Enablers for Efficient Wi-Fi Sensing

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***Abstract*—Wireless fidelity (Wi-Fi) technology gained popularity due to its ability to provide reliable connectivity, enabling high-speed communication and information sharing. However, in recent years, the focus has shifted from mere communications to sensing and awareness of the environment that can be attained using the same communication signals. Along with this line, there are wide varieties of promising sensing applications, such as crowd counting, person tracking, and sick person detection. However, different sensing applications require different performance and quality of service metrics, so it is difficult to enable all of these applications simultaneously. In this paper, we highlight the importance of the usage of flexible and adaptable Wi-Fi sensing parameters for different applications, environments, and scenarios. Afterward, we introduce our perspective for efficient Wi-Fi sensing through a framework. The first aspect of this framework is about flexible and adaptable transmission design. The second one is about identifying sensing applications according to frame design. In the last aspect of the framework, multi-access point coordination is highlighted in different scenarios of Wi-Fi sensing.**

***Index Terms*—Adaptable parameters, flexible transmission design, multi-AP coordination, sensing application identification, Wi-Fi sensing.**

I. INTRODUCTION

Wireless sensing and integrated sensing and communication (ISAC) systems are envisioned as a second functionality for future generation networks [1]. As such, the Institute of Electric and Electrical Engineering Standards Association (IEEE-SA) for wide local area networks (WLAN), the 802.11, has formed a task group (TG), TGbf - WLAN Sensing [2], to standardize wireless sensing Wi-Fi networks [2], which has already released its first, albeit tentative, draft. Similarly, the 3rd Generation Partnership Project (3GPP) has listed ISAC as a study item for Release 19 and is documenting their progress in the technical report, TR 22.837: Study on ISAC [3]. With standardization momentum, commercial implementations of wireless sensing are expected to increase in the coming years. However, there are still some open issues. For example, the variety of the sensing implementations, their performance requirements, wireless device capabilities, and physical as well as radio environment conditions render it difficult to unite and standardize under a single scheme.

Currently, the academic literature focuses on the co-existence, co-habitation, and co-design of the ISAC systems. Co-existence refers to sharing the time and frequency resources without interference or signal degradation. Co-habitation is when a device can perform both sensing and communication, i.e., it can transmit, receive, and process both communication and sensing signals. Co-design usually refers to designs that jointly utilize resources, such as designing a waveform or frame capable of meeting both the communication and sensing performance requirements [4]. Of these, co-design may seem to be the most desirable, but communication and sensing performance requirements and associated parameters are generally conflicting. Co-existence may be more feasible, but the increasing number of sensing devices and transmissions may significantly increase network traffic, reducing the channel access opportunities for communicating devices. Another issue is that the environment variation, mobility of the sensed object, mobility of the sensing devices, and spectrum conditions may require flexible systems to maintain the sensing performance.

To this end, this paper aims to introduce a framework, which will be integral for adaptive and robust wireless sensing, allowing decreased false alarm rates and efficient spectrum utilization in dynamic environments. In the remainder of this section, an overview of the Wi-Fi sensing developments is given. Then, the framework is summarized. Section II motivates our perspective in the wireless communication standards and highlights the importance of flexibility and adaptability in Wi-Fi sensing with the aid of a generic scenario. Section III discusses the introduced framework in depth. The paper is concluded in Section IV.

A. Overview of Wi-Fi Sensing Developments

Sensing using Wi-Fi signals was first realized in 2013 [5]. The aim was to provide a low-cost, non-invasive method for human detection and communication through gesture recognition, which could also be used commercially. Since then, numerous works have been published [6], focusing on applications such as crowd counting, person tracking, sick person detection, and much more. What enabled and motivated these publications were perhaps Intel's channel state information (CSI) tool for the 802.11n, or Wi-Fi 5, standard [7], made available in 2010. This is because obtaining CSI information beforehand was extremely difficult, and most wireless sensing implementations were designed from scratch, limiting the availability to the general public and researchers. The trials and successes of Wi-Fi sensing merited economic value and potential, and thus the IEEE-SA formed a study group to investigate Wi-Fi sensing from a standardization perspective in

