbers.
- **Smart Meeting Rooms**: Automate meeting rooms with presence detection, attendee counting, and localization of active people. MSPs can offer this as an additional service for their enterprise customers, with additional revenue possible from the initial network setup and configuration.
- **Hidden Object Detection**: Augmenting human sense to reveal concealed objects, such as weapons. Carries potential as a low-cost, easy-to-implement security service for building managers, provided by MSPs.
- **Child Presence Detection in Automobiles**: Alert vehicle owners *via* mobile notification or car action (*e.g.*, honking the horn) that a child has been left in the vehicle, avoiding child hot car deaths. Vehicle manufacturers—not the end consumers—will pay for this service. The manufacturers will likely work directly with software vendors to create a custom sensing platform, and the business model will be a one-off purchase for the lifetime of the vehicle.

Certain applications will require sensing with the higher granularity that only Millimeter Wave (mmWave) can provide. These include:

- **Gesture Recognition**: Short- and medium-range gesture recognition (down to the finger level) will require mmWave. This can mean advanced control of smart home appliances through finger movements, or activities like playing a virtual piano. The advantage of this method over other gesture recognition technologies based on video is that it will work both through walls and in the dark.Audio Tracking: Track people within a room so the audio system can target them. Can be added as an additional revenue stream or differentiator for smart speaker systems.
- **Breathing Monitoring**: Track a subject's chest displacement with CSI measurements. One of the most promising applications of this technology is vital sign monitoring, which could further enhance sensing healthcare services.
- **Animal Health**: Detect atypical variations in animal behavior or abnormal heartbeat fluctuations, both of which could be expected if they had contracted a virus or suffered an injury. ISPs and animal welfare companies can bring this service to consumers, potentially through dual-function dedicated devices, such as pet bowls.
- **Emotional Reactions to Content**: Wi-Fi Sensing could infer the emotional response of viewers to content by measuring fluctuations in their heartbeat. Potential target businesses include video streaming platforms or video game developers that wish to gain further insight into the audience's engagement or reaction to content.
- **People Identification**: Height, gait, breathing rate, and even facial recognition could be tracked by Wi-Fi Sensing to determine a person's identity. This could be used to send customized notifications, or to distinguish whether the individual is familiar or unfamiliar (and thus trusted or untrusted). Vendors of Wi-Fi Sensing security or smart home automation platforms can use this to further enhance their value proposition to consumers.
- **Sneeze Sensing**: Detection and localization of person and sneeze droplet volume. Go-to-market strategy will be in conjunction with other healthcare services.
- **Driver Drowsiness Detection**: Identify signs of drowsiness, such as a low heart rate or drooping eyelids. As with child presence detection, this application will be developed specifically for this use case, either in partnership with software developers, or potentially in-house if the manufacturer builds its capabilities sufficiently.
- **Three-Dimensional (3D) Vision**: Build a 3D matrix of an environment using multiple Stations (STAs) within a room.

In the future, the convergence of Wi-Fi Sensing with other next-generation wireless technologies like 6G for combined ISAC functionality will unlock a plethora of possibilities, particularly in enterprise. Some examples include:

- **Vehicle-to-Everything**: Secure hands-free access, high-precision location, Simultaneous Localization and Mapping (SLAM), vehicle platooning.
- **Remote Sensing**: Drone Synthetic Aperture Radar (SAR) imaging, satellite imaging and broadcasting.
- **Smart Manufacturing and Industrial IoT (IIoT)**: High-accuracy robotics localization and tracking, Automated Guided Vehicle (AGV) navigation, remote facility monitoring, employee health oversight, employee localization and authorization, and predictive maintenance.
- **Sensing-as-a-Service**: Mobile crowd sensing, cooperative localization and imaging, channel knowledge map construction, drone monitoring and management.
- **Environmental Monitoring**: Such as rain, pollution, or insect monitoring.

STANDARDIZATION OF WI-FI SENSING

THE NEED FOR STANDARDIZATION

Academic research on Wi-Fi Sensing began appearing roughly a decade ago, but it remained purely academic and conceptual at the time. Numerous Wi-Fi-based sensing technologies were proposed in the early 2010s, such as WiSee and Wi-Vi, which were introduced for whole-home human detection and gesture recognition using Wi-Fi signals. Other more recent examples from 2018 include PeriFi, which suggested measuring each multipath reflection component independently to detect moving and static occupants, and CrossSense, a Machine Learning (ML) model to enable the scaling up of Wi-Fi Sensing to new environments. Promising though they were, these isolated approaches lacked support from the broader industry ecosystem, and thus could never be scalable. Therefore, in order for the technology to evolve from an academic theory to a viable industry-wide technology, and to truly become scalable, a unified set of agreed upon standards for the technology has now become necessary. Key advantages of standardization include:

