TND6334/D
Rev. 1, August − 2021

Wi−Fi® Sensing: Revolutionizing Motion Sensing with Wi−Fi technology

Wi−Fi® Sensing: Revolutionizing Motion Sensing with Wi−Fi technology

Abstract

While Wi−Fi is well known and universally used as a communication protocol, interest has grown recently in using the properties of the Wi−Fi signal itself to enable new applications. Specifically, a smart analysis of the physical properties of the Wi−Fi signal allows one to infer certain characteristics of the environment the system is deployed in. This application is known as “Wi−Fi sensing” and is gathering a lot of interest for its potential use in areas like home security, healthcare monitoring, automation, and localization.

Introduction

Wi−Fi sensing is the use of Wi−Fi technology to detect events or changes in the environment such as the motion, proximity, and velocity of people and objects. In Wi−Fi sensing, the Wi−Fi signals aren’t used primarily or exclusively for data transmission, but instead function more like radar signals. The observed changes in the Wi−Fi channel over time can then be correlated to specific types of environmental changes.

Wi−Fi sensing enables a host of applications that are traditionally performed by other sensing technologies, such as IR detectors and camera−based video surveillance. It also enables new applications like gait analysis, fall detection and heartbeat detection. It’s important to note that this new application can be built on top of standard Wi−Fi devices and deployed systems. The nature of Wi−Fi signals and the wireless environment itself provide rich information beyond what is needed for the basic communication function of the Wi−Fi system. Moreover, motion detection does not require that detected objects themselves are Wi−Fi enabled.

Although other dedicated technologies may exist to perform the sensing role, using Wi−Fi for this application is attractive for several reasons. First, Wi−Fi is near−ubiquitous in many indoor environments such as the home or the office and even some outdoor environments. There is no need to build a new ecosystem since many devices are already available to participate or assist in the sensing operation.

Furthermore, the signal processing performed by Wi−Fi devices as part of their main function (data communication) already provides some insight into the channel between the communicating units. The Wi−Fi channel is highly variable and sensitive to even small changes in the environment (even as small as hand gestures or a person breathing). Even objects that are not in the direct line of sight between devices can impact the channel due to the scattering of the Wi−Fi signal off these objects. Normally, those changes are not explicitly considered or tracked, but they form a solid basis for scanning or sensing of the environment.

Additionally, the possible reuse of a widely deployed technology will shorten the development of many sensing applications. Ideally, some forms of Wi−Fi sensing could be enabled without a change in hardware. Enabling sensing with an existing technology will also add new value to Wi−Fi itself.

Use Cases and Applications

Security

Home monitoring is one of the early use−cases for Wi−Fi sensing. Using Wi−Fi sensing, insights can be derived about any activity inside the house when residents are not present. These insights can be in the form of detection of motion caused by a burglar, including location and timing of such motion. Similar monitoring can be performed for secure or infrequently accessed areas in commercial buildings. Higher sampling frequency and improved motion sensitivity can also enable Wi−Fi motion sensing to perform measurements of some physiological signals and motion patterns. By associating this biometric information to a whitelist of people, this information can be used to separate the residents or other expected visitors from an intruder.

Some of the challenges which can affect sensing performance for these use−cases are:

1. High SNR coverage of an entire home including multiple floors with existing devices
2. Classification of human motion against other motions (appliances, pets, outside home movements)
3. Accuracy of Localization using motion based on CSI information

Healthcare

Wi−Fi sensing can be used for identifications of expected patterns (breathing, gestures, movements while awake) and unexpected patterns (slip/fall detection, lack of motion etc.). By combining these methods, Wi−Fi sensing can enable non−invasive and privacy−focused monitoring for elderly to notify a medical provider or caretaker when needed.

Automation

Wi–Fi sensing can be utilized for home or building automation through presence detection and gesture recognition. For example, we can consider an application which turns on the light in a room by detecting the motion just outside the room and predicting that a person is going to enter the room. IR–based sensors are limited in such use cases to only act on line–of–sight events. Other automations like controlling the door, windows, cooling system, etc. can be implemented using data from Wi–Fi based motion and presence sensors.

Localization

When paired with an indoor mapping signature, Wi–Fi sensing can be used to locate a device in a room or identifying which floor a device is located inside a building. Wi–Fi localization data can also be combined with location estimates from other sensors using SLAM (Simultaneous Localization and Mapping) techniques to improve the accuracy of this data. Such localization can be used for enabling applications like tracking a customer in a store or locating a tagged item in a warehouse.