2019. This group investigated popular sensing applications and their requirements in terms of sensing performance, such as the probability of false alarms and various measurement resolutions. Consequently, the 802.11bf TG was formed to improve the quality of sensing through the design of various protocols and make it easier for developers to access a variety of wireless measurements. The 802.11bf TG aims to incorporate wireless sensing into the Wi-Fi standards with appropriate, minimal alterations to the physical (PHY) and medium access control (MAC) layers. To this end, they have defined the phases of a sensing session, procedures for devices operating in different frequencies and with different capabilities, measurement types, and formats, and more, which can be found in [8].

B. Adaptive Wi-Fi Sensing Framework

As mentioned before, integrating the plethora of wireless sensing applications to present communication frameworks is challenging. Although great effort is made by the TGbf and there are several existing surveys in the literature [8]–[15], it is still difficult to enable a wide variety of sensing applications. Along with this line, this paper proposes a framework for the efficient use of Wi-Fi sensing with the following aspects:

- *Adaptive parameter selection*: Different sensing applications may require different performance and quality of service (QoS) metrics. This, in turn, requires different transmission parameters and/or frame design. Changing channel and environment conditions also greatly affect the performance of sensing. Therefore, a single framework containing different frame designs and transmission mechanisms for the selection of an appropriate frame design and transmission mechanism is introduced.
- *Sensing application identification*: There is a relationship between the sensing applications and frame design parameters. For example, applications requiring distance precision can be satisfied with a larger bandwidth signal. Therefore, applications can be identified based on the parameters used. If the sensing application is known, other devices can schedule their transmissions accordingly without interfering with the other sensing or communication signals, or can utilize the present sensing transmissions for their own sensing applications. Thereby, the spectrum, power, and other resources can be used efficiently. A generalized framework is introduced to enable this.
- *Multi-AP coordination*: Multi-AP coordination is a recent topic of discussion for the upcoming Wi-Fi standards. The aim is to reduce collisions and improve throughput with minimal interaction of neighboring APs. At the same time, collaboration between devices in sensing has been shown to improve detection performance [16]. To this end, the scenarios, benefits, and approaches to collaboration should be investigated. The third aspect aims to initiate this by providing a first sketch of what collaborating networks for sensing could look like.

II. MOTIVATION

A. Motivation From Wireless Communication Standards

1) Motivation for adaptive parameter selection: Flexibility and adaptivity have been desired since the beginning of wireless communication systems. For example, flexible signaling with link adaptation techniques (adaptive modulation and coding and power control) has been aimed in the second-generation (2G) standardization of wireless cellular systems [17]–[19]. Besides that, in long-term evolution-advanced, depending on the cell size, orthogonal frequency division multiplexing (OFDM) symbols are designed with either normal cyclic prefix (CP) or extended CP [20]. Also, to support a wide variety of communication applications, waveform flexibility is extended to additional parameters' flexibility, such as subcarrier spacing [21], [22] in the 5G standardization of new radio (NR), where depending on the channel conditions and the communication service required, the suitable numerology is selected. Therefore, flexibility and adaptivity are essential for wireless communication systems. Similarly, Wi-Fi sensing parameters can be adaptively and flexibly changed to support various applications and channel conditions in future standards.

2) Motivation for sensing application identification: In future standards, some parameters or requirements can be mapped to applications, or each sensing application can require respective minimum performance requirements for a sensing signal to perform its sensing tasks. The preliminary of this idea is already made in 3GPP. For example, there are three classes, namely enhanced mobile broadband (eMBB), massive machine type communications (mMTC), and ultra-reliable low latency communications (URLLC), for fifth-generation (5G) communication systems. This can be considered a step for categorization. Accordingly, sensing parameters and applications can be categorized, or some ranges of parameters for some applications can be defined. In Table I, based on [23], we categorize some Wi-Fi sensing requirements; network load, range separability, angular separability, and maximum range/distance to applications. Based on the categorization, sensing signals can be identified and used by different sensing receivers for their own applications if suitable. However, there are also limitations to doing these categorizations in standards. For example, new applications/use cases can be defined after the standardization process, and assigning parameters for this new application may be difficult. Besides that, in some cases, the wireless devices are mobile, or the environment changes rapidly. These cases can also affect the parameter selections.