- **Vendor Interoperability**: Standardization will ensure that all equipment and components are interoperable with each other, improving the versatility, accessibility, and scalability of Wi-Fi Sensing.
- **Ecosystem Collaboration**: Strategic partnerships between different vendors within the ecosystem (for example, between software and chipset vendors) will be simplified if they are all operating off the same standard foundation.
- **Network Load**: Wi-Fi Sensing leverages pre-existing Wi-Fi signals, so it is essential that Wi-Fi Sensing operation does not interfere with the core communications network operation in any discernable way.CSI Availability: CSI access has traditionally been a restricted private feature on commercial Wi-Fi chipsets, but standardization will ensure that these essential data are readily available from all 802.11bf supporting chipsets.
- **Streamline Regulation**: Certification of Wi-Fi Sensing products by national regulators will be simplified if all products conform to the same set of standards. For example, if there are Wi-Fi Sensing privacy concerns in certain markets, standardization would mean decisions could be applied industry-wide, and not on a case-by-case basis.
- **Quality Control**: All technical features to be included in the final 802.11bf standard must first be rigorously tested and approved by 802.11 members. This will ensure that all Wi-Fi Sensing features are functionally reliable, helping to raise consumer confidence in the technology and, by extension, aiding its adoption.
- **Bridging Research and Market**: The transition from academic theory to marketable product will be easier if the research is aligned with a common standardized framework, instead of being built from the ground up each time.
- **Innovation Acceleration**: Instead of having to manually implement operations like CSI collection, feature extraction, and classification, standardization will provide developers with access to clear and proven Wi-Fi Sensing procedures, with established protocols for the interaction with Physical Layer (PHY) and Medium Access Control (MAC) layers. This will expedite innovation.
- **Technology Awareness**: Consumers are still broadly uninformed on Wi-Fi Sensing, so standardization has an important role to play in boosting both awareness and confidence in the technology.

THE ROAD TO IEEE 802.11BF

Recognizing the need for standardization, in September 2020 the IEEE 802.11 Working Group (WG) approved a Project Authorization Request (PAR) for a new Task Group (TG) to work on the IEEE 802.11bf (Wi-Fi Sensing) standard, called TGbf. TGbf's leadership includes representatives from companies including Huawei, LG Electronics, Qualcomm, Ericsson, and Meta Platforms, and the group's stated mission is to work on the development of the 802.11bf standard amendment for Wi-Fi Sensing in the unlicensed sub-7 GHz and mmWave frequencies. The goal is for 802.11bf to be backward compatible with existing 802.11 standards, including 802.11n (Wi-Fi 4), 802.11ac (Wi-Fi 5), 802.11ax (Wi-Fi 6), and 802.11be (Wi-Fi 7) standards, as well as 802.11ad and 802.11ay (collectively referred to as WiGig). Alterations will also be made to the IEEE 802.11 MAC. Multiple rounds of voting will decide which features are included, with at least 75% of the 802.11 voting members agreeing to the features' inclusion at each round. The first draft of the standard (D0.1) was originally scheduled for January 2022, but has now been pushed back to a predicted January 2023 release. Subsequent drafts are anticipated for July 2023 and September 2023, with the finalization of the standard projected for September 2024.

MARKET DYNAMICS

The market is currently split across software, hardware, and chipset vendors, with most current route-to-market strategies operating *via* ISPs. To date, most Wi-Fi Sensing solutions have gone to market *via* ISPs, as this enables them to leverage the ISP's deployed Wi-Fi infrastructure, and because the sensing solutions can seamlessly be bundled into service packages, meaning they can reach a large customer base from the outset. The exception to this rule is nami, which has mainly partnered with third-party vendors in the fields of security, healthcare, and home automation. Origin has also made and is pursuing further partnerships with OEMs in security, healthcare, and home automation. While partnering with ISPs will remain a core go-to-market strategy, going forward, Wi-Fi Sensing vendors will also expand their partnerships with established firms in the healthcare, security, and home automation markets, in order to further aid the commercialization of their technology.

Standardization in 2024 will further stimulate the ecosystem, allowing new entrants to become active in the market and helping to open up new service models. One result of this expansion is likely to be the emergence of additional Wi-Fi Sensing developers focusing on tailoring their solutions for specific use cases, as opposed to designing an underlying technology that can serve multiple verticals, which is the standard model today. Specialized Wi-Fi Sensing vendors could devote resources to the development of algorithms and dedicated devices for a specific use case, which will accelerate innovation for the application, and facilitate market acceptance of the technology. Through partnerships with OEMs, this could enable Direct-to-Consumer (DTC) service models, with initial equipment costs and then economical monthly subscription fees for the consumers (much like the Ring doorbell from Amazon). In the long term, once these Wi-Fi Sensing solutions have matured and have proven to be drivers of additional revenue streams, they will likely be the target of acquisition by large technology firms.

