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Wireless sensing – enabler of future wireless technologies

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Abstract: With the completion of the 5G standardization efforts, the wireless communication world has now turned to the road ahead, the future wireless communication visions. One common vision is that future networks will be flexible, or able to accommodate an even richer variety of services with stringent, often conflicting requirements. This ambitious feat can only be accomplished with a ubiquitous awareness of the radio and physical environment. To this end, this paper highlights the importance of wireless sensing as a means for radio environment awareness and surveys wireless sensing methods under different domains. Then, a review of wireless sensing from a standardization perspective is given. These standardization efforts will provide the initial landscape upon which research into future wireless sensing methods will be built upon. Therefore, the paper is concluded by outlining imperative standardization requirements and future directions in wireless sensing.

Key words: 6G, 802.11bf, joint radar and communication (JRC), radio environment mapping (REM), wireless sensing, WLAN sensing

1. Introduction

Future wireless communication visions have introduced a humanitarian perspective in the form of digital societies [1] and twins [2]. This has led to a paradigm shift in wireless networks, going from mere communication systems to a convergence of multiple functionalities [3]. Enabling such a vision requires ubiquitous connectivity, intelligence, awareness, and flexibility [4]. Ubiquitous connectivity is being studied under the context of heterogeneous networks [5], cognitive radios (CRs) [6], mobile/aerial base stations [7], and much more. Optimization and adaptive resource allocation algorithms have somewhat supported network intelligence, with more recent works incorporating machine learning (ML) and deep learning (DL) [8]. Similarly, flexibility is also actualized in a limited manner with the introduction of service-based numerologies and heterogeneous networks. However, in order to support the exceedingly stringent requirements of higher data rates, increased reliability, stronger security and reduced latency for a larger number of connected devices in future networks, a higher level of intelligence and flexibility is required [9]. Awareness of the radio scene and physical environment is a key enabler of network intelligence and flexibility, and is studied under the radio environment map/mapping (REM) concept [10, 11]. While REM has been around for some time, its actualization was impeded by the shortage of processing power in easy-to-access devices and a gap in standardization efforts. Full awareness and REM is

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attainable through ubiquitous sensing of the radio environment. As such, wireless sensing is a vital functionality and performance indicator in future visions [1, 2, 9].

Despite the current peak in interest, wireless sensing is not a novel concept and has existed for decades under radar and channel sounding. While radar and channel sounding give some information on an object in the environment and channel conditions respectively, these and similar techniques alone are not sufficient to enable the level of awareness mentioned above. For this, the radio should be able to know and perceive information about the physical and radio environment, the users and their activities. Fortunately, the widespread availability of wireless local area network (WLAN) devices has propelled further research into wireless sensing. The extent of WLAN networks have steadily climbed since their introduction, with the number of WLAN capable devices reaching an estimated seven devices per household as of 2019 [12] and an overall 40 billion by the end of 2025 [13]. These networks are generally smaller in size and more manageable in semidecentralized architectures. In light of this, and to facilitate the aforementioned applications, the Institute of Electrical and Electronics Engineers (IEEE) 802.11 WLAN standardization society has charged a task group with determining the necessary amendments to incorporate wireless sensing, or WLAN sensing, in the standards. This has made WLAN networks an optimum platform for researchers to demonstrate ubiquitous sensing. The contributions of this paper are as follows:

- The significance of wireless sensing for future communication technologies is stressed, with a general introduction to REM and wireless sensing domains. Popular measurements and their domains for sensing are categorized and briefly explained. Additionally, selected applications are provided to illustrate the importance of multidomain wireless sensing for enhancing network performance.

- The possibility of using WLAN networks as test platforms for ubiquitous sensing is proposed. In light of this, the timeline of the evolution of WLAN sensing from a technological and standardization perspective is presented, including the newly formed 802.11 task group (TG)bf. An overview of discussed use cases is given, singling out the ones with more potential.

- The standardization gaps for WLAN sensing are highlighted, giving a preview of what is expected from the 802.11 TGbf, as well its preemptive deadline for completion. The current discussions in the task group are thoroughly reviewed, categorized and presented. Insights into possible standardization directions are provided, bringing to light critical issues.

- Compared to other surveys and reviews, which collect and classify wireless sensing methods based on its applications and/or the measurements used (either channel state information (CSI) or received signal strength (RSS)/received signal strength indicator (RSSI)), our work inspects the wireless sensing domains, the measurements that can be extracted from each domain, their features and relation to the channel, applications, and the methods by which they can be extracted.

- Various challenges to both WLAN sensing and its standardization are discussed, along with future directions in view of developing wireless communication technologies and their place in WLAN sensing.