3) Motivation for Multi-AP coordination: Coordination is desired in several wireless communication networks. For example, coordinated multi-points are considered in long-term evolution to improve cell edge user data rate and spectral efficiency [24]. Also, IEEE 802.11be discusses multi-AP coordination to use the network resources more optimally [25]. Similarly, multi-AP coordination concept can be considered for Wi-Fi sensing applications.

TABLE I
WI-FI SENSING APPLICATION REQUIREMENTS.

	Values	Applications
Network load (%)	≤2	Presence detection, human counting, localization, motion detection, proximity detection
	≤5	Detection of humans in car, gesture recognition (finger + hand), human counting, localization, speed detection
	≤10	Intruder detection, gesture detection (body), aliveness detection, face/body recognition, fall detection, sneeze detection, driver sleepiness detection, heart rate, breathing rate measurements, person localization and tracking
Range separability (m)	≤0.1	3D vision
	≤0.5	Presence detection, human counting, human tracking, breathing rate, heart rate detection, sneeze sensing, fall detection, detection of human in car
	≤1	Person tracking, motion/gesture detection
	≤2	Proximity detection
Angular separability (°)	≤3	3D vision
	3-4	Presence detection, human counting, localization, detection of humans in car
	5-6	Sneeze detection
Maximum range/distance (m)	≤1	Gesture recognition (finger movement), aliveness detection, face/body recognition, proximity detection
	≤5	Gesture recognition (hand movement), human detection in car, driver sleepiness detection, breathing rate, heart rate measurement
	≤10	Presence detection (home security), human counting (meeting room), human localization, motion detection, human tracking, gesture recognition (full body movement), fall detection, sneeze detection, 3D vision
	>10	Presence detection (number of persons in room, store sensing), human counting (store sensing)

B. Motivating Example

Figure 1 illustrates an exemplary home environment containing wireless devices, i.e., two access points (APs), three devices communicating over Wi-Fi (STA1, STA2, STA3), one wireless sensing transmitter-receiver pair operating over Wi-Fi, and a stand-alone wireless sensing device consisting of a transmitter-receiver pair. Two different scenarios are given for the different rooms of Fig. 1.

The first scenario involves the stand-alone wireless sensing device and is depicted in the bathroom in Fig. 1. Here, if the device is isolated from the Wi-Fi network, it can adjust frame design and scheduling parameters considering only its own transmission. If the system is not isolated and it does not have the capability of coordinating with other devices, it should adaptively change its frame design and scheduling parameters with changing spectrum conditions. In the case of a sensing device or system serving multiple sensing applications with varying performance requirements, the operation parameters can be selected such that the performance requirement maximum number of applications can be met with minimum transmissions. This can be done by grouping sensing applications with similar performance requirements.