SOFTWARE VENDORS

- **Aerial**: A Canadian-based Wi-Fi Sensing software provider established in 2015. In 1Q 2019, Aerial launched a proprietary smart plug-in device for extending Wi-Fi Sensing coverage, in 4Q 2021, its Wi-Fi Sensing applications were made available on Qualcomm's Networking Pro Series platform, and in 1Q 2022, it was announced that Broadcom's Wi-Fi 6/6E AP and mesh solutions were now compatible with its technology. Aerial is currently in the testing phase of its platform. Trials are being conducted by more than 100 operators globally, with each operator deploying approximately 100 units operating their platform.
- **Cognitive**: Cognitive is a Canadian-based Wi-Fi Sensing software provider founded in 2014. Initially, Cognitive developed its own chipset, the R10, which provided it access to the CSI data not typically available on commercial chipsets. The company used the R10 to refine its algorithm, and in 4Q 2017, was able to launch a proof-of-concept sensor product named the Aura Home, which helped persuade major chipset vendors to open the required CSI data to it. Today, Cognitive' Wi-Fi Sensing solution, called Wi-Fi Motion, enables applications that include home monitoring, wellness monitoring, and smart home automation. More than 100 ISPs are currently using its products, a majority of which have enabled consumers to use Cognitive' sensing solution for home security. One of its partnerships is with Plume, with Plume's HomePass Sense and WorkPass Flow features being based on Cognitive's Wi-Fi sensing solution. Cognitive differentiates itself from the other vendors through its greater emphasis on the insights that can be gathered from the high volume of data that its platform collects, and uses real-time AI statistical sensing models as opposed to AI trained algorithms, which is critical for scalability of current and future capabilities. Based on the physics for Wi-Fi waves, Cognitive asserts that Wi-Fi Sensing will be unable to reliably solve problems that require extreme precision, such as detecting falls. These solutions are best solved using dedicated hardware.
- **nami**: The founders of nami first discovered Wi-Fi Sensing when they were trying to find the optimal smart lightbulb automation technology for their smart lighting company WiZ. After more than 10 million Wi-Fi Sensing-enabled smart lightbulbs were sold and the company was acquired by Signify, the founders established "nami" (a name that means wave in Japanese) in Singapore. The goal was to expand the application of Wi-Fi Sensing to other domains outside lighting, and to incorporate other positioning technologies to augment its potential. nami describes itself as a middleware topology player, and its go-to-market strategy differs slightly from the other software vendors, as instead of mainly partnering with ISPs, nami supplies third-party vendors in the fields of security, healthcare, and home automation with turnkey middleware solutions for their respective verticals. nami also implements its tech onto Real-Time Operating Systems (RTOSs) to insert its solution into devices, such as smart plugs. nami is an investor in Origin, and in 1Q 2022, the two companies announced a partnership, augmenting Origin's Wi-Fi Sensing with nami's AIoT infrastructure (including firmware, cloud, Application Programming Interface (API), and User Interface (UI)/User Experience (UX) layers) to form the "now" platform. Going forward, nami is working on improving topology to raise the fps of the sensing programs from the current 30 Hz up to 300 Hz, which will result in increased granularity. It is also working on the WiDar sensing topology, with the Wi-Fi transceiver and receiver co-located in a radar setup.
- **Origin**: The company's beginnings date back to 2009, when Chief Executive Officer (CEO) Dr. Ray Liu, then a University of Maryland Professor, was contracted by the Defense Advanced Research Projects Agency (DARPA) to solve communication problems in submarines. The technology developed for this challenge inspired Ray Liu to found Origin in 2013, and its first commercial product was launched in 2019. To date, the company has been granted more than 60 patents, and Ray Liu is currently serving as the 2022 President of the IEEE. Applications powered by Origin's Wi-Fi Sensing include security, care monitoring, and home automation, and the technology uses uncompressed CSI with all processing and AI conducted at the edge. Verizon is an investor and partner of Origin, and Verizon's recently launched Home Awareness platform is based on Origin's patented Wi-Fi Sensing technology. Origin also maintains a subsidiary called Hex, which sells dedicated Wi-Fi infrastructure for home security. Much like a mesh network, the solution consists of dedicated Hex Command hubs and Sense nodes

that the consumer can place throughout the home for the best coverage. The company has partnered with Signify to produce Wi-Fi Sensing lightbulbs that can activate and deactivate the lights according to whether a human presence is detected in the room. A sensing zone is created between two or more installed bulbs, and the processing occurs on the device with a 500 ms response time.

