Wi-Fi Sensing Based on IEEE 802.11bf

Cheng Chen, Hao Song, Qinghua Li, Francesca Meneghello, Francesco Restuccia, and Carlos Cordeiro

Abstract

Conventionally, Wi-Fi radio signals are widely used for data transmissions in a wireless local area network (WLAN). Recently, it has been an interesting topic to also apply Wi-Fi radio signals to sense the environment where these signals propagate and identify changes associated with certain activities. This technique is referred to as Wi-Fi sensing, and it has been proven effective in a variety of use cases, such as proximity detection, gesture recognition, target counting, and health monitoring. As a result, the IEEE 802.11 working group has formed a new Task Group, 802.11bf, to develop a new amendment to define necessary PHY and MAC protocols to support Wi-Fi sensing in all spectrum bands, including sub-7 GHz bands (2.4 GHz, 5 GHz, and 6 GHz band), as well as 60 GHz millimeter-wave band. In this article, our primary goal is to identify and describe the basic elements that have been developed in IEEE 802.11bf to enable Wi-Fi sensing applications in different WLAN scenarios.

Introduction

The discovery of the wireless wave has led to diverse revolutionary technologies. One good example is Wi-Fi, which is based on the family of IEEE 802.11 standards and has become one of the most popular wireless technologies for data transmission. It is estimated that by 2022, approximately 60 percent of global mobile traffic will be offloaded to Wi-Fi, and 51 percent of total IP traffic will be Wi-Fi [1].

While Wi-Fi has been used primarily for delivering data traffic so far, recent advances in wireless research have identified that Wi-Fi signals are sensitive enough to capture and identify environmental dynamics, which makes it a promising technology for sensing applications in various scenarios. For example, researchers in [2] showed that a pair of Wi-Fi transceivers are capable of counting a crowd of stationary people, whereas in [3] Wi-Fi was used to reconstruct the 3D human pose. Wi-Fi sensing is also shown to be effective in health monitoring, such as nocturnal seizure detection [4] and personal identification [5]. There are many other applications where Wi-Fi sensing is shown to be useful, which have been thoroughly investigated in surveys and tutorials including [6–10].

Compared to conventional sensing technologies that typically rely on the use of camera, ultrasound, or laser, Wi-Fi sensing enjoys unique benefits. First, thanks to the enormous market penetration across the globe, Wi-Fi signals are ubiquitous with a large amount of Wi-Fi devices in residential homes and enterprise offices, which significantly reduces the deployment cost. Second, Wi-Fi sensing can overcome drawbacks of alternative technologies. For example, camera-based sensing is restricted by field of view, privacy, and power consumption, whereas ultrasound-based and laser-based sensing can easily be blocked by objects. On the other hand, developing Wi-Fi sensing features will also boost the Wi-Fi industry as it increases user stickiness by expanding the use of Wi-Fi to applications beyond data communication.

Most existing Wi-Fi sensing applications require the availability of the channel state information (CSI), which is built on proprietary means that rely on specific configurations and additional setup on devices to trigger the sensing transmission and CSI collection. Although it works without standards support, it suffers from several critical issues. First, field measurements have indicated that sensing performance is remarkably improved if measurement is taken closer to the target object with sufficient transmit diversity and receive diversity, which requires cooperation among multiple devices. Second, to ensure reliable measurements, negotiation between sensing devices is necessary to agree on a fixed set of transmission parameters, such as number of antennas, channel bandwidth, as well as scheduling parameters, such as measurement duration, measurement periodicity. Third, devices designed by different vendors do not necessarily support the same configurations due to different implementation considerations.

As opposed to proprietary implementations, introducing a standardized tool to enable the occurrence of sensing transmissions and sensing report delivery is beneficial in multiple aspects. First, it provides a guaranteed tool to generate sensing transmissions and feedback collection whenever requested, which are critical for any sensing application to work. Second, it enables interoperability among Wi-Fi devices designed and manufactured by different vendors. Third, using standardized technology lowers implementation costs as there is no need for additional configurations or setup.

Incorporating sensing techniques and consequently developing joint design of communication and sensing standards have attracted interest in both the cellular [11] and Wi-Fi communications communities [13]. In October 2020, the IEEE 802.11 Working Group initiated a new Task Group BF (TGbf) to develop a new amendment for WLAN sensing to support Wi-Fi sensing in both sub-7 GHz bands, including the 2.4 GHz, 5 GHz, and 6 GHz bands, as well as 60 GHz milli-

The authors' primary goal is to identify and describe the basic elements that have been developed in IEEE 802.11bf to enable Wi-Fi sensing applications in different WLAN scenarios.

Cheng Chen, Hao Song, Qinghua Li, and Carlos Cordeiro are with Intel Corporation, USA; Francesca Meneghello is with University of Padova, Italy; Francesco Restuccia is with Northeastern University, USA.

Digital Object Identifier: 10.1109/MCOM.007.2200347

If the sensing initiator is also the sensing receiver, the initiator takes the measurement by itself and obtains the results through the measurement, so there is no need for any additional sensing measurement report. In contrast, if the sensing initiator is the sensing transmitter, it relies on the sensing receiver to take measurements.