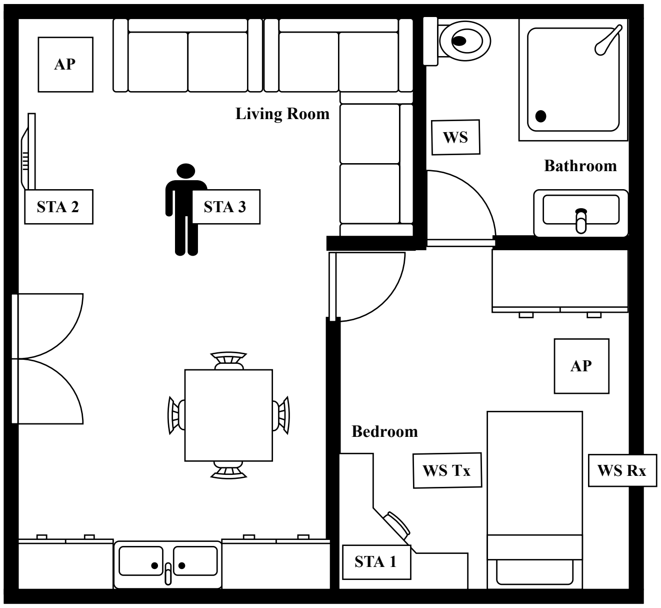


Fig. 1. Example scenarios for in-home sensing and communication.

The second scenario in Fig. 1 is a Wi-Fi network with sensing and communicating devices. This scenario is depicted, e.g., in the bedroom and living room. As before, the sole purpose of the sensing device is to detect an action/object/person/etc., however, the sensing devices are a part of the network and have some level of coordination with the AP. Here, the AP adaptively changes the frame design and scheduling parameters such that the maximum number and type of devices can utilize the sensing signal. Adaptive changes are made by coordinating with multiple APs (coordinating two APs in the figure), so there will be more awareness of the applications, environments, etc., and adaptation can be more reliable.

III. ADAPTIVE WI-FI SENSING

In order to realize the scenarios described in Fig. 1, supporting frameworks should be defined. This section aims to introduce three such frameworks.

A. Adaptable Wi-Fi Sensing Parameters

In the future, there will likely be a wide variety of Wi-Fi sensing applications with different performance and QoS metrics. Each application may require a different frame design and transmission mechanism to work optimally. Thus, a single framework containing different frame designs and transmission mechanisms and the selection of an appropriate frame design and transmission mechanism is desirable. Additionally, these sensing applications will be integrated into communication networks, meaning they should coexist with the current wireless communication devices while maintaining their sensing performance. Changing channel and environment conditions may also greatly affect the performance of sensing [10]. As a result, the framework should include the ability to select sensing parameters adaptively and flexibly based on channel conditions and application requirements.

Some changeable frame and scheduling parameters can be bandwidth, sensing duration, sensing start/end times, periodicity, power, beam width, beam sweep rate, training sequences, carrier frequency, and waveform. The mentioned parameters are explained in detail in the following.