The remainder of this paper is divided in the following manner. Section 2 introduces REM and the main domains in WLAN sensing. An introduction to the 802.11 TGbf and the standardization expectations are given in Section 3. Section 4 examines the current proposals and discussions in the task group. Then, the challenges and future directions are discussed in Section 5. Finally, Section 6 concludes the paper.

2. REM and wireless sensing

REM is defined as a multidimensional database consisting of past, current, and predicted information on the radio scene, elements, and environment [14]. The radio scene encompasses wireless capable devices or network users' behavior and wireless transmission (communication or sensing) activities in the network/region. Examples of such information are communication patterns, device locations, mobility information, and policies/protocols. Information on radio elements is related to the identification and capabilities of the network devices and users. The radio environment reflects the interaction of wireless signals with the physical environment and can provide information comprising geographical and terrain maps, propagation models, interference, and signal strength maps. Evidently, the collection and management of all this information is problematic. Even if present in an off-grid database, the dissemination of this information to network devices, users, and other wireless capable devices is inefficient, if not impossible. This is where wireless sensing comes into play.

Wireless sensing can be broadly defined as extracting information from electromagnetic signals on possibly everything that they encounter. To put it more precisely, due to non-ideal hardware, the vulnerability of the signal to outside factors, and the propagation environment, the received signal is not an exact replica of the transmitted signal. The discrepancies between the transmitted and received signal can be exploited to infer REM information, particularly about the wireless technology, device, user condition and behavior, and physical environment. Figure 1 illustrates the generic wireless communication block diagram from this perspective, showing the sources of footprints on the transmitted signal. Intuitively, knowledge of the medium access control (MAC) layer information can help determine the wireless technology [15], the radio frequency (RF) impairments can help identify the wireless device [16], and channel information can be mapped to the physical environment [17]. This mapping can be based on theoretical or empirical models, for example, utilizing geometric models or look-up tables, like in environment fingerprinting, respectively. The measured information must be distinct, meaning that there should be a detectable difference from measurements of other things, and have temporal consistency, they should be reproducible, for accuracy in both approaches. Additionally, wireless sensing can be active or passive, with active sensing requiring transmissions from the sensed device/object and passive utilizing transmissions between other devices. It is also worth noting that MAC layer parameters can significantly affect physical environment sensing performance.

The remainder of this section will explore wireless sensing in the better known domains. Keep in mind that this is not a full list, and useful information can be found in other domains as well. Then, example applications are given to illustrate how relationships formed between different domains can support awareness.

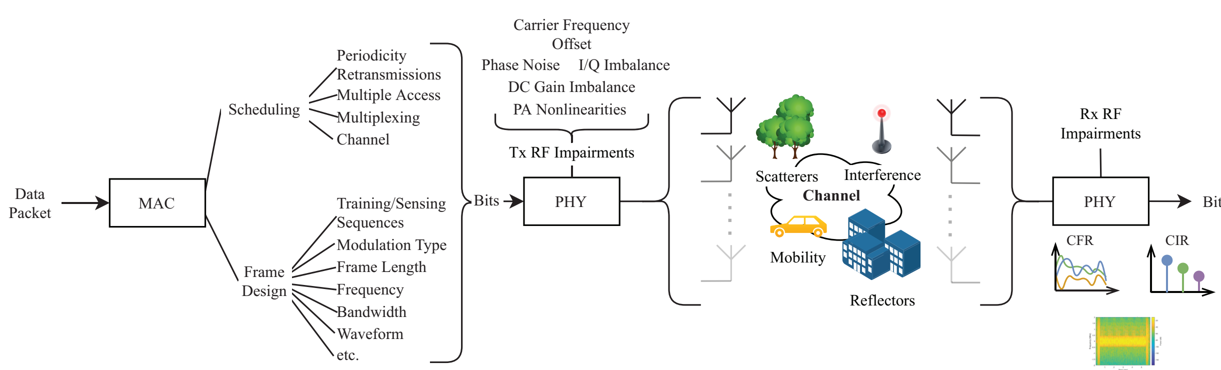

Figure 1. Illustration of the effects added to the signal as it traverses the environment.

2.1. Sensing domains

From the communication perspective, the received signal can be analyzed in different domains, independently or jointly by employing multidimensional signal analysis techniques. This is also possible in wireless sensing. Hence, this section will touch on sensing in different domains, their use cases, and advantages.

2.1.1. Power domain

RSSI is the measurement most frequently associated with wireless sensing. In particular, singular and time series power measurements are utilized for localization or positioning [18] and tracking, respectively. RSSI is considered coarse-grained information due to small-scale fading. As such, they are not reliable or consistent in complex, high-mobility environments due to drastic changes in multipath components. These components are summed constructively or destructively at the receiver and can lead to significant fluctuations in the measured RSSI value. The multipath effects can somewhat be mitigated using peer-assisted error control [19], error-coding, and channel aware RSSI localization techniques [20]. However, finer-grained features are required to go beyond localization and positioning.