EQUIPMENT VENDORS

Wi-Fi Customer Premises Equipment (CPE) vendors view Wi-Fi Sensing as a means to add new capabilities to their hardware, with the goal of differentiating themselves from the competition and raising their value proposition to purchasers. Examples of equipment vendors include:

- **Mercku**: Mercku has partnered with Aerial for its application of Wi-Fi Sensing, and is currently undergoing testing of the technology in several deployments globally. The hardware manufacturer believes that micro-level Wi-Fi Sensing using higher frequency wavelengths will unlock greater sensing granularity, so it is installing mmWave radios into its equipment for this purpose.
- **Linksys**: Linksys has partnered with Origin so that the mesh backhaul of its Linksys Velop mesh Wi-Fi routers, combined with the Wi-Fi signals of other smart home devices throughout homes, can be leveraged for motion detection. The company then makes these data available to consumers in its Linksys Aware app, which enables users to set up motion detection alerts, review the past 60 days of past motion events, and toggle the sensitivity of specific devices. The app in the United States costs US$2.99 a month, or US$24.99 a year.
- **OpenSync**: The past several years have seen a marked uptick in the number of Wi-Fi CPE vendors choosing to pre-integrate their CPE with Plume's open-source cloud software OpenSync, which unlocks instant access to value-added services, including the Wi-Fi Sensing application Sense. Plume partnered with Cognitive to develop Sense, which can leverage Wi-Fi signals from Plume's proprietary Wi-Fi mesh SuperPods, Wi-Fi-enabled IoT devices throughout the home, and OpenSync compatible CPE. As of September 2022, there are 35 CPE solutions that are OpenSync certified from 22 vendors, and Plume reports that HomePass is currently deployed in 43 million homes, with many of these having access to Sense.

CHIPSET VENDORS

One of the key enablers of Wi-Fi Sensing has been the advances in computational capacity, system integration, and efficiency of Wi-Fi chipsets over recent years. After having realized the potential of Wi-Fi Sensing, the major chipset vendors (*e.g.*, Qualcomm, Broadcom, and MediaTek) now frequently collaborate with the software ecosystem to ensure compatibility of their chips with the latest versions of the sensing platforms. Many major chipset vendors are also involved in the standardization of 802.11bf, including Qualcomm, MediaTek, NXP, and Intel. In addition, select chipset vendors have produced their own proprietary Wi-Fi Sensing solutions, which are detailed below:

- **Renesas**: Renesas acquired its Wi-Fi Sensing capabilities through its US$315 million acquisition of Celeno in late 2021. Celeno had previously developed a unique hardware-based proprietary Wi-Fi Sensing technology called doppler imaging that uses full-duplex operation with the transmitter and receiver co-located, a synchronization that enables the collection of detailed doppler spectrograms. The raw data can then be extracted through an API to be used for inference at the software level. The advantages of this approach are that one device alone can perform the sensing, everything can be processed locally so there is no need for a home network, and greater granularity can be attained over sub-7 GHz channels at close range. Celeno had prototyped its Wi-Fi Doppler imaging technology in its Wi-Fi 5 CL2400 chipset in 2020, which enabled it to test the technology and identify key use cases. After having successfully incorporated Celeno, Renesas is now working on a Wi-Fi 6E chipset with Doppler Imaging technology, which is scheduled for production in the next 18 months. It has also partnered with Orange Labs to develop people counting applications with its technology.

- **Intel**: Intel's latest 13th Gen Raptor Lake CPU, released 4Q 2022, is the company's first product to support its proprietary Wi-Fi Sensing solution. The main use case currently being promoted by Intel is for Personal Computers (PCs) to wake when humans are detected and sleep when they leave the device's vicinity, but new applications are also being developed by the company. All Raptor Lake CPUs have this ability, but it is up to the equipment manufacturer's discretion whether or not to activate the feature.