- *Bandwidth*: Wide bandwidth is needed for higher range resolution, which sensing applications such as high-resolution wireless imaging or detecting minute objects and motions require. On the other hand, bandwidth is limited, and we need to use it efficiently.
- *Periodicity*: Applications detecting fast-changing actions/motions/objects require a higher periodicity or packet rate and vice versa. For example, a lower packet rate in radar-based sensing can be a factor that increases the maximum range. On the other hand, the higher the packet rate, the less time the receiver listens for reflections.
- *Power*: The transmission power affects the maximum range for sensing. For example, if the device/motion to be sensed is far away from the receiver, the detection/tracking/sensing performance can be low. Therefore, it may be desirable to have high power as shown in the classical radar range equation, ($\sqrt[4]{\frac{P_t G^2 \lambda^2 \sigma}{P_{min}(4\pi)^3}}$), where P_t, G, λ, σ, and P_{min} represent transmit power, antenna gain, transmit wavelength, target radar cross-section, and minimum detectable signal, respectively. However, if the power is high, it may also create interference and cost unnecessary energy consumption.
- *Beam width and beam sweep rate*: In highly cluttered environments, omnidirectional transmissions of sensing signals result in too many reflections and multipath, which cannot be processed correctly. In these scenarios, some devices use beamforming, where a signal is transmitted in a narrow-beam to reduce the number of multipath and reflections. Here, the beam parameters may need to be adaptively changed based on the clutter and size of the target. For example, the beam width can be affected by the number of antennas [26]. If the beam width is too narrow, the signal may miss or hit the object. Conversely, if the beam width is too large, it may interfere with the beams for other applications or increase multipath. Similarly, the beam should be able to track the object.
- *Training sequence*: Training sequences used in Wi-Fi sensing can affect correlation properties and thus the performance [27]. A certain type or length of the sequence may be a requirement for a sensing application. For example, in Wi-Fi 802.11, short training sequences are used for signal detection, coarse frequency offset estimation and timing synchronization, and diversity selection while long training sequences are used for channel and fine frequency offset estimation.
- *Carrier frequency*: Applications for detecting minute changes in location can be better performed with higher frequencies, such as millimeter waves, thanks to the availability of wider bandwidths. However, sensing in these frequencies results in many peaks for large objects or motions. Therefore, sensing for these applications can be done in lower frequency bands, such as 2.4 GHz or 5 GHz, but there would be less resolution. The selected frequency also affects the Wi-Fi sensing range due to the changing attenuation properties.
- *Waveform*: Currently, orthogonal frequency-division multiplexing (OFDM) is the standard waveform used in Wi-Fi. However, this waveform should be studied in detail to support features and applications of Wi-Fi 7 and beyond in terms of communication and sensing. In the literature, some of its advantages and disadvantages are investigated [28]. Due to the drawbacks of OFDM, such as high peak to average power ratio and its sensitivity to phase noise and frequency offset [29], a different waveform or more than one waveform can be supported by IEEE 802.11 standards. For example, orthogonal time frequency space (OTFS) [30], [31] is mentioned in several documents as a promising waveform for integrated communication and sensing thanks to allowing longer range radar and/or faster target tracking rate by requiring less CP [32]. Also, pulse radar, and frequency modulated continuous wave (FMCW) chirp radar waveforms are highly preferred for radar sensing. In pulse radar, the signal is "on" (or being transmitted) during some time of the total frame time and "off" (not transmitted) the rest of the time. The duration of the signal is "on" or "off" (duty cycle), giving a trade-off between range and range resolution. Longer "on" periods (wider pulse width) provides better range but poor resolution and vice versa. FMCW chirps are continuous (no off time) and can detect relative velocity [33].

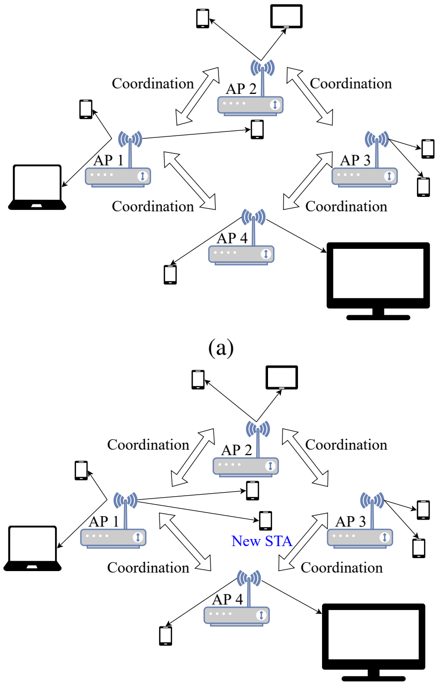
One or more of these parameters can be changed from user to user. Therefore, personal usage style can also be used to have better system performance. For example, the duration of sensing applications such as home monitoring or sleep monitoring may depend on the personal preferences of a user.

B. *Wi-Fi Sensing Application Identification and Prediction*

From the previous section, it is clear that some sensing applications may require specialized transmissions with varying signal parameters. Effectively scheduling and managing these transmissions would result in less spectrum and power wastage. If a device can determine which sensing application is utilizing the spectrum, it can either plan its own transmissions that fall in the empty slots or use signals suitable for its application rather than transmitting its own sensing signals. For example, once an STA detects that an AP is transmitting a sensing signal, it may use the sensing signal in addition to or alternatively to the sensing signal from the other AP, which would start transmission for the STA. It is even possible that the other AP detects the sensing signal from the first AP and stops transmitting its own sensing signal since one sensing signal may be sufficient. Therefore, it would be desirable to provide an approach for sensing application identification and prediction in order to improve resource access and utilization.