Wi–Fi Background

Properties of the Wireless Medium

The wireless medium between a pair of transmitting and receiving antennas is typically termed the “channel”. The characteristics of a wireless signal change as it travels in this medium and this change can be attributed to multiple phenomena:

1. Line of sight path between the antennas
2. Reflection, refraction and diffraction of the signal due to the objects in between the antennas
3. The relative motion between the antennas and the objects in between them
4. The signal attenuation as it travels through the medium

The overall effect of these phenomena can be broken down into three main components and modeled separately:

1. Signal Propagation Path Loss
2. Slow fading or Shadowing
3. Fast fading or multipath fading

Other than the channel, noise and distortion due to transmitter and receiver also affect the final observed signal at the receiver.

Signal propagation path loss refers to attenuation of radio energy received at the antenna due to propagation in the wireless medium and due to absorption by walls and surroundings between transmit and receive antennas. Fading refers to destructive interference between copies of the received signal caused by reflections from surrounding objects and surfaces.

Fading is often characterized as slow or fast based on relative stability of channel response (coherence time) over the duration of transmission. It manifests itself as a frequency−dependent attenuation on top of the overall path loss experienced by the signal.

Modeling of multipath propagation can be very complex, but the use of OFDM modulation in Wi−Fi systems allows modeling of a multipath channel independently for each narrow−band OFDM carrier as a single complex−valued scaling. This modeling simplifies channel estimation for OFDM systems and enables simple equalizer structures at high sampling rates required for high bandwidth operation.

Wi−Fi Channel Measurement

Wi−Fi channel measurements are performed by the physical layer as part of receive processing. Although the various generations of the Wi−Fi protocol support different types of physical layers, recent standards use the multi−carrier CP−OFDM physical layer. To allow successful demodulation of data at receiver, an estimation of the channel response is required at the receiver’s end. Wi−Fi standards define specific “training fields” which are transmitted as part of the packet preamble (see Figure 1) and which enable a high−resolution and frequent estimate of channel at receiver. These training fields allow the receiver to estimate the channel in the frequency domain, as illustrated in Figure 2.

Figure 1. Structure of an 802.11ax Packets Showing HE−LTF Fields Used for CSI Measurement

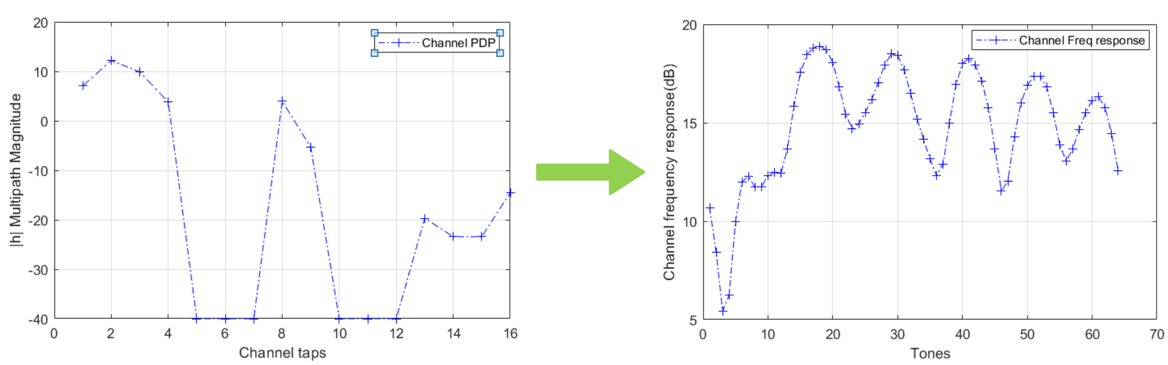

Figure 2. Magnitude of Channel Taps for a Multipath Channel (Left) and Corresponding Channel Frequency Response (Right)

Although the use of training fields in every transmission results in some overhead, measurement of the channel estimate for every Wi−Fi transmission provides robustness against any changes in environment between subsequent transmissions.

Wi−Fi standards also support a mechanism through which a transmitter can request a receiver to “feedback” the channel measurement. This is done through special sounding packets sent by transmitter for which receiver measures the channel. The channel measurement is then communicated back to the transmitter, typically in some compressed and quantized format.

Resolution and accuracy of the channel measurement depends on multiple factors including signal bandwidth, number of receive antennas and receive signal power. Recent advancements in Wi−Fi physical layer specification including bandwidths up to 160 MHz, 8x8 MIMO and beamforming techniques result in improved channel estimates for these systems.