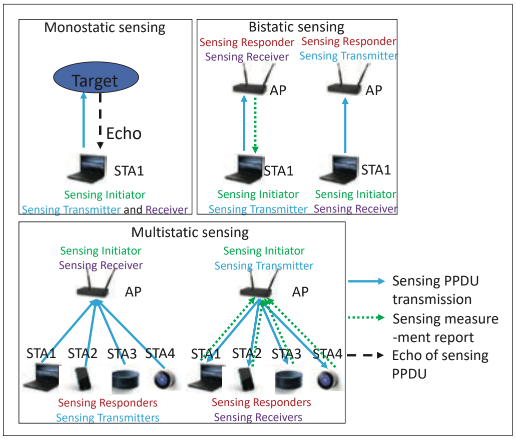

FIGURE 1. Different types of sensing scenarios.

meter-wave (mmWave) bands. In [14], the TGbf includes all targeted use cases that are planned to be supported, covering a broad range of applications such as room sensing (presence detection, number counting, motion detection etc.), gesture recognition (finger movement, hand movement, face recognition etc.), healthcare (fall detection, remote diagnostics, sneeze sensing etc.), 3D vision, and in-car sensing. In April 2022, TGbf completed the first major milestone, releasing IEEE 802.11bf draft D0.1 [12], which specifies the necessary protocols to enable Wi-Fi sensing. In this article, our primary goal is to identify and describe the essential elements of the supporting mechanisms for Wi-Fi sensing based on IEEE 802.11bf.

Note that although IEEE 802.11bf aims to support a large set of assorted use cases, it only focuses on providing the essential tools for these use cases to obtain needed sensing measurement results through triggering over-the-air sensing measurement transmissions. However, for a specific application to work, the obtained results will typically need to run through a customized data processing and/or machine learning algorithm in order to extract the information for the application to make a decision. This application-layer processing is beyond the scope of IEEE 802.11bf and is left open for any implementation.

There are few papers in the literature that investigate IEEE 802.11bf thoroughly. In [13], shortly after TGbf was established, the author provided a preliminary study of IEEE 802.11bf, mainly focusing on the timeline, objectives, and a few initial technical proposals. However, because there was no mature draft and most protocols were not developed yet, [13] does not capture the essential features and the enabling mechanisms that fundamentally shape IEEE 802.11bf. To the best of our knowledge, we are the first to aim to present a comprehensive overview of the primary features and protocols defined in IEEE 802.11bf to support Wi-Fi sensing.

The rest of the article is organized as follows. We introduce the overall 802.11bf framework for a Wi-Fi sensing procedure. We then dive deep into the design elements that support sensing measurement in sub-7 GHz bands and 60 GHz mmWave band, respectively. We present sensing by proxy, a critical feature adopted by IEEE 802.11bf. Different formats of sensing measurement results are investigated along with simulation results on performance evaluation. We conclude and explore future directions in the final section.

Overview of Wi-Fi Sensing Procedure

IEEE 802.11bf reuses existing Wi-Fi waveform and channels defined by earlier IEEE 802.11 standards to support Wi-Fi sensing in both sub-7 GHz bands (i.e., the 2.4 GHz, 5 GHz, and 6 GHz band) and 60 GHz mmWave bands. In sub-7 GHz bands, the waveform modulation is orthogonal frequency-division multiplex (OFDM)-based. One channel is typically 20 MHz wide, and we can have a channel bandwidth up to 320 MHz. In the 60 GHz band, the waveform modulation is single-carrier. Each channel is 2.16 GHz wide, and we can have a bonded channel up to 8.64 GHz.

In order to accommodate different use cases with a set of interoperable protocols, IEEE 802.11bf defines a unified sensing procedure to enable a device to obtain sensing measurements of the channel(s) between two or more devices and/or the channel between a receive (Rx) antenna and a transmit (Tx) antenna of a device. The device can be either an access point (AP) or a client station (STA). The WLAN sensing procedure covers all identified sensing scenarios by introducing different roles to devices participating in the sensing procedure, which can be summarized as follows:

- *Sensing initiator*: A device that initiates a WLAN sensing procedure. Typically, the sensing application resides in the sensing initiator.
- *Sensing responder*: A device that participates in a WLAN sensing procedure initiated by a sensing initiator.
- *Sensing transmitter*: A device that transmits physical layer protocol data units (PPDUs) for sensing measurements.
- *Sensing receiver*: A device that receives PPDUs sent by a sensing transmitter and performs sensing measurements.

Depending on the number of devices involved in a sensing procedure, as well as the roles for each of them, there can be the following sensing types, as illustrated in Fig. 1.

- *Monostatic sensing*: The sensing transmitter and sensing receiver is the same device. The sensing measurement takes place in a radar-like manner by measuring the echoes of a sensing transmission.
- *Bistatic sensing*: The sensing transmitter and sensing receiver are two distinct devices, typically an AP and a STA. The sensing measurement is carried out at the sensing receiver by taking measurements over the sensing PPDUs transmitted from the sensing transmitter.
- *Multistatic sensing*: This case extends the bistatic sensing to involve more than one sensing transmitter or receiver. Typically, it happens between an AP and multiple STAs.