Here, we provide a framework to identify sensing applications. The framework includes obtaining a received wireless signal and estimating, by a trained model, the presence of (one or more) sensing signals in the received signal, the sensing signal being a signal generated by a sensing application. The trained model (e.g. a machine learning algorithm) can be implemented by a statistic algorithm or another decision algorithm, e.g., based on conditions distinguishing between the sensing applications based on predefined features (such as periodicity, carrier, bandwidth, and waveform). For example, the periodicity of the sensing signal can be determined based on the presence or absence at a plurality of measurement time instances. This can be performed by capturing the presence/absence detection of the sensing signal within the received signal and then by analyzing the past captured signal. It can also be achieved by correlating the waveform of a specific sensing application with the received signal. If it is observed that a signal is repeating periodically, machine learning methods are not necessary to detect the presence of such a sensing signal. It can be determined deterministically whether sensing is taking place or not. Similarly, identification can be performed for sensing application identification, given a predefined set of features and their values for particular applications. Furthermore, where sensing applications use specific header information for detecting network types, this or other header information can be detected and utilized deterministically to determine the identification of an application.

The detected sensing application can be used to improve spectrum occupancy prediction and its features can be used for scheduling. Meaning, a device that knows the presence (and prediction for future presence in certain resources) of a particular sensing application signal can schedule its data or sensing signal to avoid using the same time and bandwidth, or it can use the sensing signal for its sensing.



(a)

(d)

Fig. 2. An example of multi-AP coordination (a) the first scenario and (b) after a new user is added to the system.

C. *Multi-AP Coordination for Wi-Fi Sensing*

A single AP would not be aware of all of the transmissions, and blind techniques cannot work perfectly to learn existing signals or applications in the environment. To improve network performance, IEEE 802.11 aims to bring multi-AP coordination technology by allowing numerous APs to communicate, coordinate, and serve STAs consistently [25]. This concept can also be applied to Wi-Fi sensing. Thereby, the spectrum, power, and other resources can be used more efficiently.

An example use case of the multi-AP coordination is illustrated in Fig. 2. In this figure, there are two scenarios. In both scenarios, four APs are coordinating their sensing transmissions. Some of the associated STAs (tablets, mobile phones, laptops) have similar requirements for sensing performance, and they are grouped. The grouping can be done based on resolution, maximum or minimum velocity, maximum or minimum range for sensing, detection rate, false alarm rate, and the like by coordinating APs. Here, the requirements are mapped to sensing parameters such as periodicity, bandwidth, frame duration, training and sensing sequences, carrier frequency, and the like.

In Fig. 2 (b), a new STA enters the environment and is associated with first AP, even if it is closer to third AP. This is because the new STA has similar requirements to clients of first AP, so the new STA can use first AP's resources. Also, first AP may support the new STA without generating specific signals to the new STA. To decide whether new signals are to be generated or existing signals to be used, the features of existing sensing signals are compared with the respective requirements of sensing performance for each group. If the predetermined requirements for a group are fulfilled, the information about existing sensing signals is provided to the group of one or more wireless devices. In other words, if the received signals meet the minimum requirements of the sensing application, there may be no need to generate new signals. Instead, the available signals are used. If the predetermined requirements for the group are not fulfilled, existing sensing signals can be adjusted.

IV. CONCLUSIONS

Wi-Fi sensing has a wide variety of promising applications. However, it is difficult to enable all of the applications with a single transmission design. This paper introduced an adaptive transmission design framework for Wi-Fi sensing. In this framework, several adaptable parameters were highlighted based on application, user preference, and environment. These parameters were bandwidth, periodicity, power, beam width, beam sweep rate, training sequence, carrier frequency, and waveform. Still, the framework was not limited to these parameters. Also, we highlighted that in future standards, it may be possible to map certain parameters or parameter ranges to the application, although it has several challenges. Based on these parameters, applications can be identified. Thus, resources can be used more efficiently. In some cases, some applications do not need to generate new signals. Rather identified or predicted applications signals can be used. Furthermore, the importance of multi-AP coordination was highlighted in a scenario. Thus, the Wi-Fi sensing system will be more aware of the environment and devices to use sensing resources more efficiently.