INTERNET SERVICE PROVIDERS

Over the past several years, many ISPs have begun rolling out Wi-Fi Sensing as a value-added service for their consumers. Recent examples include Verizon in the United States (which is leveraging Origin's solution), Deutsche Glasfaser in Germany (as part of Plume's HomePass, which it is offering to customers), and Cablenet in Cyprus (also through a partnership with Plume). Several converging trends have driven ISPs to increase their deployment of Wi-Fi Sensing in recent years:

- **Hardware Supply Disruptions**: Recent supply chain disruptions severely extended the lead time for Wi-Fi CPE, making it challenging for ISPs to secure new hardware to improve the customer experience. To counter this, many turned to value-added software services, such as Wi-Fi Sensing, which could be delivered remotely *via* a firmware update and did not require any additional equipment.Extending
- **Equipment Life Span**: Remotely installing firmware updates can add new features to already deployed hardware, extending the equipment's life span. This can save costs or deal with supply constraints.
- **Increased Market Competition**: Market saturation, increased competition, and financial pressures on consumers have led ISPs to attempt to remain competitive by increasing their value proposition to consumers through the rollout of value-added services like Wi-Fi Sensing.
- **New Service Models**: Wi-Fi Sensing can unlock the creation of additional service models, with the examples including but not limited to healthcare, home security, and energy management.

WI-FI SENSING TECHNICAL OVERVIEW

This section covers the technological foundations of Wi-Fi Sensing, enabling the reader to comprehend the transformational power of Wi-Fi Sensing, and how different sensing solutions differentiate themselves at a technical level.

SPECTRUM FREQUENCIES

There are two main frequency categories available for Wi-Fi Sensing in the home—the sub-7 GHz and mmWave. The most prevalent are the sub-7 GHz frequencies, which include the unlicensed 2.4 GHz, 5 GHz, and 6 GHz spectrums. Support for the two former frequencies is already widespread in currently deployed consumer Wi-Fi equipment, and 6 GHz compatibility is projected to increase rapidly over the coming years, with 44% of all Wi-Fi networking chipsets shipped in 2027 forecast to be 6 GHz enabled. Each of these three bands exhibits different RF propagation properties (the heightened granularity and reduced interference of the higher frequencies is paired with diminished range and penetration abilities), and most vendors leverage a combination of all three for best performance.

The higher frequencies of mmWave, which encompass the unlicensed 45 GHz and 60 GHz bands, offer significantly faster data rates than sub-7 GHz; however, propagation limitations make them unsuited for typical consumer use cases. This has led to a lack of existing mmWave infrastructure, which alongside limited range and penetration abilities, has led software vendors to typically eschew these frequencies. Yet, some vendors are bucking the trend in order to harness the more precise Wi-Fi Sensing possible with mmWave's wider channel bandwidths and smaller wavelengths. For example, equipment vendor Mercku is incorporating 60 GHz radios into its consumer APs specifically for the purpose of Wi-Fi Sensing, and is working with Aerial for software support.

SENSING CONFIGURATIONS

Sensing configurations can be found in one of the following configurations:

- **Monostatic**: The transmitter and receiver are co-located, and the reflected signals are measured. This is the approach of Renesas' proprietary doppler imaging technology. The advantages of this approach are that only one device is necessary for operation, and everything can be run locally without an Internet connection, but a key shortcoming is that it covers comparatively less range.
- **Bistatic**: The transmitter and receiver are separate devices, and the attenuation of the RF waves as they pass through materials between the two is measured. Coverage can exceed monostatic approaches, but with sub-7 GHz bands, the granularity is poor.
- **Multistatic**: Received signals from multiple transmitters are measured. This can be a single AP that coordinates and measures signals from multiple associated STAs, or multiple APs (*e.g.*, in mesh networks) each with a network of connected STAs. Processing can occur on numerous APs simultaneously, and the wireless backhaul connection between APs can also be leveraged for sensing. This setup provides the greatest coverage, but transmission coordination and elicitation can be challenging today, as not all devices support the required protocols.

SENSING MEASUREMENTS

There are several potential methods by which the Wi-Fi RF waves can be measured for sensing. Early Wi-Fi Sensing approaches used the Received Signal Strength Indicator (RSSI) method, which simply tracked fluctuations in the received signal strength at receivers to identify motion. This method was low-cost and simple to implement, but also provided only basic insights, and was prone to high levels of interference. For this reason, the industry made extensive efforts to persuade semiconductor manufacturers to make available the CSI data from chipsets, which had previously been restricted. Around 2017, they were granted access. This more advanced method measures wireless signal propagation between the transmitter and receiver at certain carrier frequencies along multiple paths. More specifically, Multiple Input, Multiple Output (MIMO) and Orthogonal Frequency-Division Multiplexing (OFDM) are leveraged to capture amplitude attenuation and phase information of multi-path Wi-Fi channels, and a time series of these CSI measurements can record how wireless signals travel through surrounding objects in the time, frequency, and spatial domains for the purpose of sensing applications. For example, the CSI amplitude variations in the time domain have unique patterns for different objects (*e.g.*, humans, activities, or gestures), and recognition of these patterns can then be leveraged for applications, such as motion detection or gesture recognition. Before use, these CSI signals must be processed with noise reduction (to clean the measurements), signal transform (a method for time-frequency analysis of a time series CSI measurement), and signal extraction (extracting the target signal from pre-processed CSI measurement).