Wi−Fi Topology (In−House)

The below diagram (see Figure 3) shows a common network topology for an in−house Wi−Fi network with a single Wi−Fi access point (AP) and multiple station (STA) devices. The wireless channel between the AP and a given STA comprises multiple line−of−sight (LOS) and non−line−of−sight (NLOS) paths with the reflection from different fixed and mobile objects.

In the example shown in the diagram, the multiple paths between the AP and one of the STAs are highlighted. Any change in position or orientation of objects between the transmitter and the receiver can affect the magnitude and phase of signal arriving at the STA’s receiver and affects the overall channel measured by the receiver.

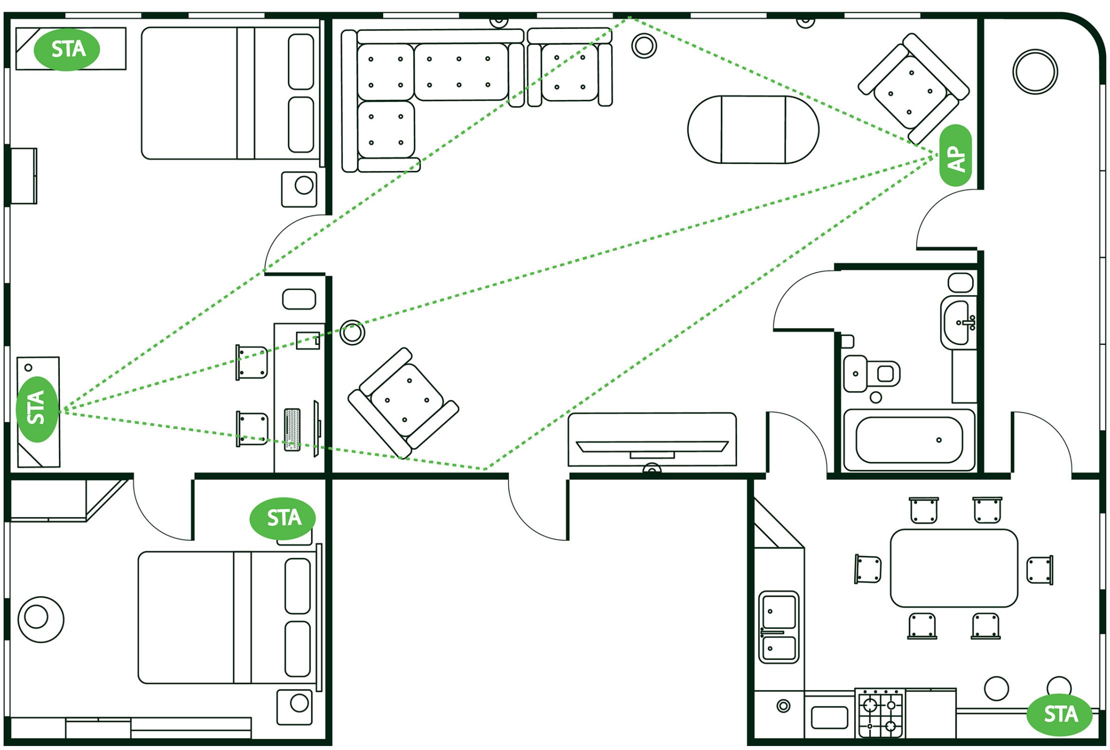

Figure 3. A Typical In−home Wi−Fi Network Showing Multipath between AP and STA

Detection/Sensing with Wi−Fi

How Channel Measurements can be Used to Enable Sensing

Wi−Fi sensing relies on the use of the channel measurements taken by the receiver. This is also referred to as CSI−based sensing (Channel State Information).

To enable CSI−based sensing in an existing Wi−Fi network, different methods can be utilized to trigger packet transmissions from associated devices on a periodic basis. Here, we distinguish between "physical layer methods", where triggering is achieved using only the Wi−Fi protocol, and "network layer methods", where triggering is achieved through higher−layer protocols. As part of the receiving process for these transmissions, a device can collect CSI information between the device and different transmitters.

Physical Layer Methods

At the physical layer, a device can perform CSI measurements by sending a Wi−Fi packet to another device and then measuring the CSI from the ACK response packet. In many cases, wireless networks would carry data traffic on a frequent basis and corresponding Wi−Fi packets can be used for performing CSI measurement. This can remove the need of dedicated transmission for CSI measurement eliminating associated airtime overhead in such a network.

