IEEE 802.11bf: Toward Ubiquitous Wi-Fi Sensing

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Abstract—Wi-Fi is among the most successful wireless technologies ever invented. As Wi-Fi becomes more and more present in public and private spaces, it becomes natural to leverage its ubiquitousness to implement groundbreaking wireless sensing applications such as human presence detection, activity recognition, and object tracking, just to name a few. This paper reports ongoing efforts by the IEEE 802.11bf Task Group (TGbf), which is defining the appropriate modifications to existing Wi-Fi standards to enhance sensing capabilities through 802.11-compliant waveforms. We summarize objectives and timeline of TGbf, and discuss some of the most interesting proposed technical features discussed so far. We also introduce a roadmap of research challenges pertaining to Wi-Fi sensing and its integration with future Wi-Fi technologies and emerging spectrum bands, hoping to elicit further activities by both the research community and TGbf.

I. INTRODUCTION

Since its inception in September 1990, Wi-Fi has transitioned from a low-rate replacement to Ethernet to one of the most successful wireless technologies ever invented. Today, Wi-Fi is ubiquitous and widely employed to provide plug-and-play Internet connectivity in almost any public and private space, including homes, offices, parks, airports, shopping malls, university campuses, and so on. Wi-Fi hotspots are so omnipresent that cellular operators are expected to offload 63% of their global mobile data traffic to Wi-Fi by 2021. For this reason, it is not hard to believe that a whopping 541.6M public Wi-Fi hotspots will be deployed by 2021 – a sixfold increase from 94M hotspots deployed in 2016, according to the Cisco Visual Networking Index (VNI) [1]. As a consequence, the global Wi-Fi economy is forecast to increase from today’s $1.96T to $3.46T by 2023, according to the study in [2].

The staggering increase in Wi-Fi devices, coupled with the unprecedented throughput demands of next-generation multimedia applications, will inevitably create complex wireless networking challenges. However, from a sensing standpoint, the sudden explosion in Wi-Fi devices may also constitute a “blessing in disguise.” Indeed, Wi-Fi devices are not only becoming more bandwidth-hungry, but also more and more diverse, spanning from personal computers, smartphones, televisions, tablets, sensors and many others. This extremely dense and heterogeneous concentration of WiFi devices – placed in almost every corner of our indoor environments – will create the perfect opportunity to continuously “map” the surrounding environment using Wi-Fi signals as sounding waveforms.

Figure[1] shows a very high-level overview of Wi-Fi sensing, also called SENS in the IEEE 802.11 community. The key idea behind SENS is to leverage Channel State Information (CSI) measurements to detect (and possibly, track) the presence of obstacles between a transmitter and a receiver. This way, complex classification tasks such as human activity recognition (HAR) [3], health monitoring [4], and object detection [5] can be achieved, for example, through computation of phase differences [6] or Doppler shifts [7]. Since surveying SENS procedures is outside the scope of this paper, we refer the reader to [8] for an excellent summary.

The vast majority on the literature on CSI-based SENS has focused on finding new application scenarios, or improving the classification accuracy of existing SENS algorithms. This deluge of interest by the research community has definitely helped SENS establish itself as one of the top candidates to perform device-free sensing in the years to come. Somehow surprisingly, despite the...
success of SENS, current Wi-Fi standards do not provide the support for sensing activities. To truly transition SENS from a research-only process to a widespread, systematically used feature, extending existing Wi-Fi standards to support SENS become quintessential. Recognizing the importance of the issue, the IEEE 802.11 Working Group (WG) has approved in September 2020 a Project Authorization Request (PAR) defining a new Task Group (TG), called IEEE 802.11bf (TGbf) [9]. According to the PAR, TGbf will tackle the development of an amendment that defines modifications to state-of-the-art IEEE 802.11 standards at both the Medium Access Control (MAC) and Physical Layer (PHY). This will help enhance SENS operation in license-exempt frequency bands between 1 GHz and 7.125 GHz, as well as above 45 GHz, which will enable sensing at millimeter wave (mmWave) frequencies.