With the increased availability of commercial millimeter-wave (mmWave) devices, spatial beam signal-to-noise ratio (SNR) based approaches to localization have recently been studied [21]. SNR is deemed midgrained information since they are more stable than RSSI, while not providing knowledge of multipath. These approaches are examples of active sensing, where either one or multiple network devices sequentially transmit beams in all directions while the receiver measures the SNR. Intuitively, the beam angle with the highest SNR value should be the line-of-sight (LoS). Then, it is a matter of mapping the SNR to distance.

2.1.2. Time domain

Time-of-arrival (ToA) and time-of-flight (ToF) are typically used in ranging, or finding the distance of an object/device relative to the transmitter. This active sensing approach uses the time information along with the speed to calculate the distance traversed by the signal. It yields accurate results in LoS conditions and with wideband signals due to increased time resolution [22]. However, this increased resolution comes at the cost of high analog-to-digital converter (ADC) sampling rate and transmitter receiver clock synchronization requirements. One use case for ToA- and ToF-based approaches is the well-known triangulation, where the ToF information of signals from three network devices or stations can be utilized for localization.

Another time domain feature is the channel impulse response (CIR). This information is considered to be a fine-grained measurement as it provides high dimension information in the form of individual delays of the multipath. Thus, it also gives some information on the physical environment. The orthogonal frequency division multiplexing (OFDM) waveform is particularly favorable for CIR based sensing. This is because each subcarrier corresponds to a spectrum sample or channel frequency response (CFR) measurement, from which CIR can be obtained through the inverse Fourier transform already incorporated in OFDM receivers. Single CIR measurements can be used for active localization by employing similar approaches to that of RSSI based sensing. Motion or actions in the environment change the multipath, which can be detected through time series of CIR measurements using pattern recognition and ML algorithms [23]. Intuitively, CIR measurements are more distinct than RSSI or other measurements, as different locations are expected to have different multipath characteristics. CIR based localization is, therefore, more reliable. However, there are some drawbacks. Firstly, the CIR measurement resolution is dependent on the bandwidth. To get distinguishable peaks, wide bandwidths are required. However, higher bandwidth generally corresponds to more multipath, which adds to processing time and complexity [24]. It should be noted that not all multipath would change significantly with location. Therefore, feature selection can be employed to select those which are distinguishable at different locations [25]. Radar ranging employs CIR approach to calculate the relative distance of the objects within its range. The main principle of radar is to transmit a signal, and collect and process its reflections. Reflections from different objects will have different delays, which are then mapped to the range of said objects [26].

2.1.3. Frequency domain

CFR reflects the frequency selective fading in the channel due to constructive and destructive addition of phases. As mentioned previously, it is readily available in OFDM systems in the CSI and is also a fine-grained measurement. Although CIR and CFR measurements have the same dimensions, useful information in CIR is spread over a few of the time indices, while it spans all the samples in CFR [25]. As a result, CFR measurements are more distinguishable and trackable, making them more feasible. The curse of dimensionality still remains though, and extracting the most distinguishable features becomes more difficult since the effects of the changes are spread throughout the indices. However, CFR based sensing still performs better than CIR, especially in narrower bandwidths. Single and time series CFR based sensing can be applied for localization and detecting environmental changes as in CIR based sensing. Additionally, Doppler shifts can be used to detect mobility in the environment, like in radar systems. Here, a copy of the original signal is present at the receiver and mixed with the received reflected signal. The resulting frequency is called the beat frequency and contains the Doppler shifts due to the mobility of objects in the environment [26].

2.1.4. Angle domain

Angle domain sensing is used jointly with other approaches for localization and positioning. There are two popular ways the angle of arrival (AoA) can be determined. The first is using rotating directional antennas or beamforming. Here, the AoA can be deduced by noting the orientation of the antenna for the maximum received power or LoS signal. The other utilizes array antennas and calculates the time-difference-of-arrival (TDoA) between individual array elements from the phase differences [27]. AoA can also be calculated using a single antenna that moves such that it mimics antenna arrays. Then, the aforementioned approach can be used.

2.1.5. Waveform domain

Waveform domain identification represents the ability to sense the signal and determine the possible propagating waveform shape i.e. rectangular pulse, Gaussian pulse, and variants of sinc shape. Not only the shape of the emitted signal but also signal parameters such modulation, data rate, and coding rate need to be considered for the signal identification. Blind signal analysis (BSA) is the main trending research area where the aim is to learn about a signal with limited or no apriori information. Main works include blind signal identification, where information such as waveform and wireless communication technology are estimated [28], and blind signal separation, where interfering signals are identified and removed from the desired signal [29]. Maximum likelihood-based approach where the likelihood function of the received waveform is evaluated under the hypotheses that different signals i.e., OFDM, single carrier and code division multiplexing (CDM) with various parameters i.e., modulation order, code rate, and frequency offset are emitted, and the decision is made considering the maximum value of this function. Additionally, multidimensional signal analysis is a methodology not only limited to waveform identification but also the occupancy of the spectrum, parameters related to the channel and other MAC layer information as shown in Figure 1 and discussed in [15]. In this sense, hyperspace signal representation of a given waveform can be utilized to explore the corresponding environmental features. As an example, single carrier and OFDM can easily explore time and frequency domain diversity, respectively.