Note that depending on whether the sensing initiator is also the sensing transmitter or sensing receiver, the sensing measurement report may or may not be needed in a WLAN sensing procedure. Specifically, if the sensing initiator is also the sensing receiver, the initiator takes the measurement by itself and obtains the results through the measurement, so there is no need for any additional sensing measurement report. In contrast, if the sensing initiator is the sensing transmitter, it relies on the sensing receiver to take measurements. Therefore, unless otherwise specified, the sensing receiver is obligated to feed the report back to the initiator.

Currently in IEEE 802.11bf, all three sensing scenarios are considered in 60 GHz band sensing protocols, whereas in sub-7 GHz bands only bistatic and multistatic sensing are included. For sensing in both sub-7 GHz and 60 GHz bands, IEEE 802.11bf defines a unified framework to address different sensing scenarios. Generally, a sensing procedure entails the following phases.

Sensing session setup is a process for sensing-capable devices to discover each other, establish security context, and exchange basic sensing capabilities, which builds the initial steps necessary for initiating subsequent sensing measurements. For associated STAs, sensing session setup automatically takes place through the regular association procedure. For unassociated STAs, this can be achieved via the preassociation security negotiation (PASN) protocol. For monostatic sensing, this process could be omitted.

Sensing measurement setup is a process for the sensing initiator and sensing responder(s) to negotiate and agree on operational parameters associated with a specific sensing application, including role assignment (transmitter or receiver), PHY parameters (bandwidth, number of spatial streams, etc.), type of sensing measurement report, and preferred scheduling information (sensing periodicity, duration, etc.). Again, this process could be omitted for monostatic sensing.

Sensing measurement instance is a process where actual sensing measurements take place.

Sensing measurement setup termination and *sensing session termination* terminate an established sensing measurement setup and sensing session, respectively.

Overall, for both sub-7 GHz and 60 GHz sensing, the sensing session setup, sensing measurement setup, sensing measurement termination, and sensing session termination are straightforward and share the conventional request and response frame exchanges. However, sensing measurement instances for these two bands are fundamentally distinct. As the core part of a WLAN sensing procedure, IEEE 802.11bf defines different sensing measurement instances to support both AP-initiated and client-initiated sensing scenarios in these two bands, which are presented below.

Sensing measurements in both sub-7 GHz and 60 GHz bands are largely built on existing beamforming protocols, which are separated from the regular data communications in the time domain. Therefore, sensing measurements occur in a dedicated time window without interfering with any data transmission. However, this may cause one issue. That is, if sensing measurements occupy too much airtime, the data transmission will be interrupted. The solution to this problem is the sensing measurement setup process, where the involved devices need to agree on a set of sensing parameters, including the scheduling information. If the proposed sensing schedule interrupts regular data transmission for any device, it can always reject the measurement setup and propose an alternate sensing schedule that does not jeopardize its own data transmission.

Sensing Measurement in Sub-7 GHz Bands

Sensing measurement in sub-7 GHz band defined in IEEE 802.11bf is built on existing beamforming sounding sequences with some customized modifications to support sensing use cases. Reusing the sounding null data packets (NDPs) brings multiple benefits. First, most existing Wi-Fi devices have already implemented the IEEE 802.11 beamforming protocols. As a result, it will be relatively easy for these devices to be upgraded to support sensing capabilities by reusing similar sounding frame exchange. Second, the NDPs used for beamforming have all the training fields, such as short training field (STF) and long training field (LTF), that are necessary for sensing purposes, and meanwhile do not have any data payload that is unneeded for sensing. Consequently, using NDP frames for sensing minimizes the communication overhead.

A sensing application can run on either an AP or a client STA, so a sensing procedure can be initiated by either end. However, AP-initiated and STA-initiated sensing procedures are different in terms of the number of sensing responders involved. Since an AP manages a basic service set (BSS) that consists of multiple devices, it can coordinate multiple sensing-capable devices for a sensing application. A client STA typically only communicates with the associated AP and does not necessarily know other client devices nearby. Therefore, multi-responder sensing is a common scenario for AP-initiated sensing measurement, as opposed to single-responder sensing for STA-initiated sensing measurement.

IEEE 802.11bf defines two variants of sensing measurement for sub-7 GHz sensing. Trigger-based (TB) sensing measurement is used when an AP is the sensing initiator, whereas non-trigger-based (non-TB) sensing measurement applies to scenarios where a non-AP STA is the sensing initiator.

TB Sensing Measurement Instance

TB sensing measurement is an AP-centric mechanism. It is used when an AP is the sensing initiator, and one or more non-AP STAs are sensing responders. To start with, the AP sends a Sensing Polling Trigger frame to one or more STAs that are expected to participate in the sensing measurement. A STA responds with a clear to send (CTS)-to-self frame to confirm the participation in the following sensing measurement. The polling is important because STAs are not necessarily available for various reasons, including power saving, being busy with other data transmissions, or being silenced by nearby transmissions.