In certain scenarios, when the network is idle and there is no actual data to carry, a device can transmit packets with control data to other associated devices. These transmissions do result in an increased airtime use, but in such scenarios (a lightly used wireless network) this airtime consumption is not a concern.

Another physical layer method to perform channel measurements can be through sounding packets if both transmit and receive device support it. Sounding packets or NDP (Null Data Packets) are special packets defined by Wi−Fi standards which are used by a transmitter to request measurement and feedback of certain channel metrics from an associated device. These metrics can for instance be used for beamforming subsequent transmissions from this transmitter. The below diagram (see Figure 4) describes the packet sequence for NDP based channel sounding method. The Beamformer (originating device) sends an NDP announcement followed by an NDP packet over the wireless medium. NDP announcements contains the information required by the intended Beamformee (responding device) to respond to NDP correctly. Once NDP is received, the Beamformee performs channel matrix measurement and computes SVD (Singular Value Decomposition) of the channel matrix and compresses the information into a standard specified format. This information is sent as a data packet called Action Frame. The Beamformee can parse this Action Frame and retrieve the information.

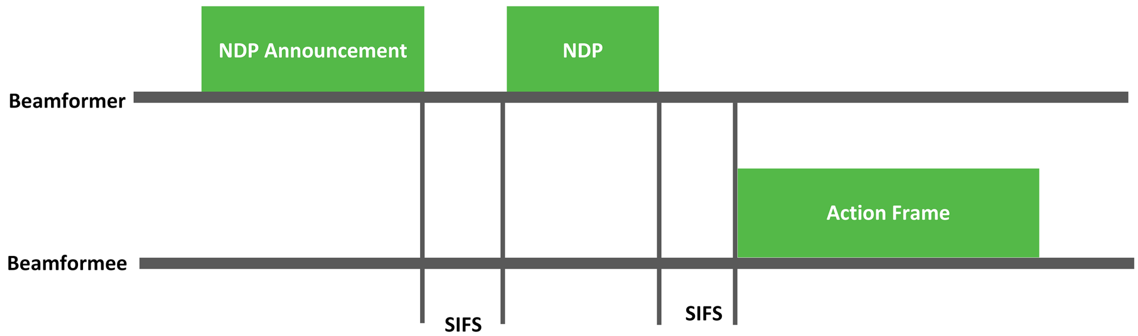

Figure 4. Typical Wi−Fi Sounding and Channel Feedback Sequence

Network Layer Methods

At the network layer, a CSI measurement can be initiated by use of existing control protocols which will then be carried in Wi−Fi packets between two associated terminals. For example, a CSI measuring device can send an ICMP (Internet Control Message Protocol) echo request to any of the associated stations and in response receive ICMP echo reply from that station. By extracting the channel estimates for this response packet, this device can get CSI information for the channel between the two devices.

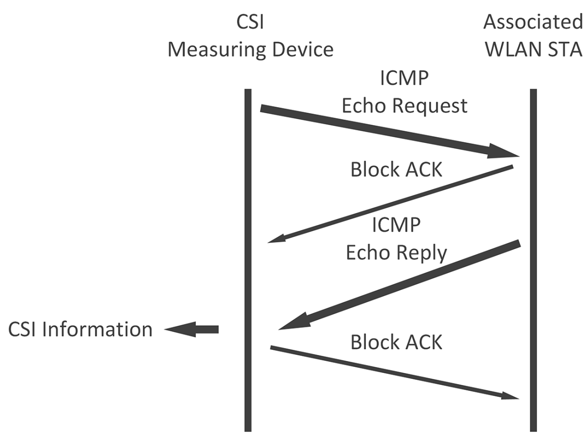

Figure 5. Using Higher−layer Protocol to Trigger Wi−Fi Transmissions

Complete Architecture of Wi−Fi Sensing Application

The architecture of a typical Wi−Fi sensing application consists of four high level processing blocks. These blocks can be implemented on−device or on a remote server using a client−server architecture. Below diagram (see Figure 6) shows these blocks with common methods used for each block.