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REFERENCES

[1] F. Liu, Y. Cui, C. Masouros, J. Xu, T. X. Han, Y. C. Eldar, and S. Buzzi, "Integrated sensing and communications: Toward dual-functional wireless networks for 6G and beyond," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 6, pp. 1728–1767, 2022.

[2] "Meeting update," https://www.ieee802.org/11/Reports/tgbf_update.htm, accessed: 2023-07-21.

[3] 3GPP, "Study on Integrated Sensing and Communication," 3rd Generation Partnership Project (3GPP), Tech. Rep. 22.837, 03 2022, version 0.1.0.

[4] S. Mazahir, S. Ahmed, and M.-S. Alouini, "A survey on joint communication-radar systems," *Frontiers Commun. Netw.*, vol. 1, 2021.

[5] F. Adib and D. Katabi, "See through walls with WiFi!" *SIGCOMM Comput. Commun. Rev.*, vol. 43, no. 4, p. 75–86, Aug. 2013. [Online]. Available: 10.1145/2534169.2486039

[6] Y. Ma, G. Zhou, and S. Wang, "WiFi sensing with channel state information: A survey," *ACM Comput. Surv.*, vol. 52, no. 3, jun 2019. [Online]. Available: 10.1145/3310194

[7] D. Halperin, W. Hu, A. Sheth, and D. Wetherall, "Tool release: Gathering 802.11n traces with channel state information," *ACM SIGCOMM CCR*, vol. 41, no. 1, p. 53, Jan. 2011. [Online]. Available: 10.1145/1925861.1925870

[8] R. Du, H. Xie, M. Hu, Y. Xin, S. McCann, M. Montemurro, T. X. Han, J. Xu *et al.*, "An overview on IEEE 802.11bf: WLAN sensing," *arXiv preprint arXiv:2207.04859*, 2022.

[9] H. Jiang, C. Cai, X. Ma, Y. Yang, and J. Liu, "Smart home based on WiFi sensing: A survey," *IEEE Access*, vol. 6, pp. 13 317–13 325, 2018.

[10] Y. Ma, G. Zhou, and S. Wang, "WiFi sensing with channel state information: A survey," *ACM Comput. Surv. (CSUR)*, vol. 52, no. 3, pp. 1–36, 2019.

[11] S. Tan, Y. Ren, J. Yang, and Y. Chen, "Commodity WiFi sensing in 10 years: Status, challenges, and opportunities," *IEEE Internet Things J.*, 2022.

[12] Y. He, Y. Chen, Y. Hu, and B. Zeng, "WiFi vision: Sensing, recognition, and detection with commodity MIMO-OFDM WiFi," *IEEE Internet Things J.*, vol. 7, no. 9, pp. 8296–8317, 2020.

[13] J. Liu, H. Liu, Y. Chen, Y. Wang, and C. Wang, "Wireless sensing for human activity: A survey," *IEEE Commun. Surveys Tuts.*, vol. 22, no. 3, pp. 1629–1645, 2019.

[14] Y. Ge, A. Taha, S. A. Shah, K. Dashtipour, S. Zhu, J. M. Cooper, Q. Abbasi, and M. Imran, "Contactless WiFi sensing and monitoring for future healthcare-emerging trends, challenges and opportunities," *IEEE Reviews Biomedical Eng.*, 2022.

[15] C. Chen, H. Song, Q. Li, F. Meneghello, F. Restuccia, and C. Cordeiro, "Wi-Fi sensing based on IEEE 802.11 bf," *IEEE Commun. Mag.*, vol. 61, no. 1, pp. 121–127, 2022.