Following the polling, the AP will initiate the Trigger frame (TF) sounding and/or the NDP Announcement (NDPA) sounding depending on the negotiated roles of the STAs, which are used to perform sensing in the uplink direction and downlink direction, respectively. In the TF sounding phase, the AP sends a Sensing Sounding Trigger frame to trigger one or more STAs that are sensing transmitters to send responder-to-initiator (R2I) NDPs for the AP to take measurements. In contrast, in the NDPA sounding phase, the AP sends a Sensing NDPA frame, followed by initiator-to-responder (I2R) NDPs to one or more STAs that are sensing receivers for them to take sensing measurements.

Figure 2a illustrates an example of a TB sensing measurement instance. The AP first polls five STAs, where STAs 1 and 2 are sensing transmitters and

Sensing measurements in both sub-7 GHz and 60 GHz bands are largely built on existing beamforming protocols, which are separated from the regular data communications in the time domain. Therefore, sensing measurements occur in a dedicated time window without interfering any data transmission.

A non-TB sensing measurement instance is a client-centric mechanism. It is used when a non-AP STA is the sensing initiator, and one AP is the sensing responder. Note that since a non-AP STA typically does not support multi-user functions, a non-TB sensing measurement instance does not support multiple responders.

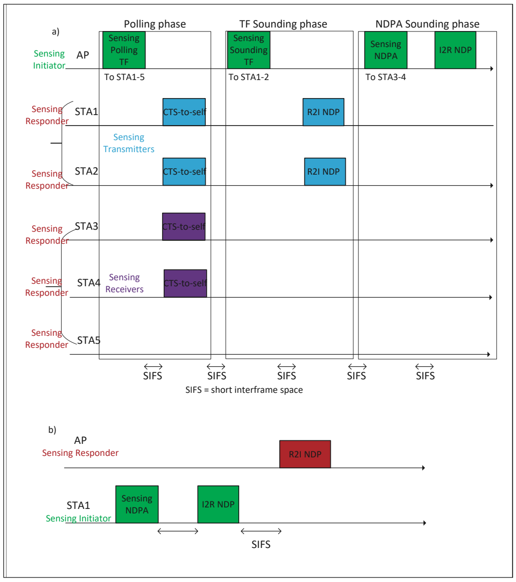

FIGURE 2. Examples of sensing measurement instances in sub-7 GHz: a) TB sensing measurement instance; b) non-TB sensing measurement instance.

STAs 3–5 are sensing receivers. STAs 1–4 respond to the AP with CTS-to-self, so both the TF sounding phase and NDPA sounding phase are present. In the TF sounding phase, the AP sends a Sensing Sounding Trigger frame to STA1 and STA2 to solicit R2I NDP transmissions. In the NDPA sounding phase, the AP sends a Sensing NDP Announcement frame followed by I2R NDP to STA3 and STA4.

Non-TB Sensing Measurement Instance

A non-TB sensing measurement instance is a client-centric mechanism. It is used when a non-AP STA is the sensing initiator, and one AP is the sensing responder. Note that since a non-AP STA typically does not support multi-user functions, a non-TB sensing measurement instance does not support multiple responders.

As opposed to the TB sensing measurement instance where the AP needs to poll responder STAs first before proceeding with downlink or uplink sensing transmissions, a STA can directly initiate a non-TB sensing measurement instance and start transmitting. This is because generally an AP does not go to power save, so whenever a STA obtains a transmit opportunity, it can confidently assume that the AP is always ready for sensing transmission or reception.

In a non-TB sensing measurement instance, as shown in Fig. 2b, the STA initiator transmits a Sensing NDPA frame to the AP, followed by an I2R NDP, which is used for uplink sensing. After receiving the I2R NDP from the STA, the AP also transmits an R2I NDP to the STA, which is used for downlink sensing. Therefore, this unified flow is able to cover all possible sensing scenarios, including unidirectional uplink sensing, unidirectional downlink sensing, or bidirectional uplink and downlink sensing.

Note that in the case of unidirectional uplink sensing, it may be argued that the downlink R2I NDP is technically redundant because it is not used for actual sensing purposes. Similar reasoning could apply to the uplink I2R NDP in the case of unidirectional downlink sensing. However, IEEE 802.11bf decides to keep them in all non-TB sensing measurement instances for the following reasons. First, the R2I NDP in the case of unidirectional uplink sensing acts as an acknowledgment from the AP to confirm the reception of the sensing NDPA frame and the I2R NDP. It also gives more time for the AP to process and prepare the sensing report for the I2R NDP measurement. Second, if we remove the I2R NDP in the case of unidirectional downlink sensing, the AP may not have enough time to configure and transmit the R2I NDP. Moreover, creating different sensing measurement flows for the same client-initiated scenario is generally not preferred for interoperability considerations. Having said that, in the case of unidirectional uplink (or downlink) sensing, the Sensing NDPA frame is advised to configure the R2I NDP (or I2R NDP) to be transmitted with minimum possible length so that the overhead is minimized.

Sensing Measurement in 60 GHz Band

Sensing measurement in 60 GHz band adopted by IEEE 802.11bf is built on the IEEE 802.11ad and IEEE 802.11ay standards, which define directional multi-gigabit (DMG) and enhanced DMG (EDMG) Wi-Fi communication in 60 GHz mmWave band, both of which have been incorporated into the IEEE 802.11 standard specifications [15]. IEEE 802.11bf tries to reuse existing (E)DMG protocols as much as possible with necessary changes to accommodate sensing requirements.