2.1.6. Multidomain sensing

Multidomain sensing involves jointly utilizing information from two or more domains to sense the physical and radio environment activities. The SNR based sensing example given in 2.1.1 is an example of multidomain sensing because it involves information from both the power and angle domains. Here, the signal is not the main focus and the domains involved can include information outside of the time, frequency, and power domains. For example, sensor and image information can be used.

2.2. Selected applications of wireless sensing

There are many applications of wireless sensing, some of which were touched upon in the previous sections. This section will detail further applications that can be used to improve the performance of future communication performance by aiding concepts such as cognitive radio and awareness.

2.2.1. Radio frequency fingerprinting

As mentioned before, and shown in Figure 1, there are impairments added to the signal at the transmitter and receiver due to nonideal hardware. These impairments can be used to identify the transmitting device [30]. This concept of extracting the unique device fingerprints from the received signal has gained attention as a means of physical layer (PHY) authentication [16].

2.2.2. User behavior prediction

As a part of the fifth generation (5G) cellular communication standards, different communication services are performed with different waveform numerologies. Assuming that a user will require the same or similar services, then their behavior can be predicted from the statistical information on their service usage. Multidimensional signal analysis, specifically in the time and frequency domains, can be used to identify the numerologies, and thus the type of service being used [31]. RF fingerprinting could be performed to label and identify the user. Afterward, a statistical analysis could be made to determine the behavior pattern of the user. Information such as the time, frequency, and duration of communication, along with expected service type to be used can be used for scheduling and resource allocation.

2.2.3. User mobility patterns

Network information, such as user-cell association information, or any of the device/object tracking methods mentioned above, along with RF fingerprinting based user authentication, can be used to generate and associate mobility patterns with the user. Mobility patterns are derived from statistical tracking information or mobility models and define how the user moves throughout the network. Knowledge of such information can enable mobility-aware network optimization, such as beamforming and handovers [32]. It can also enable non-communication related applications, such as traffic management and elderly/child tracking or activity monitoring.

2.2.4. Spectrum occupancy prediction

Time, frequency, and space/location information can be used to predict the occupancy of the future spectrum [33] based on their correlation. The validity of this can be intuitively deduced. Most users are creatures of habit, and as mentioned before, their behavior can be predicted. In addition, there will be some space-time correlation as well, which can be predicted by user mobility patterns. In this application, historical spectrum occupancy information for some regions are collected. Then, users can be identified, either by the network or by applying BSA methods to separate individual signals and then RF fingerprinting to differentiate between the devices. The mobility of the users can be tracked with one of the methods mentioned previously, and mobility patterns can be generated. Similarly, their behavior during the time period can be tracked as well. What remains is joining this information to predict the spectrum occupancy for the future. However, because these multidomain relationships cannot be easily deduced mathematically, ML or DL methods are commonly used.

2.2.5. Environment fingerprinting

Environment fingerprinting essentially uses sensed information at specific locations to form a look-up or fingerprint table for localization. The advantages and disadvantages of using a single type of measurement for fingerprinting based localization were discussed in the previous sections. However, these measurements can also be used jointly to increase accuracy at the cost of increased dimensions [34].

3. Wireless sensing in WLAN standards

Commercial applications can be considered as the stimulating factors that led to the network level wireless sensing. These factors are the developments in autonomous vehicle technology and its wireless communication requirements, the maturing of mmWave equipment, and interest in non-invasive sensing/monitoring. This prompted efforts from the IEEE Standardization Association, resulting in the formation of wireless sensing friendly amendments to existing WLAN standards. The 802.11p amendment formed the basis for vehicle-to-vehicle (V2V) and vehicle-to-everything (V2X) communication using dedicated short-range communication (DSRC) [35], propelling research into 802.11p based radar for obstacle detection in autonomous vehicles as an alternative to expensive Light Detection and Ranging (LiDAR) and computationally taxing computer vision based techniques. The overcrowding of lower frequency spectrum and higher data rate demands prompted research into mmWave frequencies, resulting in the 802.11ad/aj/ay standard amendments [36]. The development of these standards, and associated devices, motivated research into finer resolution wireless sensing, adding sensing via beamforming and sensing for beam management to the wireless sensing landscape. Additionally, the dependency of beamforming on user location, as well as the fact that the channel is somewhat dependent on the location, necessitated finer resolution relative positioning and tracking. This produced the 802.11az standard amendment to the MAC and PHY [37]. The overview of these standards is given in Table 1.