The impact that IEEE 802.11bf will have on our society at large cannot be overstated. When 802.11bf will be finalized and introduced as an IEEE standard in September 2024, Wi-Fi will cease to be a communication-only standard and will legitimately become a full-fledged sensing paradigm. This standardization effort, coupled with the numerous SENS systems currently being developed at the research stage, will create the “perfect storm” for the introduction into the market of groundbreaking applications that we cannot even imagine today. Through 802.11bf, Wi-Fi sensing will be merged into WiFi and become part of our daily lives, as every standard-compliant router will need to implement SENS capabilities. At the same time, IEEE 802.11bf is still in its infancy, and although the activities of TGbf have only recently started and discussions are ongoing, some possible features that will become part of IEEE 802.11bf have already been discussed during TGbf’s meetings. Moreover, there are still some critical issues that need to be addressed to really make SENS effective and efficient in a variety of circumstances.

This paper makes the following contributions. First, we discuss in Section II a series of reasons as to why the standardization of SENS procedures through IEEE 802.11bf has become a compelling necessity for the future of Wi-Fi. We then introduce the reader to the use cases, objectives and timeline of TGbf in Section III and discuss the most relevant features that have been discussed during TGbf meetings in Section IV. We then introduce a series of research challenges that will need to be tackled to improve SENS and that could inform future TGbf activities in Section V. The paper is concluded in Section VI.

II. IEEE 802.11BF: THE NEED TO STANDARDIZE SENSING PROCEDURES

Since its inception, SENS has enjoyed a sustained interest by the wireless research community, which has proposed and improved new techniques to leverage Wi-Fi signals to sense a diverse number of phenomena [8]. After several years of continuous improvement, and realizing its economic impact, the IEEE 802.11 community is now supporting the integration and facilitation of SENS procedures through the IEEE 802.11bf standard, to increase compatibility, facilitate interoperability and support safety. This does not come as a surprise; to be successfully adopted at the scale of billions of devices, SENS techniques must necessarily be integrated into the bigger IEEE 802.11 family, which will impose manufacturers wanting to produce standard-compliant Wi-Fi chips to support SENS.

Beyond widespread adoption, we can provide at least two reasons that make 802.11bf compelling from a technical standpoint. First, the standardization process will impose strict quality control to the technical features that will be part of the standard. Promoting 802.11bf to a full standard will require several years and iterations, as explained in Section III-B, and will involve the participation of hundreds of experts in Wi-Fi technologies. Each proposed technical feature will go through many iterations before ending up into a standard draft. According to the TGbf Selection Procedures document [10], the proposed technical contributions will go through three voting procedures, where at least 75% of the 802.11 voting members will have to approve the contributions. Finally, the draft document will need to satisfy 802.11bf technical requirements before making it to a WG ballot.

The second reason is that through standardization into the 802.11 family, researchers and developers of sensing applications will have the access to well-defined SENS procedures, where data collection and analysis will be facilitated. Nowadays, researchers need to manually implement operations such as CSI collection, feature extraction, and classification. With established protocols defining the interaction...
with the PHY and MAC layers, innovation in the critical SENS field will be severely expedited.

III. IEEE 802.11bf: Objectives and Timeline

At the time of writing, the TGbf community is regularly meeting to define the use cases and technical contribution that should be included in the final 802.11bf standard. However, a number of key objectives and use cases have already been defined, including the project timeline, which are the focus of this section.

A. TGbf Objectives

The TGbf’s final target is to define modifications to the 802.11ad, 802.11ay, 802.11n, 802.11ac, 802.11ax and 802.11be PHY, as well as the IEEE 802.11 MAC, to enhance sensing operations through Wi-Fi signals. Finally, 802.11bf will provide backward compatibility and coexistence with existing IEEE 802.11 standards operating in the same bands. It will enable sensing measurements to be obtained using transmissions that are requested, unsolicited, or both, and define a MAC service interface for layers above the MAC to request and retrieve SENS measurements.

More formally, the TGbf defines Wi-Fi Sensing (SENS) as the usage of received Wi-Fi signals from a Wireless Station (STA) to detect features (i.e., range, velocity, angular, motion, presence or proximity, gesture, etc) of intended targets (i.e., object, human, animal, etc) in a given environment (i.e., house, office, room, vehicle, enterprise, etc). As specified in the Functional Requirement Document (FRD) redacted by the TGbf, SENS operations will occur in license-exempt frequency bands between 1 GHz and 7.125 GHz and above 45 GHz. The IEEE 802.11bf amendment will enable STAs to perform the following: (i) exchange information regarding their SENS capabilities to other STAs; (ii) request and setup transmissions that enable SENS measurements to be performed; (iii) indicate a transmission can be used for SENS; (iv) exchange of SENS feedback and information.