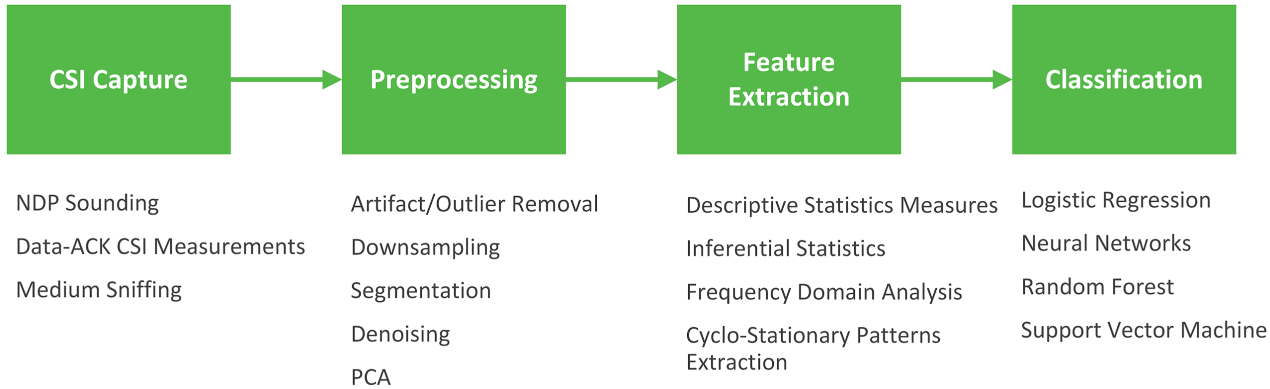

Figure 6. Wi–Fi Sensing Architecture

CSI Capture

The CSI capture block provides CSI captured on a periodic basis. For an on–device implementation, this block can capture CSI information between the host device and multiple other associated Wi–Fi devices.

For a cloud or server–based implementation, this block can capture CSI information from host devices where each host device can generate CSI from multiple associated Wi–Fi devices. Such architecture can provide better CSI information which can be utilized to improve sensing performance. Figure 7 shows an example of CSI output for a 4x4 channel measurement.

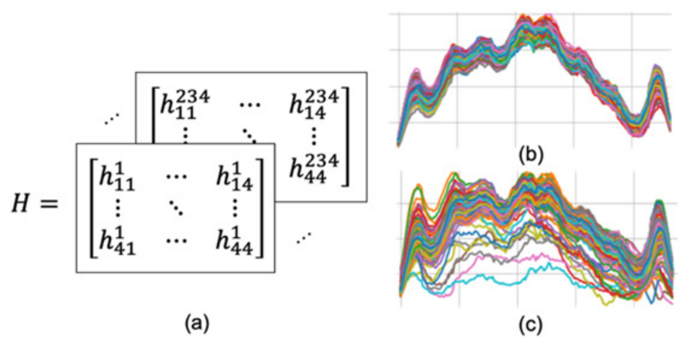

Figure 7. (a) Typical 80 MHz 4x4 CSI Matrix, (b) Channel Amplitude without Motion, (c) with Motion

Preprocessing

Preprocessing is performed on CSI data to improve the quality of collected information before feature extraction is done on this data. Different methods used for preprocessing are artifact removal, down–sampling, segmentation, denoising, etc.

Feature Extraction

Feature extraction generates different descriptive and inferential statistics measures from the preprocessed CSI data. It can also generate some features which are specific to different motion patterns. For example, for a gait analysis application, some cyclo−stationary measures like time correlation and spectral density can provide good classification performance.

Classification

The classification block implements the final decision logic through machine learning models which can be trained through supervised training as well as some unsupervised methods like clustering etc. Classification can use different machine learning models including logistical regression, neural networks, decision trees and SVM (Support Vector Machines). As an example, a classifier can use medium absolute deviation and standard deviation of CSI metrics over time and use a decision tree to classify between motion and no−motion scenarios.

Standardization

Several companies have already built platforms that incorporate Wi−Fi sensing. Some of these have led to commercially available solutions in spaces like home security or healthcare monitoring.

While this shows that Wi−Fi sensing can be enabled on already existing products, more can be done if certain baseline requirements are commonly agreed upon. The IEEE 802.11 Working Group that is responsible for the definition of Wi−Fi has started an effort to standardize some of the requirements for Wi−Fi sensing.

Possible areas of standardization are:

- Enabling pairs or groups of devices to negotiate the sensing parameters and set up specific schedules for transmission of packets that can be used for sensing
- Enabling devices to negotiate the specific formats of the packets that will be sent and processed for sensing
- Define power saving modes that are compatible with the requirements of sensing

Even as new requirements are being formulated, the intention is to maintain backwards compatibility to existing generations of Wi−Fi. In this way, Wi−Fi sensing can be made available even before the official standard is ratified.