In recent years, noninvasive wireless sensing has been an area of interest, both due to privacy concerns and the availability of WLAN devices in nearly all areas of human life. Applications supported by wireless sensing range from health monitoring to elderly care to enabling smart environments [17]. As a result, and because of the tendency of the previous amendments to being used for wireless sensing, IEEE formed a Topic Interest Group (TIG) to discuss the possibility of incorporating sensing in WLAN networks. The TIG met for the first time during the November 2019 plenary session, and was then converted to a Study Group (SG), ultimately forming the 802.11 TGbf–WLAN sensing group after acceptance of the project authorization request

Table 1. Summary of WLAN amendments commonly used in the wireless sensing literature.

WLAN amendment	Frequency band	Status	Objective	Measurements
802.11p [35]	5.9 GHz	Completed (2004–2010)	DSRC for intelligent transport systems	Delay, frequency offset, AoA, CFR
802.11ad/aj/ay [36]	Above 45 GHz	Ongoing (2015–2021)	Ultrawide band communciations for mmWave multiple-input multiple-output (MIMO) systems	CFR, RSSI/RSS, CIR, SNR
802.11az [37]	2.4/5/60 GHz	Ongoing (2015–2022)	Timing based localization, positioning, and tracking	ToA, ToF

(PAR) in September 2020. The complete timeline for this amendment with the intermediate stages is shown in Figure 2 [38]. The remainder of this section describes the expectations from the IEEE 802.11 TGbf in terms of targeted amendments to the MAC and PHY protocols for sensing enhancements. It should be noted that this standard is built to support the sensing applications using WLANs, where the foremost purpose is to carry out reliable communication. Therefore, the standard only discusses enhancements, such as the ones highlighted below, that can help improve the sensing performance without (significantly) affecting the communication.

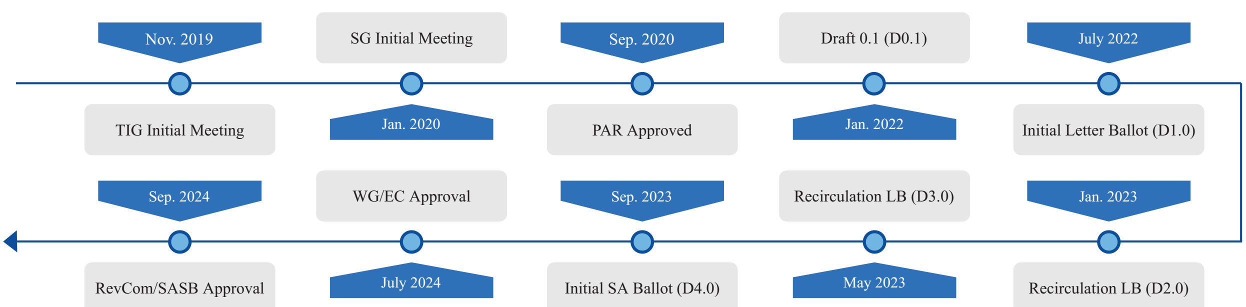

Figure 2. The proposed timeline of IEEE 802.11 TGbf.

3.1. Requirements related to MAC layer

MAC layer is responsible for the advertisement of the sensing capabilities and roles of different devices. This includes aspects such as identification of the initiator/responder, supported measurement rate and resolution, and resources available for sensing [39].

The standard, therefore, needs to develop mechanisms for assigning and advertising the sensing roles. These roles depend upon the nature of transmissions used, which can either be passive, i.e. using the ongoing WLAN transmissions, or triggered especially for sensing purpose. The decision mechanism for selecting the specific nodes, either stations (STAs) or access point (AP), that should be involved in a specific measurement also has to be defined taking into consideration the (sensing) capabilities of the said node. These capabilities also need to be shared between the devices before the sensing measurements commence. While a possible approach may be to associate the device's MAC address with its capabilities, it should be kept in mind that reassociation and the consequent change of MAC address can occur for long-lasting applications such as home or health monitoring. In such a case, an improved reassociation mechanism is needed for reliable sensing performance.

3.2. Requirements related to PHY

In terms of sensing, the basic role of PHY is to enable measurements that can help gain information related to the environment. The specific measurements are defined by the particular PHY design being used out of direct sequence spread spectrum (DSSS), OFDM, and directional multigigabit (DMG). The latter two, in particular, make use of the preambles to estimate the channel characteristics for sensing purposes. An important point to note here is the difference in available bandwidth for different PHY designs. For instance, 802.11a offered 20 MHz while the upcoming 802.11be, also referred to as wireless fidelity (Wi-Fi)-7, promises bandwidths of up to 320 MHz. Similarly, despite the limited range, 802.11ad/ay provide high resolution for sensing due to the wide bandwidth availability in the 60 GHz bands. Table 2 summarizes PHY properties of the different WLAN amendments as a reference [40, 41].