Monostatic Sensing Measurement

As stated earlier, different from sensing in sub-7 GHz bands, monostatic sensing is also considered in 60 GHz band as a viable option for sensing measurement, which is sufficiently achieved by using preamble fields and training (TRN) fields already defined in DMG or EDMG PPDUs. Consequently, there is no need to define a new waveform for monostatic sensing in 60 GHz band.

The flow sequence for monostatic sensing is straightforward. The same STA transmits (E)DMG PPDU, receives the echo of the PPDU, and takes measurement. Then the STA transmits the measurement report to the sensing initiator.

Bistatic Sensing Measurement

Bistatic sensing measurement in 60 GHz band is based on the beam refinement protocol (BRP), which was originally used for refined beamforming training in 60 GHz band. The sensing transmitter sends a BRP frame to the sensing receiver appended with the TRN fields for the receiver to take measurement. The sensing receiver responds with a BRP frame and includes the measurement results.

Multistatic Sensing Measurement

Different from monostatic and bistatic sensing, multistatic sensing measurement in 60 GHz band requires more coordination among multiple devices, which impacts the protocol design mainly in two aspects.

First, the sensing initiator needs to send a DMG Sensing Request frame to each responder individually to initiate the sensing measurement instance so that they all get prepared for the upcoming sensing PPDU reception. Each responder sends back a DMG Sensing Response frame as an acknowledgment and then directs its receive antennas toward the initiator. This is because the communication in mmWave band is highly directional. If multiple STAs are expected to receive the same sensing PPDU, they typically need different antenna configurations. Without prior notifications, some STAs may miss the PPDU transmission.

Second, the multistatic sensing PPDU, which is basically a DMG PPDU appended with several TRN fields, is further added by a few sync fields. The inclusion of sync fields is critical. Again, due to the highly directional transmission in the mmWave band, one STA may not be able to receive sequences directed to other STAs. Therefore, any STA that comes after the first STA may not be able to receive the preamble, header, and data part of the sensing PPDU since they are all directed to the first STA. Furthermore, each STA needs to understand when the TRN fields start so that it can take sensing measurements accordingly. In this case, we need to add one unique sync file for each STA that comes after the first STA to enable accurate synchronization.

Figure 3 illustrates examples of sensing measurement for monostatic, bistatic, and multistatic sensing.

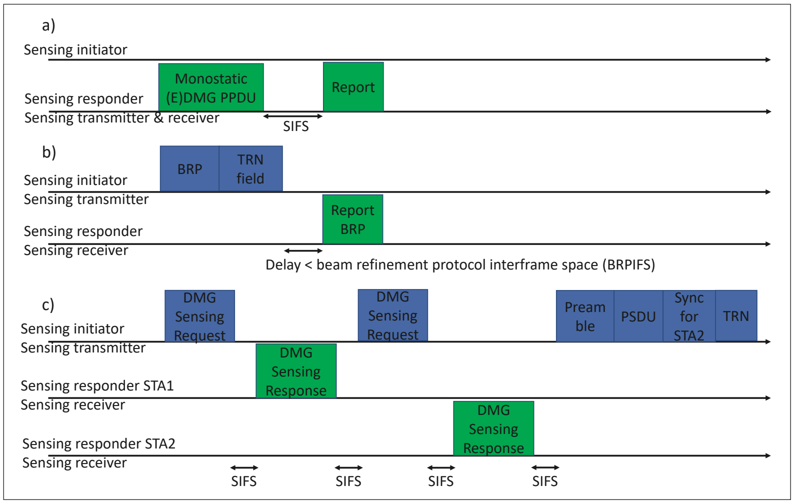

FIGURE 3. Examples of sensing measurement instances in 60 GHz: a) monostatic sensing measurement, b) bistatic sensing measurement; c) multistatic sensing measurement.

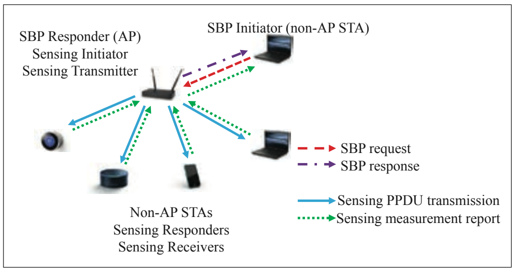

FIGURE 4. Illustration of sensing by proxy.

Sensing by Proxy

Sensing by proxy (SBP) is a critical feature introduced in IEEE 802.11bf to enable a client (i.e., a non-AP STA) to obtain more measurement results with the assistance of an AP to act as a proxy for the client. In the IEEE 802.11 standards framework, only the AP-STA connection is assumed. There is no direct client-to-client communication, which largely depends on other technologies out of the scope of IEEE 802.11 standards. As a result, a STA mostly only talks to an AP in a BSS and therefore can perform sensing measurement with the AP only, as described in non-TB sensing measurement. Moreover, due to different transmission powers, a client generally has less transmission range than an AP, which again limits its ability to conduct sensing measurements with devices far away. In addition, while most APs support multi-user functions and are capable of doing sensing measurements with multiple clients simultaneously, as described in TB sensing measurement, a client typically does not.