SENSING ALGORITHMS

The models used to interpret data in Wi-Fi Sensing can either be model-based algorithms, which are founded on theories or statistical models, or ML-based algorithms, in which the model is trained to identify objects or movements with sample data. The former is better suited to estimation applications where a numerical value must be determined, while the latter is ideal for recognition applications. The advantages and disadvantages of each type of Wi-Fi Sensing algorithm, alongside examples, are outlined in Table 2 below.

Table 2: Benefits and Drawbacks of Model-Based and Machine-Learning Based Wi-Fi Sensing Algorithms

(Source: ABI Research)

	MODEL ALGORITHMS	MACHINE LEARNING ALGORITHMS
Advantages	▪ Only requires simple algorithms. ▪ Does not require training data collection, model training, or ground truth labeling. ▪ Comparatively low cost.	▪ Low level of signal processing required. ▪ Improves over time with more training data. ▪ Versatile as pre-trained models can be applied to other tasks.
Disadvantages	▪ Requires very accurate measurements, estimations, and model parameter tuning. ▪ High levels of signal processing necessary. ▪ Not scalable for use in new environments or tasks.	▪ Comparatively high costs. ▪ Demands large amounts of training data collection for different settings and ground truth labeling. ▪ High potential of overfitting, where model is unable to predict with unseen data.

Cognitive relies primarily on statistical model algorithms, as the company believes that ML training cannot account for the vast array of different building structures and layouts, or for the diversity of objects and movement dynamics within them. Origin, nami, and Aerial, on the other hand, have a greater focus on AI and ML in their algorithms. Origin maintains and is developing several AI Engines (motion, speed, breathing, *etc.*), which are dynamically adopted according to need in what it calls "AI Engine Fusion." nami uses a hybrid algorithm, which is then fine-tuned to the specific environment. Aerial Technology's approach includes pre-built and ready-to-integrate foundation algorithms, which are then personalized through training customized algorithms and AI-powered feedback.

EDGE VERSUS CLOUD

Deployment architectures can support either processing at the edge (the AP) or on the cloud (central server). The low-latency requirements of Wi-Fi Sensing (802.11bf is set to establish 100 ms as the benchmark) are better served by processing at the edge, so all vendors choose to conduct basic sensing measurements at the edge. Other advantages of edge processing include that no bandwidth is needed for communication to and from the cloud; the processing can still occur without an Internet connection, it is a lower-cost approach, and it offers greater privacy and security. Origin and nami choose to process all data at the edge for these reasons, after which they transfer the aggregated motion information to the cloud. Cognitive also processes the vast majority at the edge, but certain long-term data inferences (*e.g.*, elderly activity tracking) will be processed on the cloud. Aerial has a hybrid deployment model that leverages the advantages of both the edge and cloud.

One of the key benefits of transferring data to the cloud is that it enables conducting recognition tasks on the amassed real-world data for greater ML, which can be used to further advance and refine the sensing algorithm.

SENSING TOPOLOGY

Finally, the sensing topology of the network also has a significant impact on Wi-Fi Sensing's performance. Some of the key deployment and environmental factors impacting a sensing network include the coverage area, building layout, construction materials, device positioning and density, and electrical or mechanical interference. It is challenging to retroactively build an optimal Wi-Fi Sensing architecture from a topology that was not originally intended for sensing purposes. Moreover, the topology demands for communications and sensing are often unaligned. For example, the ideal mesh topology for maximizing throughput and latency in multi-storied residences is to position APs in vertical alignment with little horizontal distance. Yet, this arrangement would severely restrict the coverage area of the backhaul, limiting its usability for Wi-Fi Sensing. Thus, the best topology for mesh networks seeking to use backhaul for sensing is to have the maximum horizontal distance between APs, as this will provide the greatest coverage. Going forward, consumers (and ISPs) are likely to continue prioritizing communications over sensing for their network topology, so critical sensing applications requiring optimized topologies are likely to increasingly incorporate dedicated Wi-Fi Sensing equipment, with the additional device allowing for an optimal sensing topology without having to negatively impact communications.