Table 2. Summary of WLAN amendments from the PHY perspective.

WLAN standard	Frequency band	PHY design	Bandwidth	Range (indoor | outdoor)
802.11–1997	2.4 GHz	DSSS/FHSS	22 MHz	20 m | 100 m
802.11a	5 GHz	OFDM	20 MHz	35 m | 120 m
802.11b	2.4 GHz	DSSS	22 MHz	35 m | 140 m
802.11g	2.4 GHz	OFDM	20 MHz	38 m | 140 m
802.11n	2.4/5 GHz	OFDM	20/40 MHz	70 m | 250 m
802.11ac	2.4/5 GHz	OFDM	20/40/80/160 MHz	35 m | -
802.11ax	2.4/5 GHz	OFDM	20/40/80/160 MHz	30 m | 120 m
802.11be	2.4/5/6 GHz	OFDM	20/40/80/160/320 MHz	-
802.11ad	60 GHz	OFDM, single carrier	160 MHz	3.3 m | -
802.11ay	60 GHz	OFDM, single carrier	8000 MHz	10 m | 100 m

Since sensing applications rely on the variation of channel-dependent measurements to gain awareness, it is imperative to ensure that the observed variation is due to the channel and not the device or the PHY signal being transmitted/received. From the standardization perspective, mechanisms to ensure the stable device/PHY configuration and/or remove the effect of changing device configuration are needed.

3.3. Requirements related to measurements

As mentioned earlier, measurements related to the PHY signal such as CSI have been extensively used for WLAN sensing applications such as intrusion detection, indoor localization and tracking, vital signs monitoring, gesture recognition, and user identification [42]. While these, and other works in the literature, demonstrate the effectiveness of CSI-based sensing for various human-centric applications, the standard itself does not provide inherent support for this information to be available for the users [43].

Contributions to the SG/TG have identified issues regarding the difference in requirements related to channel measurements for: i) sensing vs communication, and ii) sensing for different tasks [44]. The TG is also interested in determining the best domain/dimension out of time, frequency, and space for channel reporting. It is also possible to consider multiple domains simultaneously, depending on the specific application. Furthermore, another challenge is determining or quantifying the quality of channel measurements for sensing in terms of consistency, accuracy, and precision [43]. One thing, however, that needs to be kept in mind is that these measurements have been defined from the communication perspective. Therefore, among other things, sensing-centric measurements need to be developed under the standard's umbrella.

4. Current standardization activities of 802.11 TGbf

This section provides an overview of the discussion that has taken place in the TG till now. The different topics ranging from basic definitions and use cases to functional requirements and evaluation methodologies have been categorized, organized, and described to enable easier understanding of the readers. This categorization and the related discussions are summarized in Table 3.

Table 3. Summary of 802.11bf task group discussions.

Discussion topic	References
Sensing definitions and procedures	[45–48]
Channel usage and models	[49–52]
Selected use cases	[53–57]
Sensing sequence design and performance	[58–60]
Evaluation and simulation methodology	[61, 62]

4.1. Basic definitions and sensing procedure

Multiple contributions in the TG have covered the general sensing procedure [45, 46]. While specific details may vary in different contributions, the procedure is primarily divided into setup, negotiation, sensing and tear down stages. Setup refers to the advertisement of device capabilities, negotiation stage assigns different sensing roles, sensing refers to the actual transmission and measurement stage, while tear down concludes the sensing session. Here, the capabilities of a device may refer to the PHY designs supported and the measurement/sensing rates it can achieve. As far as the role assignment is concerned, there are two categorizations, namely, initiating/responding and transmitting/receiving [47, 48]. The first categorization concerns the setup stage, where the initiator is the STA that requests/needs the measurements and therefore, initiates the sensing session. Correspondingly, the responders are the STAs that participate in the said sensing session. The second categorization is according to the roles in terms of the sensing packet or physical layer protocol data unit (PPDU) transmission. The STA sending the packet is the sensing transmitter, while the STA to which the packet is being sent is referred to as the sensing receiver. In a sensing session, there is a single initiator and one or more responders, transmitters, and receivers.