Because of the preceding limitations, if a sensing application is running on a client and initiates a sensing procedure, in most scenarios it can only obtain sensing measurements with an AP. However, as proved in many existing simulations and experiments, an increased amount of measurement results can significantly improve sensing performance, contributing to transmit and receive diversity. This is exactly when the SBP protocol can help with a client-initiated application to get more sensing measurement results by requesting an AP to serve as a proxy on its behalf.

Figure 4 illustrates the SBP protocol defined in IEEE 802.11bf. To establish an SBP procedure, the SBP initiator, which is a non-AP STA, sends an SBP Request frame to an SBP responder-capable AP. If the AP accepts the request, it sends back an SBP Response frame with confirmation indications, after which the SBP responder AP initiates a regular WLAN sensing procedure with one or more non-AP STAs using operational parameters derived from the SBP Request frame requested by the SBP initiator. After the SBP responder AP obtains the sensing measurement results, it needs to further deliver the results to the SBP initiator upon request from the SBP initiator.

Format for Sensing Measurement Report

The sensing measurement report refers to the collected measurement results reported by a sensing receiver. It is pointed out that a sensing measurement report is not always needed. In particular, only when the sensing initiator is the sensing transmitter may it request the sensing receiver to feed back the measurement report. Another common scenario that may need a sensing measurement report is in an SBP procedure, where the SBP initiator could request the SBP responder to submit the sensing measurement report.

While IEEE 802.11bf has not finalized the format of the sensing measurement report for 60 GHz sensing yet, there has been some key progress in defining the format of the sensing measurement report for sub-7 GHz, which strives to improve the measurement accuracy and reduce the computation complexity and the feedback overhead.

Per-Link CSI Feedback

Traditionally, CSI feedback has been mainly designed for multiple-input multiple-output (MIMO) beamforming, reporting the MIMO channel matrix of each subcarrier sequentially. For beamforming, even if the feedback matrix differs from the actual one by a global scaling factor, the beamforming gain is not affected. The legacy quantization defined in IEEE 802.11n exploits this property, and applies a global scaling factor to the channel matrix of each subcarrier, which is the maximum value among the real and imaginary

Unlike differential feedback, TPDP compresses the feedback in the time domain instead of the frequency domain. It is motivated by the fact that the time-domain representation of the channel response (i.e., channel impulse response) consists of a limited number of multipaths within a limited duration (i.e., delay spread).

parts of the matrix elements.

Unlike beamforming, sensing is interested in detecting the reflecting objects in the propagation path. The object of interest is typically represented by a multipath in the time-domain channel impulse response, which can be easily obtained by a fast Fourier transform (FFT) of the frequency-domain channel response. Consequently, instead of focusing on all the channel matrix elements of a given subcarrier, the sensing CSI feedback should focus on the elements in the same row and the same column of each subcarrier's channel matrix. Namely, the sensing CSI feedback needs high quantization accuracy on the relative phases and amplitudes of the channel responses of each Tx-Rx antenna pair, referred to as link, across the subcarriers. Therefore, per-link quantization is adopted by IEEE 802.11bf, as opposed to the legacy per-matrix quantization defined in IEEE 802.11n. Each link is scaled individually, and the scaled channel responses are then quantized and reported along with the scaling factors. Besides the performance improvement, the feedback overhead is reduced considerably.

Consider a 20 MHz 4 × 4 MIMO system where the channel matrix consists of 16 Tx-Rx antenna pairs for each subcarrier, and the frequency-domain channel response of each Tx-Rx antenna pair further consists of 242 complex numbers for the 242 subcarriers. Per-link feedback employs 16 scaling factors for the 16 links, while per-matrix feedback employs 242 factors for the 242 subcarriers. Furthermore, per-link scaling is robust to the power imbalance across the links. Due to the directional antenna radiation pattern and uneven occultation distribution in reality, one link may receive higher power than another (e.g., by 6 dB). Per-matrix feedback suffers an accuracy degradation on the weak link because all the links share the same scaling factor for any given subcarrier such that the quantization of the weak link suffers underflow. In contrast, the per-link scaling solves this problem since the strong and weak links are scaled separately before getting quantized.

Low-Complexity Scaling

During the discussions in IEEE 802.11bf, the complexity of the scaling factor was identified. The division and logarithm operations in the legacy 802.11n quantization increase the computation and implementation complexities. Alternatively, fractional scaling factor was proposed to address the complexity issue, which could achieve similar quantization accuracy. It uses a positive integer with limited numbers of 1s in binary as the numerator, like 1, 3, or 5, divided by a power-of-two integer such that the scaling operation can be implemented by simple bit shifts and few additions. Although the computation complexities are considerably reduced, the numerator and denominator need to be chosen carefully such that the fractional value can still approximate the optimal scaling factor. It was shown that the approximation degrades the quantization accuracy by about 2 dB compared to the legacy IEEE 802.11n scheme.