[16] N. Bahadori, J. D. Ashdown, and F. Restuccia, "ReWiS: Reliable Wi-Fi sensing through few-shot multi-antenna multi-receiver CSI learning," *CoRR*, vol. abs/2201.00869, 2022. [Online]. Available: https://arxiv.org/abs/2201.00869

[17] J. Wiart, C. Dale, A. V. Bosisio, and A. Le Cornec, "Analysis of the influence of the power control and discontinuous transmission on RF exposure with GSM mobile phones," *IEEE Trans. Electromagn. Compat.*, vol. 42, no. 4, pp. 376–385, 2000.

[18] W. T. Webb and R. Steele, "Variable rate QAM for mobile radio," *IEEE Trans. Commun.*, vol. 43, no. 7, pp. 2223–2230, 1995.

[19] A. J. Goldsmith and S.-G. Chua, "Variable-rate variable-power MQAM for fading channels," *IEEE Trans. Commun.*, vol. 45, no. 10, pp. 1218–1230, 1997.

[20] N. Guo, "Implementation aspects of 3GPP TD-LTE," 2009.

[21] M. Agiwal, A. Roy, and N. Saxena, "Next generation 5G wireless networks: A comprehensive survey," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 3, pp. 1617–1655, 2016.

[22] Z. E. Ankarali, B. Peköz, and H. Arslan, "Flexible radio access beyond 5G: A future projection on waveform, numerology, and frame design principles," *IEEE Access*, vol. 5, pp. 18 295–18 309, 2017.

[23] e. a. Assaf Kasher, "WiFi sensing use cases," IEEE 802.11 Task Group bf, Tech. Rep., 07 2020, https://mentor.ieee.org/802.11/dcn/20/11-20-1712-02-00bf-wifi-sensing-use-cases.xlsx.

[24] R. Irmer, H. Droste, P. Marsch, M. Grieger, G. Fettweis, S. Brueck, H.-P. Mayer, L. Thiele, and V. Jungnickel, "Coordinated multipoint: Concepts, performance, and field trial results," *IEEE Commun. Mag.*, vol. 49, no. 2, pp. 102–111, 2011.

[25] M. Yang and B. Li, "Survey and perspective on extremely high throughput (EHT) WLAN—IEEE 802.11be," *Mobile Netw. Appl.*, vol. 25, no. 5, pp. 1765–1780, 2020.

[26] T. Do-Hong and P. Russer, "Spatial signal processing for wideband beamforming," in *Proc. Int. Symposium Theoretical Electr. Eng. (ISTET)*, 2003, pp. 73–76.

[27] C. K. Lui, "Method of synchronization using IEEE 802.11 a OFDM training structure for indoor wireless applications," Ph.D. dissertation, School of Engineering Science-Simon Fraser University, 2004.

[28] K. Wu, J. A. Zhang, X. Huang, and Y. J. Guo, "Joint communications and sensing employing multi-or single-carrier OFDM communication signals: A tutorial on sensing methods, recent progress and a novel design," *Sensors*, vol. 22, no. 4, p. 1613, 2022.

[29] T. Hwang, C. Yang, G. Wu, S. Li, and G. Y. Li, "OFDM and its wireless applications: A survey," *IEEE Trans. Veh. Technol.*, vol. 58, no. 4, pp. 1673–1694, 2008.

[30] L. Xiao, S. Li, Y. Qian, D. Chen, and T. Jiang, "An overview of OTFS for internet of things: Concepts, benefits and challenges," *IEEE Internet Things J.*, 2021.

[31] K. Wu, J. A. Zhang, X. Huang, and Y. J. Guo, "OTFS-based joint communication and sensing for future industrial IoT," *IEEE Internet Things J.*, 2021.

[32] P. Raviteja, K. T. Phan, Y. Hong, and E. Viterbo, "Orthogonal time frequency space (OTFS) modulation based radar system," in *Proc. IEEE Radar Conf. (RadarConf)*. IEEE, 2019, pp. 1–6.

[33] S. M. S. ED, *Radar Handbook*, 3rd ed. MCGRAW HILL, 2008.