Figure 2 summarizes how 802.11bf is envisioned to support sensing operations. SENS operations will be performed during a SENS session. A SENS initiator is a STA that initiates a session, while a SENS responder is a STA that participates to a session started by an initiator. A SENS transmitter/receiver will transmit/receiver PHY Protocol Data Units (PPDUs) used for SENS measurements in a session. Notice that in a session, an initiator can be a sensing transmitter, a receiver, both or neither.

B. TGbf Timeline

Figure 3 summarizes the envisioned 4-year development timeline for 802.11bf. The first crucial step, which is the approval of the Project Authorization Request (PAR) for TGbf, has been completed in September 2020. In IEEE standards jargon, a PAR is a legal document that states the reason and objectives for the project. Moreover, it allows a WG to assign copyright and indemnification from IEEE. At the moment, TGbf is working on drafting a Specification Framework Document (SFD) to provide a top-level technical description of the functionality that the IEEE 802.11bf standard will implement.

An initial draft of the standard (D0.1) is expected to be available in January 2022, with 3 subsequent drafts, D1.0, D2.0 and D3.0) available in July 2022, January 2023 and May 2023, respectively. The IEEE Standard Association (SA) balloting process for IEEE 802.11bf is set to begin in September 2023. The balloting usually begins when the Standards Committee (SC) assigned to TGbf convenes that a draft (D4.0) has reached enough maturity. A balloting group will be formed by the SC, containing individuals or entities interested in the standard. While anyone can contribute comments, eligible members of the balloting group (i.e., IEEE SA members or buyers of a per-ballot fee) are the only votes that count toward approval. Balloters are usually stakeholders of the standard, such as chip manufacturers and final users. While no interest category can comprise over 1/3 of the balloting group, the target is to gain the greatest consensus
among balloters. At least, a 75% consensus with at least 75% of the ballots returned has to be reached to conclude the balloting process.

The IEEE 802.11 WG and 802.11 Executive Committee (EC) is set to approve the 802.11bf standard in July 2024, 10 months after the SA ballot. Before the standard can be published, the IEEE SA Standards Board has to approve it with the recommendation of the Standards Review Committee (RevCom). While the RevCom does not examine the technical nature of the standard, it ensures procedural standards were followed during the drafting and balloting process, such as consensus, due process, openness, and balance. After approval, the standard is edited by an IEEE SA editor, given a final review by the members of the WG, and published. RevCom will check over all the documentation and make sure that the IEEE SA procedures were followed.

IV. IEEE 802.11BF: PROPOSED FEATURES

Many technical contributions are currently being discussed during TGbf meetings to take SENS to the next level in future Wi-Fi networks. In this section, we provide a summary of the most promising approaches discussed so far.

A. Cooperative SENS

Traditionally, SENS has performed with one STA transmitting the sensing waveform and one (or more) STAs receiving and processing it. However, a more effective collaborative SENS (in short, CSENS) approach has been recently proposed [12], shown in the left portion of Figure 4, where multiple SENS-enabled devices can collaborate as a group in an orderly fashion to capture additional information about the surrounding environment.

This is especially true in the case of Multiple-Input Multiple-Output (MIMO) transmissions, which are the norm in modern Wi-Fi standards. Spatial diversity – achieved with multiple antennas and multiple transmitters – can indeed help improve the quality of SENS operations, as more channels between the SENS transmitters and the SENS receiver(s) can be obtained and processed, thus leading to accurate sensing. Figure 5 illustrates the envisioned way to establish a CSENS session, which is composed of three phases: (i) a trigger phase, (ii) a burst phase, and (iii) a feedback exchange phase. A SENS initiator (I) initiates the CSENS by sending a trigger packet, which signals the SENS responders (S1 and S2) that a CSENSE operation is taking place. The responders will take turn in transmitting a burst of Null Data Packets (NDPs), which are used to sound the channel between the responders and the receiving STAs.