INDUSTRY TRENDS AND ADDRESSABLE MARKET PROJECTIONS

TREND ANALYSIS

Wi-Fi Sensing is an emerging technology undergoing rapid evolution. Some of the core trends that the industry is currently witnessing are outlined below:

- **Wi-Fi as an ISAC Technology**: With the maturing of Wi-Fi Sensing, consumers' perceptions of Wi-Fi will gradually adjust from a technology that is purely communication in nature, to one that also delivers sensing. The addition of these beneficial new services will increase the overall value proposition of Wi-Fi itself.
- **Pre-Standardization 802.11bf Equipment**: As has been seen with other protocols (*e.g.*, 802.11ax and 802.11be), we will see chipsets and equipment being released in 2023 and 2024 that offers 802.11bf feature support prior to the standard's official certification in 2024.
- **Dedicated Wi-Fi Sensing Hardware**: While one of the main strengths of Wi-Fi Sensing is that it can leverage existing infrastructure, many consumers may not feel comfortable relying on undedicated low-cost Wi-Fi equipment for critical applications. Moreover, existing network topologies struggle to best serve sensing demands. For these reasons, we are likely to see an increase over the coming years of dedicated Wi-Fi Sensing hardware for specific tasks, which will help with go-to-market and topology optimization. These devices will likely also incorporate additional features associated with the use case. For example, devices designed for healthcare may include speakers and microphones for communication, or security-focused devices might include smoke alarms.
- **Long-Term Data**: Current use cases are mostly focused on presence and motion detection, but over time, insights drawn from the aggregation of large amounts of data sourced over extended periods will unlock new possibilities. This could include activity levels over the long term, or changes in a person's gait.

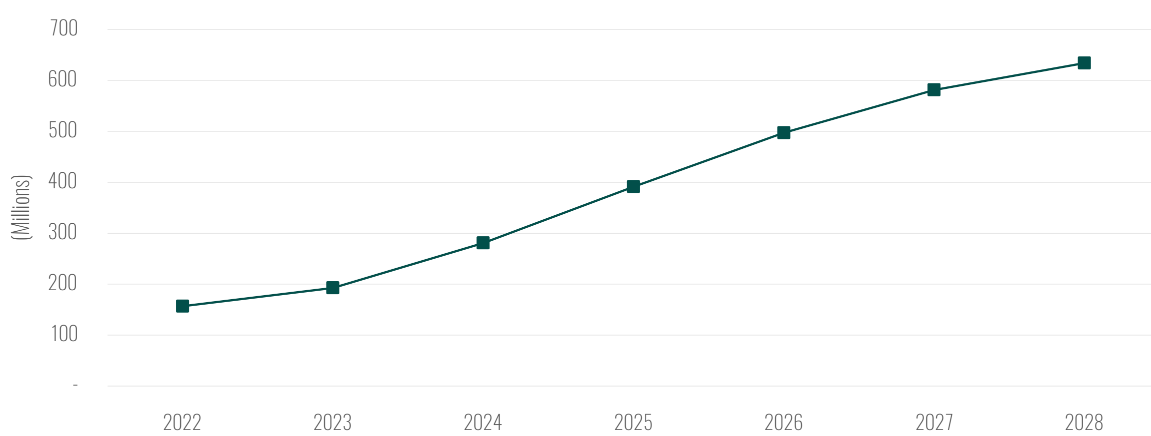
- **Greater Granularity**: Wi-Fi Sensing over the coming years will develop from low-precision, quick Time to Market (TTM) applications, to those with greater granularity, backed by more advanced algorithms. This means an evolution from the generalized detection at room-level localization today (i.e., presence in a particular room), to specific granular insights, such as shifts in gait analytics.
- **Gateway Analytics**: An expansion of local storage on chipsets and architecture adjustments so that performance can be dedicated away from communication toward sensing functions will enable localized ML for Wi-Fi Sensing applications. This will ensure greater privacy, and allow user-specific ML in the absence of an Internet connection.

TOTAL ADDRESSABLE MARKET BY WI-FI DEVICES

Chart 1 illustrates the total global installed base of Wi-Fi APs that are compatible with (although not necessarily actively operating) Wi-Fi Sensing for the period from 2022 to 2028. This includes residential APs (covering residential gateways, wireless routers, extender/repeaters, and mesh APs) and enterprise APs. Historically, software vendors have collaborated directly with chipset vendors to ensure Wi-Fi Sensing compatibility on their chipsets (for example, Cognitive began officially working with chipset providers in August of 2017), an approach that resulted in support for Wi-Fi Sensing for select chipset lines from certain vendors, but not industry-wide support. A rapid shift in gear is anticipated in 2023, as the arrival of pre-standardization 802.11bf chipsets will cause a rapid increase in the number of Wi-Fi Sensing-compatible APs. Consequently, the installed base is projected to increase from 156.77 million at the end of 2022 to 192.67 million at the close of 2023. Additional acceleration is expected following the official 802.11bf standardization in 2024, as clarity around requirements and clear market demand will result in the vast majority of networking chipsets adopting 802.11bf. Although not included in the forecast below, Wi-Fi Sensing compatibility will be further boosted by the expansion of dedicated Wi-Fi Sensing devices over the forecast period.