Per-Link Differential CSI Feedback

Besides the computation complexity, compression schemes have been proposed to reduce the burdensome feedback overhead. Differential feedback is one of the two main schemes. Note that the delay spread (e.g., a few hundred nanoseconds) is much smaller than the duration of the sounding symbol, which is typically a few microseconds. The frequency-domain channel responses are correlated across adjacent subcarriers. The correlation can be exploited by differential quantization that quantizes the difference between two adjacent channel responses. Since the variance of the differences is much smaller than that of the original channel responses, differential quantization can reduce the quantization bits or feedback overhead significantly (e.g., by a factor of 2) for the same quantization accuracy.

Truncated Power Delay Profile

Another feedback compression scheme is called truncated power delay profile (TPDP). Unlike differential feedback, TPDP compresses the feedback in the time domain instead of the frequency domain. It is motivated by the fact that the time-domain representation of the channel response (i.e., channel impulse response) consists of a limited number of multipaths within a limited duration (i.e., delay spread). TPDP picks the multipaths with noticeable energy for quantization and feedback. For overhead reduction, the feedback transmitter truncates the multipaths with negligible energy, and the feedback receiver ignores those multipaths.

Although TPDP may ideally reduce the feedback overhead significantly, it may not work well in practice. It is highly complex to estimate the time-domain multipaths from the existing frequency-domain channel response in real time. Furthermore, linear transformation like inverse FFT (IFFT) does not work well because of the following limitations. First, the frequency-domain channel response is discontinuous because there is no sounding signal on the DC subcarriers, the edge subcarriers, and punctured subchannels. Second, the sampling time at the receiver may not be exactly at the arrival times of the multipaths. Therefore, the time-domain multipaths obtained from the linear transformation suffer inter-path interference. Third, due to the selection of the FFT sample window, the time-domain multipaths obtained from the IFFT of the frequency-domain channel response suffer from a cyclic shift, whose correction incurs additional complexity.

We then present simulation results in Figs. 5 and 6 to compare the cumulative distribution function (CDF) of quantization noise-to-signal ratio (QNSR) performance for different CSI report formats. In the simulation, IEEE 802.11 channel model D is employed with 80 MHz bandwidth and 87.125 kHz subcarrier spacing. The CSI is reported every N_g subcarriers, whereas N_b denotes the number of bits used to quantize each real or imaginary part of the frequency-domain channel response. For fairness, all schemes use the same amount of feedback bits.

From Figs. 5 and 6, a general observation is that a larger N_g compromises the performance for per-link differential and TPDP, while having no effect on others. This is because a larger N_g decreases the correlation of channel responses across frequency for per-link differential. For TPDP, because we keep the total number of feedback bits the same for all schemes, the number of feedback bits decreases as N_g increases and thus the quantization accuracy decreases. It is apparent that the per-link differential always has the best performance due to the reduced quantization range resulting from the channel correlation. Additionally, TPDP has the second best performance after preserving all multipaths that are obtained from IFFT with non-negligible power. The performance of fractional scaling factor is close to but still worse than 802.11n.

Conclusions

In this article, we present the IEEE 802.11bf standard, which defines essential protocols to support Wi-Fi sensing. We provide an overview of the Wi-Fi sensing procedure and highlight the primary features, including sensing measurement instances in sub-7 GHz and 60 GHz bands, sensing by proxy, and different sensing measurement report formats. Simulation results that illustrate the performance of different CSI formats are presented and evaluated.

IEEE 802.11bf is still an ongoing project that actively calls for participation and contribution from different perspectives. There are various research directions that can be identified for further study. For example, how to define the sensing measurement report format so that we can achieve a good balance between performance and complexity is still pending. Another area of interest is how to define efficient scheduling algorithms to manage sensing traffic and minimize impacts on existing data communications. As we continue to develop IEEE 802.11bf, we are confident it will become a successful Wi-Fi standard that will support and promote Wi-Fi sensing.

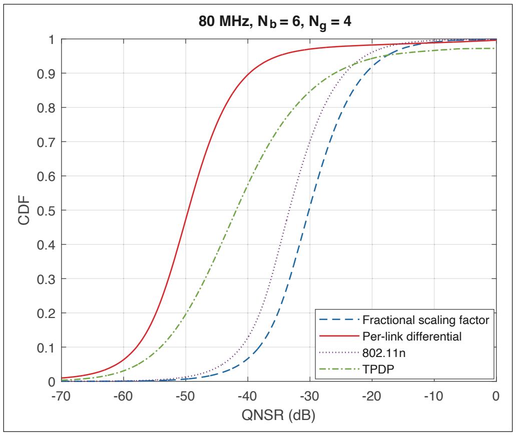

FIGURE 5. Simulation results of different CSI report formats in terms of CDF of QNSR when $N_b = 6$, $N_g = 4$.

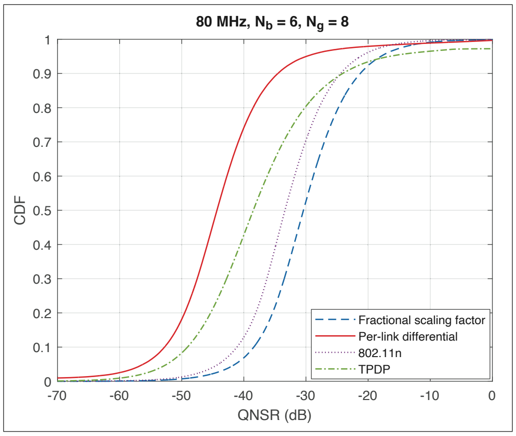

FIGURE 6. Simulation results of different CSI report formats in terms of CDF of QNSR when $N_b = 6$, $N_g = 8$.