In Figure 5, S1 sends a burst of two NDPs, one received by I and one by S2. Since an NDP is received by I, there is no need to request an explicit feedback since I can directly compute the CSI. To receive the CSI from the missing responders, I sends
a feedback request – in the example, S2 – each of them replying with a CSI reply.

B. Multi-band SENS

The vast majority of Wi-Fi devices will soon be equipped with antennas operating at both sub-7-GHz frequencies and 60 GHz, to be compatible with legacy standards – IEEE 802.11ax and earlier – and the new standards at mmWave frequencies – IEEE 802.11ad/ay and subsequent. The presence of such diverse antennas into a single device will create unprecedented sensing opportunity for Wi-Fi. On one hand, sub-7 CSI measurements will provide indication of relatively large motions, can propagate through obstacles (e.g., walls), and contain richer multipath information. On the other hand, CSI measurements are very sensitive to fading and noise, which may lead to inconsistencies in sensing measurements. CSI is also very high-dimensional, as it grows quadratically with the number of subcarriers and antennas. Conversely, Received Signal Strength Indicator (RSSI) measurements at mmWave will provide highly-directional information through the usage of beamforming toward a given receiver, but have small range due to the presence of blockers (e.g., walls). Moreover, measurement are more coarse-grained, since the complexity grows with the number of beams.

Given the substantial difference between the two measurements, it becomes consequential to “merge” together sensing inputs from sub-7 and mmWave. This is particularly useful especially for data-driven algorithms, which can work with very heterogeneous data [13]. Recent discussions in TGbf meetings [14] have unveiled the possibility of concurrently using RSSI and CSI measurements as input to a convolutional neural network (CNN) or digital signal processing (DSP) block to classify complex sensing phenomena. The approaches discussed were input concatenation, feature fusion, i.e., concatenate the output of the convolutional layers, and feature permutation, to make the learning process more robust and generalizable.

V. IEEE 802.11bf: Challenges and Opportunities

The IEEE 802.11bf standardization process is still in its infancy. Although significant research efforts have been spent in the field of Wi-Fi sensing, there are still a plethora of opportunities to further enrich the field before the standardization process is completed in September 2024. Figure [5] summarizes the challenges discussed in this section.

A. SENS Security and Privacy

While creating a plethora of life-improving benefits for ordinary citizens, the IEEE 802.11bf standard will enable Wi-Fi devices to regularly perform SENS operations in highly-populated indoor environments. As a consequence, the pervasiveness of SENS into our everyday lives will necessarily elicit security and privacy (S&P) concerns by the end users. Indeed, it has been shown that SENS-based classifiers can infer privacy-critical information such as keyboard typing, gesture recognition and activity tracking. Given the broadcast nature of the wireless channel, a malicious eavesdropper could easily “listen” to CSI reports and track the user’s activity without authorization. Worse yet, since Wi-Fi signals can penetrate hard objects and can be used without the presence of light, end-users may not even realize they are being tracked.

As yet, research and development efforts have been focused on improving the classification accuracy of the phenomena being monitored, with little regard to S&P issues. While this could be acceptable from a research perspective, we point out that to allow widespread adoption of 802.11bf, ordinary people need to trust its underlying technologies. Therefore, S&P guarantees must be provided to the end users.

We identify a number of critical issues that need to be addressed in this space, also illustrated in the top-left portion of Figure [5]. First, individuals should be provided the opportunity to opt out of SENS services – in other words, to avoid being monitored and tracked by the Wi-Fi devices around them. This would require the widespread introduction of reliable SENS algorithm for human or animal identification. Although some techniques have been proposed in literature [8], it is unclear whether they are resilient to spoofing, i.e., malicious users actively trying to impersonate other users, or adverse channel conditions, i.e., presence of noise and interference from other technologies. On the other hand, identification techniques should also be tested against adversaries trying to avoid being detected, either through active techniques, i.e., a Wi-Fi device carefully jamming the SENS activity, or passive techniques, i.e., materials shielding and/or deflecting
the Wi-Fi radiation. Since many recent SENS-based classification systems are based on CNNs, an interesting investigation could be the evaluation of the extent to which adversarial machine learning (AML) techniques can compromise the accuracy of existing CNN-based classifiers operating on CSI inputs.