4.2. Channel and usage models

The current standard and its underlying channel estimation/measurement mechanisms have been developed for communication rather than sensing. The former relies on channel information to mitigate its effect on the traversing signal. As such, the focus is on finding the simplest representation that can help recover the original message at the receiver. In sensing, however, the idea is to extract as much information regarding the channel as possible. Here, the goal is to maximize the resolution such that minute changes in the environment can be observed and utilized for sensing tasks. Accordingly, one point of discussion raised in the TG has been regarding the need for sensing-centric channel models [49]. Different options for developing these models have been discussed in [50], where the basic idea is to either do ray tracing for each scenario, try to fit the target scenario to existing models, or develop and utilize a database of the obtained traces. Since 802.11 TGbf considers two vastly different bands, i.e. sub 7 GHz and 60 GHz, the models should consider the particular band to be used, and the deployment scenario. These factors form part of the usage model along with the use case or sensing task, and its associated performance metrics/requirements [51]. The various usage models for WLAN sensing are categorized under room sensing, gesture recognition, healthcare, 3D vision, and in-car usage [52]. Some selected use cases under these usage models are described next.

4.3. Selected use cases

WLAN sensing has gained increasing popularity due to its license-exempt operation, off-the-shelf device availability, and ubiquitous connectivity. Accordingly, 802.11 TGbf has targeted a plethora of use cases ranging from relatively typical ones such as localization [53], proximity detection [54] and gesture recognition [55] to more evolved ones such as in-car sensing [56] and high-resolution imaging [57]. The latter is required for cases where discrimination is needed between similar objects. For instance, trying to monitor the vital signs of a specific individual amongst a crowd presents a challenging scenario that cannot be addressed by ordinary sensing methods. The standard, therefore, needs to enable the flexible use of different signals (waveforms) and a large number of antennas to improve the sensing resolution.

4.4. Sensing signal (sequence) design and performance

As mentioned earlier, drastic changes in PHY designs are impractical from the standard's perspective. Therefore, rather than going for some novel waveform designs, sequences such as Golay complementary codes have been borrowed from 802.11ad and 802.11ay and their performance analyzed for sensing [58]. These sequences provide the advantage of allowing the reuse of the same hardware as the preceding standards. The comparison of ambiguity function and range-Doppler map for evaluation of sensing sequence is provided in [59], where the former is proposed for fundamental analysis of the waveform while the latter is argued to be better suited to sensing performance evaluation. The impact of frequency bands, available bandwidth, and corresponding range resolution of frequency modulated continuous wave (FMCW) radar for different use cases is provided in [60]. It was shown that the sub-6GHz band provides sufficient accuracy for most tasks, but short-range gesture recognition tasks like finger movement might require the use of mmWave bands.

4.5. Evaluation and simulation methodology

All standards define a method to evaluate the performance of the new and/or modified features. In a typical wireless standard, this involves defining a system or link level simulation setup encompassing parameters such as channel models, hardware impairments and their impact, traffic models, deployment scenarios, and the different use cases [61]. This provides a baseline for performance comparison of different algorithms. Since 802.11 TGbf is expected to be supported on the same frequency bands and hardware devices as some of the other amendments, it can borrow existing models for communication from these standards. However, as for the sensing aspect of 802.11 TGbf, two approaches have been proposed. The evaluation methodology can either include some basic sensing methods/algorithms as part of the baseline model which can be used for performance analysis, or the methods can be left to the specific implementation [62]. At present, the TG lacks consensus regarding this issue, but eventually this issue will have to be addressed in the standard.

5. Challenges and future directions

In this section, anticipated challenges and future perspectives on the current WLAN sensing proposals are discussed, and summarized in Figure 3. Mainly, the importance of reliable WLAN sensing mechanisms, secure transfer of critical information, coexistence with classical communication, and an operation following regulatory restrictions is highlighted.

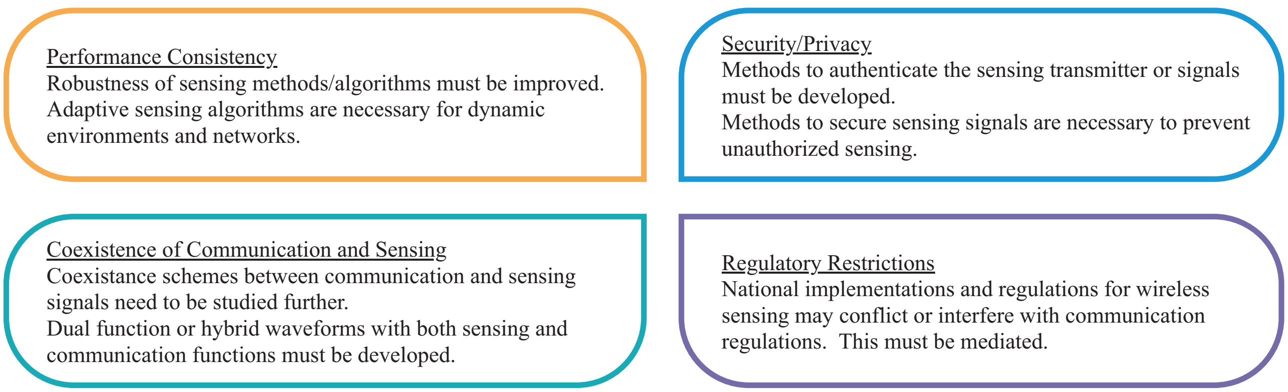

Figure 3. Summary of challenges and future directions for wireless sensing and the 802.11bf standard amendment.