References

[1] Cisco, "Cisco Annual Internet Report (2018–2023) White Paper," 2020.
[2] B. Korany *et al.*, "Counting A Stationary Crowd Using Off-the-Shelf WiFi," *Proc. 19th Annual Int'l. Conf. Mobile Systems, Applications, and Services*, 2021, pp. 202–14.
[3] W. Jiang *et al.*, "Towards 3D Human Pose Construction Using WiFi," *Proc. 26th Annual Int'l. Conf. Mobile Computing and Networking*, 2020, pp. 1–14.
[4] B. Korany *et al.*, "Nocturnal Seizure Detection Using Off-the-Shelf WiFi," *IEEE IoT J*, no. 9, 2021, pp. 6996–7008.
[5] Y. Zeng *et al.*, "WiWho: WiFi-Based Person Identification in Smart Spaces," *ACM/IEEE Int'l. Conf. Info.Processing in Sensor Networks*, 2016, pp. 1–12.
[6] Y. Ma *et al.*, "WiFi Sensing with Channel State Information: A Survey," *ACM Computing Surveys*, vol. 52, no. 3, 2019, pp. 1–36.
[7] A. Khalili *et al.*, "Wi-Fi Sensing: Applications and Challenges." *J. Engineering*, no. 3, 2020, pp. 87–97.
[8] Hongbo Jiang *et al.*, "Smart Home Based on WiFi Sensing: A Survey," *IEEE Access*, no. 6, 2018, pp. 13,317–25.
[9] F. Li *et al.*, "A Survey on the Applications of Wi-Fi Sensing," *Int'l. Conf. Artificial Intelligence and Security*, Springer, 2021, pp. 609–18.
[10] S. Tan *et al.*, "Commodity Wi-Fi Sensing in 10 Years: Current Status, Challenges, and Opportunities," arXiv preprint arXiv:2111.07038 (2021).
[11] T. Wild *et al.*, "Joint Design of Communication and Sensing for Beyond 5G and 6G Systems," *IEEE Access*, no. 9, 2021, pp. 30,845–57.
[12] IEEE 802.11 WG, "Amendment 2: Enhancements for Wireless LAN Sensing," IEEE P802.11bf D0.1, Apr. 2022.
[13] F. Restuccia, "IEEE 802.11 bf: Toward Ubiquitous Wi-Fi Sensing," arXiv preprint arXiv:2103.14918, 2021.
[14] A. Kasher *et al.*, "Wi-Fi Sensing Use Cases"; https://mentor.ieee.org/802.11/dcn/20/11-20-1712-02-00bf-wifi-sensing-use-cases.xlsx, accessed Oct. 1, 2022.
[15] IEEE 802.11 Working Group, "IEEE 802.11-2020," Feb. 2021.

Biographies

Cheng Chen is a software research engineer/scientist in Connectivity Standards at Intel Corporation. He has been an active contributor to various IEEE 802.11 programs, including IEEE 802.11ay (Next Generation 60 GHz), 802.11be (Extremely High Throughput), and 802.11bf (WLAN Sensing). He received his Ph.D. degree from Northwestern University, Evanston, Illinois.

Xiaogang Chen received his Ph.D. degree from Beijing University of Posts and Telecommunications, China. His research interest was channel coding for wireless communications. Presently, he is affiliated with Intel Corporation and focuses on Wi-Fi physical layer related algorithm and standard developments.

Dibakar Das is a software research engineer/scientist in Connectivity Standards at Intel Corporation and has several years of experience in wireless communication system design and performance evaluation. He has contributed actively to different IEEE 802.11 programs, such as 802.11az (Next Generation Position) and 802.11be (Extremely High Throughput). His current research interests include development of optimal resource allocation techniques, QoS provisioning, and extended reality applications over Wi-Fi.

Dmitry Akhmetov is a software engineer working on wireless technology at Intel Corporation. His expertise is in the areas of wireless communications, development of system-level simulators for wireless protocols, and development of wireless standards. He holds more than 10 U.S. patents with more than 20 pending patents pending. He is a graduate of the Nizhny Novgorod State University, Russia, with both Bachelor's and Master's degrees in applied mathematics.

.

Carlos Cordeiro [F] is the wireless CTO at Intel's client group and an Intel Fellow. He is responsible for Intel's next generation wireless connectivity technology strategy, standards, ecosystem engagements, and regulatory. He serves as the Chair of the Wi-Fi Alliance Board of Directors and the Associate Editor-in-Chief of *IEEE Communications Standards Magazine*, and has served as an Editor of various journals including *IEEE Transactions on Mobile Computing* and *IEEE Transactions on Wireless Communications*. He is the co-author of two textbooks on wireless, has published over 120 papers, and holds over 400 patents.