Chart 1: Total Addressable Market by Wi-Fi Sensing Devices
World Markets: 2022 to 2028

(Source: ABI Research)



RECOMMENDATIONS

- **Technology Trials**: To both raise awareness and boost confidence in Wi-Fi Sensing, further trials of the technology should be conducted by industry associations and ecosystem vendors. These will demonstrate the technology's power and suitability for positioning tasks, which will help stimulate adoption.
- **AI-Enhanced Network Topology**: Advanced intelligent network topology tools exist for communications (*e.g.*, Wi-Fi Alliance EasyMesh), but not for sensing. The two applications' demands are often not aligned, and therefore Wi-Fi Sensing vendors should invest in AI-enhanced network topology tools specifically for Wi-Fi Sensing.
- **Deep Learning**: Most Wi-Fi Sensing methods today only consider a single smart home scenario, but for Wi-Fi Sensing algorithms to become scalable to diverse environments, vendors should invest further in cloud compute to perform Deep Learning (DL) on the anonymized aggregating data they have collected from their user base. Partnerships with AI firms can also be pursued to develop more advanced AI capabilities.
- **Enterprise and Industrial Applications**: To date, most vendors have focused primarily on residential applications of Wi-Fi Sensing, but as 802.11 increasingly penetrates commercial and industrial facilities, vendors should develop solutions that can leverage the additional RF waves in these environments.
- **Advocate 6 GHz**: The 6 GHz band offers finer sensing granularity and valuable additional unlicensed spectrum that can reduce the conflict for bandwidth between communications and sensing. Thus, industry associations should highlight the economic potential of Wi-Fi Sensing to convince national regulators to expand 6 GHz access.
- **Strategic Partnerships**: Identify other vendors in the ecosystem with complementary products and establish a strategic partnership so that their solution can augment your own. If close synergy can be reached, then resources can be pooled into the development of a single shared product. The example of the collaboration between Origin and nami, where the firmware, middleware, and AI of the latter augmented the Wi-Fi Sensing capabilities of the former, is a good example here.
- **Industry Partnerships**: To facilitate go-to-market, Wi-Fi Sensing Software vendors should expand partnerships with organizations serving the markets they are targeting, such as with insurance companies for healthcare.
- **Explore mmWave**: Applications like gesture recognition, which require precise sensing, will struggle to be possible without mmWave. Vendors looking to differentiate themselves with more granular sensing abilities should therefore invest in mmWave sensing technologies, and form partnerships to develop hardware.
- **Dedicated Devices**: As discussed above, undedicated Wi-Fi Sensing equipment offers subpar topology and is viewed by some consumers as unreliable. Therefore, vendors should devise dedicated equipment for critical use cases for better market acceptance. This could include devices with monostatic (co-located transceivers and receivers) abilities that could be used to ensure continued operation in the event of no peer or network failure.
- **Cellular Backup**: For critical applications requiring contact with the outside world, Wi-Fi Sensing devices dedicated for a particular use case (health monitoring or security) should be embedded with Long Term Evolution (LTE)/5G backup, so that alerts can be issued *via* cellular, even if broadband Internet access is down.
- **Combine Tag Sensing**: Develop double-layer engines that incorporate other technologies alongside Wi-Fi Sensing to provide more data points. For example, Bluetooth, Matter, or Global Positioning System (GPS) data could be combined with Wi-Fi Sensing to provide greater sensing granularity.

Wi-Fi Sensing is still in the early stages of maturity, and we have barely scratched the surface of what is possible. 802.11bf's standardization will provide the necessary framework for Wi-Fi Sensing to realize its true potential, enabling the technology to scale to new applications and environments.

At the same time, additional innovative use cases will emerge alongside the advancements in sensing AI algorithms, the exploration of mmWave, and the entry of new players to the market. Furthermore, the new service models enabled by the technology will also drive additional revenue for the ecosystem, and Wi-Fi Sensing will prove important across all aspects of the value chain, as the combination of sensing alongside communications will raise the value proposition of all Wi-Fi products. In the long term, Wi-Fi will become a fundamental component of the future of ISAC, converging with other next-generation wireless technologies like 6G to help deliver fully integrated communication and sensing functionality across multiple consumer and enterprise applications.

Published December, 2022

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