### B. Multi-band CSENS-aided Wi-Fi Systems

Cooperative SENS (CSENS), as mentioned in Section IV-A, has been discussed as a viable option to increase the reliability of SENS operations. This feature, combined with the possibility of multi-band SENS (Section IV-B), will provide a unique opportunity to not only increase the classification accuracy of sensed phenomena, but also to leverage the increased location-awareness of blockages – due to humans, animals and objects – to design intelligent multi-band CSENS-aided Wi-Fi communications that will increase the performance of mmWave Wi-Fi links. For example, understanding the size and movement of blocking entities through sub-7 CSI reports could eventually guide beam selection in the mmWave link, as shown in Figure 6. By the same token, understanding the location of a STA by using sub-7 SENS can help reduce the overhead associated with beam scanning and alignment.

Moving forward, a key challenge will be to coordinate time-sensitive CSENS operations among multiple Wi-Fi devices in different spectrum bands. Indeed, conversely from the vast majority of SENS classification tasks, communication-related SENS will be extremely time-sensitive, with maximum tolerable deadlines in the order of milliseconds. To this end, a possible strategy could be to introduce control channels in the sub-7 band exclusively dedicated to the coordination of low-latency CSENS operations. This option is particularly enticing, also thanks to the increased number – up to 16 – of MIMO spatial streams supported by future Wi-Fi standards such as IEEE 802.11be.

### C. SENS in Spectrum Sharing Environments

From IEEE 802.11ax onward, Wi-Fi is poised to utilize the additional 1.2 GHz of spectrum between 5.925 and 7.125 GHz. Of particular relevance to IEEE 802.11bf, this pristine spectrum band will allow the usage of very large bandwidths – up to 320 MHz – and as a consequence, the usage of an increased number of subcarriers – 996x2, if the same subcarrier allocation of IEEE 802.11ax will persist. This will imply that finer-grained CSI reports could be utilized for SENS, with the possibility of severely improving performance.

Two major showstoppers to this much-needed enhancement, however, are (i) the increased path loss at 6 GHz frequencies; and (ii) the need to
share the spectrum with other wireless technologies. Currently, the 6 GHz band is reserved to licensed users (also called incumbents). These include cellular carriers and mobile virtual network operators (MVNOs) who have already deployed thousands of backhaul point-to-point links. Incumbents such as satellite, public safety and ultra-wideband systems will also be in the 6 GHz band, as well as upcoming 5th generation (5G) technologies such as NR-Unlicensed. To protect incumbent services, restrictions will likely be placed in terms of maximum emitted power and communication time by other technologies. Thus, (i) Wi-Fi transmissions may utilize significantly lower power in some cases, and (ii) severe interference from incumbent and upcoming SENS has to be expected, especially when listen-before-talk is not used to handle coexistence. Therefore, further investigations should address how to make SENS robust to interference.

D. Integrating SENS and Data Transmissions

SENS operations are set to coexist with data-only transmissions in future 802.11 standards. On one hand, since both data packets (DPs) and NDPS contain CSI, SENS transmissions could be “piggy-backed” into DPs to avoid decreasing throughput to a significant extent. On the other hand, as explained earlier, DPs may be subject to significant interference in the 6 GHz band, which may be tolerable from a data recovery perspective but intolerable from a SENS perspective. Therefore, a core issue is to determine the optimal trade-off between making reserved use of the spectrum for SENS operations and piggybacking SENS into DP. Similar to multi-band SENS, dedicated channels – either through MIMO spatial multiplexing or through periodic channel reservation – could be used to improve SENS performance without a significant decrease in system throughput.

VI. CONCLUSIONS

With the introduction of IEEE 802.11bf, we are starting to see almost 10 years of research efforts come to fruition. However, there are still many challenges and opportunities for the research community to contribute to a successful standard. In this paper, we have summarized current IEEE 802.11bf standardization efforts, as well as some of the proposed technical features. We have also discussed a set of research challenges that if addressed, could improve the finalized IEEE 802.11bf standard. We hope our paper will elicit further research activities by the wireless research community on this timely topic.

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