5.1. Performance consistency

The performance of sensing devices is significantly impacted by the system design and environment of the operation. Since sensing applications rely on models, mathematical or learned, they suffer when the data or environment is altered. This can be due to changes in transceiver positions or modification of the surrounding objects. Therefore, it is important to i) improve the robustness of current methods, ii) develop algorithms that can instantaneously self-adapt to changes in the environment [63]. However, the power and computational limitations of the typical transceiver presents a challenging constraint. A possible solution around this could be designing multidomain sensing mechanisms to track rapid changes in the environment with respect to the preset scenarios. For example, the Doppler spectrum can be useful for tracking the environment or the variation of the angle of arrival for the incoming signal [64]. Additionally, various waveforms, modulation options, transmission protocols can be investigated to ensure a balance between sensing accuracy and application demands.

5.2. Security/privacy

The broadcast nature of wireless signals renders them vulnerable to various security threats. For instance, a malicious node can acquire the identity of a sensing transmitter and share misleading information, leading to incorrect sensing. There needs to be a method to authenticate the identity of the transmitter. While this is relatively easy when the receiver and transmitter are part of the same basic service set (BSS), some mechanisms might be needed to share the authentication in neighboring BSSs. Here, it might be possible to consider multi-AP coordination feature, currently under discussion in 802.11be. Another crucial aspect of sensing security is the protection of a user/node's information from being sensed by a malicious node. Attackers can use this information to compromise the integrity of the sensing process, leading to wastage or exploitation of the legitimate users' resources. These threats highlight the need of adapting security mechanisms from the domains of physical layer security (PLS), radar, and ML that can ensure a user's privacy and the sensing process's authenticity [65].

5.3. Coexistence of communication and sensing

The hardware limitations, power constraints, and spectrum scarcity necessitate the coexistence of classical communication and sensing functionalities in the same system. There are three basic approaches to this: cohabitation, cooperation, and codesign. In cohabitation, communication and sensing signals operate over the same radio resources, resulting in cochannel interference, which limits the desired signal-to-interference noise ratio. An appropriate selection of waveform features and single/multiapplication interference cancellation receiver designs are needed to satisfy system demands. In cooperative systems, signal characteristics should be considered along with the development of novel resource assignment methods, i.e., persistent... semipersistent, and competition-free protocols. Of the three, codesign is arguably the most interesting as it promotes the design of new waveforms with both functionalities, i.e., modifying a communication waveform to have sensing properties and vice versa [66]. Similarly, a multidimensional waveform can be utilized for conveying both data and multidomain feature sensing. Due to the exponential increase in transceiver complexity, processing time and power consummation with the increase of the number of signal domains, the choice of the emitted signal becomes critical [67].

5.4. Regulatory restrictions

Wireless networks are subject to various regulations regarding power levels, spectrum utilization, and supported waveforms by institutions such as Federal Communications Commission (FCC) and its regional counterparts. Interestingly, these regulations vary significantly between communication and sensing applications, particularly in terms of allowed transmitted power. As such, this presents a challenge to 802.11 TGbf which, although, primarily uses communication signals for sensing purposes, but might require dedicated sensing transmissions when communication transmissions are absent or insufficient. Another example of the nonhomogeneity between regional regulations is the mandatory support of FMCW in 60GHz band in Japan [68]. This means either the standard has to allow the flexibility to use chirp waveform in this band or avoid its usage, at least in Japan.

6. Conclusion

The diversity of applications envisaged for sixth generation (6G) networks accentuates that realizing ubiquitous wireless sensing is a must to move beyond previous generations. As such, this paper has reviewed the most common wireless sensing methods under their relative domains, and provided examples to further solidify the standing of wireless sensing within communication technologies. Wireless sensing utilizing WLAN devices has captured the attention of industry and academia, resulting in ongoing standardization efforts. This, and the accessibility of WLAN devices, makes WLAN networks prime candidates for implementing the challenging task of ubiquitous sensing on a network-level. Consequently, the standardization progress, expectations, and challenges were reviewed to give a fundamental idea of the direction of near-future technologies, as well as possible research areas. However, since the use cases in WLAN sensing are mostly catered towards noncommunication related commercial applications, there is a possibility that wireless sensing may be constrained to sensing the physical environment only, turning a blind eye to other measurements or things that can be sensed.

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Contribution of authors

H.A. gave the idea of the paper, H.T. contributed the overview of REM/wireless sensing and its need for future wireless networks. M.S.J.S. reviewed the current standardization status, while A.T. contributed the future directions.

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