Products

onsemi has enabled Wi−Fi sensing in its line of Wi−Fi products. The chosen solution is based on making Channel State Information (CSI) available for analysis by an independent analysis engine. CSI can be extracted for every received packet. The captured information is made available through an API to third−party developers. The interface is capable of collecting CSI from multiple stations simultaneously, which enables the AP to have a better motion detection coverage.

The process is illustrated in Figure 8.

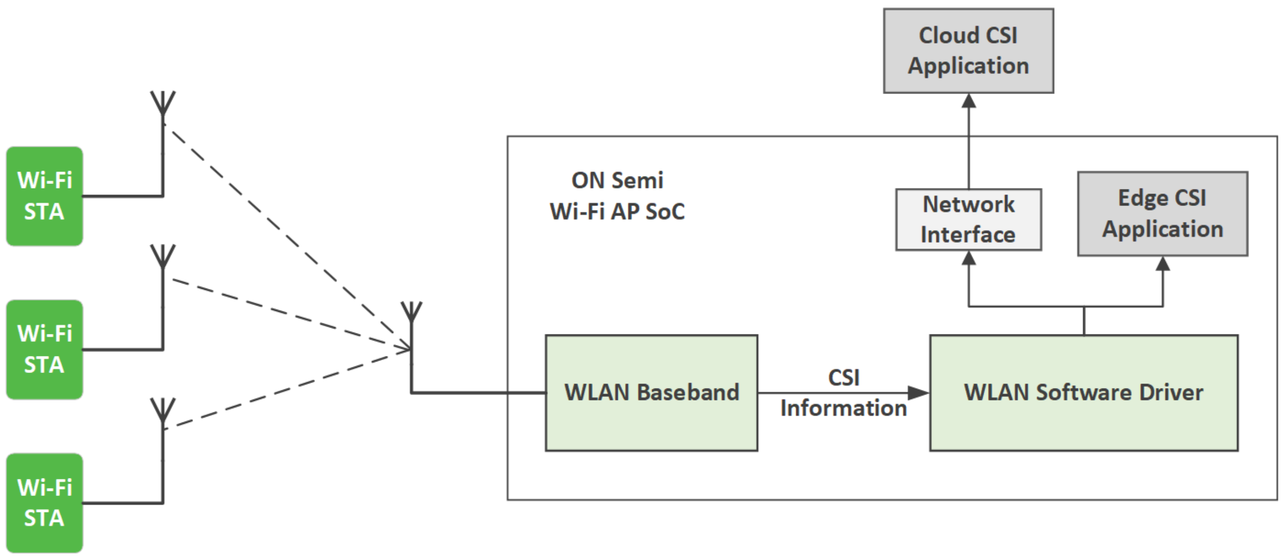

Figure 8. Typical Architecture for CSI Capture over Wi−Fi Networks (c) with Motion

An external engine can monitor the measured CSI values over time to analyze them for changes that could be indicative of motion or other changes in the environment. A set of tightly clustered channel values (see Figure 7(b)) indicates that the environment is stable, while significant variation among the CSI values can indicate motion (see Figure 7(c)).

onsemi is working with several companies to bring Wi−Fi sensing technology based on CSI extraction to market. In addition, **onsemi** has partnered with several universities to further explore the possibilities of this new technology.

Conclusion

Wi−Fi sensing is an exciting new field that can reuse existing capabilities of Wi−Fi to enable a whole range of new applications. It leverages channel information that is naturally known to the Wi−Fi receiver and makes it available for external analysis. A classification and analysis engine can process the provided information to determine changes in the environment related to proximity and motion. These capabilities enable different Wi−Fi sensing applications in security, healthcare, automation, localization and other fields.

While existing products can already provide the data necessary to enable Wi−Fi sensing, ongoing efforts in standardization can further improve the technology and enable the next generation of Wi−Fi sensing applications.

PUBLICATION ORDERING INFORMATION

LITERATURE FULFILLMENT:
Email Requests to: orderlit@onsemi.com

onsemi Website: www.onsemi.com

TECHNICAL SUPPORT
North American Technical Support:
Voice Mail: 1 800−282−9855 Toll Free USA/Canada
Phone: 011 421 33 790 2910

Europe, Middle East and Africa Technical Support:
Phone: 00421 33 790 2910
For additional information, please contact your local Sales Representative