An Introduction to Wi-Fi Sensing and IEEE 802.11bf

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Intro to Wi-Fi sensing

Sensing

- Process of acquiring information about the environment, including objects/targets within it.
  - Enables devices to become aware of their surroundings - including their users.
- Enabled by advances in wireless and computing, sensing has recently been incorporated into multiple platforms, from consumer electronics to vehicular applications.

Lenovo – ThinkPad X1 – Proximity detection (wake on approach, walk away lock)

(UWB)

BMW – Multiple models – Gesture control (new form of UI)

(camera)

Google – Nest Hub (2nd gen) – Sleep tracking and gesture control

(FMCW)

Sensing technologies

- Sensing may be enabled by a variety of technologies, including wireless, camera, ultrasound, sensors…
- Key features of wireless sensing:
  - Privacy preserving (image/video not captured)
  - Does not depend on light; works in dark and low-light environments
  - See through materials (sensor could be hidden behind plastic, for example)
  - Ability to detect fine movement
- In turn, wireless sensing can be implemented with multiple technologies, such as radar (e.g., FMCW), Wi-Fi, UWB, cellular (6G)…
- Each technology has its own characteristics, there is not a one size fits all
  - Signal characteristics, architecture (radio and network), protocol limitations…
  - “Best fit” technology is determined by application and platform constraints

Wi-Fi sensing

- Wi-Fi sensing: Process of acquiring environment/user information through the detection of 802.11 packets.
- 802.11 packets include “training” sequences that are used for channel estimation.
- Feasibility of Wi-Fi sensing has been evaluated and demonstrated over the past two decades.
- Several commercial Wi-Fi sensing solutions are already found in the market.

MIT News

ON CAMPUS AND AROUND THE WORLD

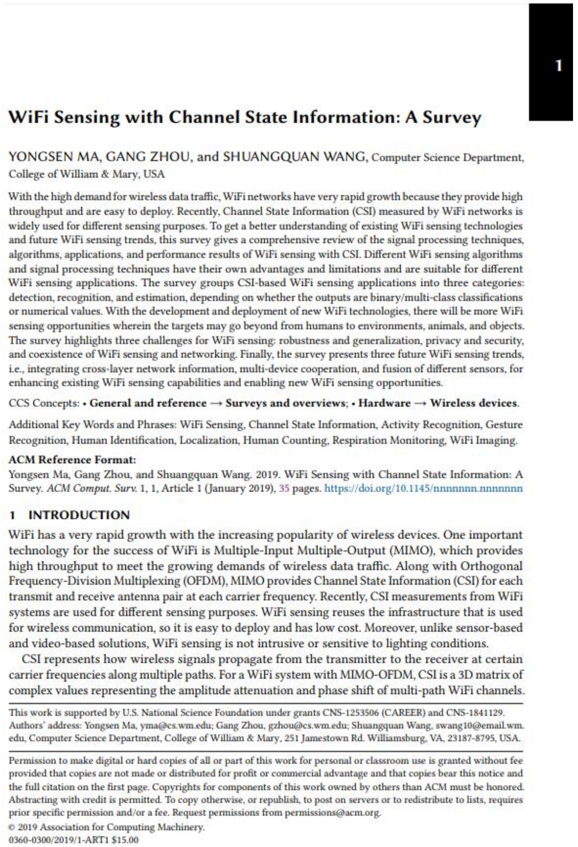
New system uses low-power Wi-Fi signal to track moving humans — even behind walls

‘Wi-Vi’ is based on a concept similar to radar and sonar imaging.

Helen Knight, MIT News correspondent

June 28, 2013

The comic-book hero Superman uses his X-ray vision to spot bad guys lurking behind walls and other objects. Now we could all have X-ray vision, thanks to researchers at MIT's Computer Science and Artificial Intelligence Laboratory.



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WiFi Sensing with Channel State Information: A Survey

YONGSEN MA, GANG ZHOU, and SHUANGQUAN WANG, Computer Science Department, College of William & Mary, USA

With the high demand for wireless data traffic, WiFi networks have very rapid growth because they provide high throughput and are easy to deploy. Recently, Channel State Information (CSI) measured by WiFi networks is widely used for different sensing purposes. To get a better understanding of existing WiFi sensing technologies and future WiFi sensing trends, this survey gives a comprehensive review of the signal processing techniques, algorithms, applications, and performance results of WiFi sensing with CSI. Different WiFi sensing algorithms and signal processing techniques have their own advantages and limitations and are suitable for different WiFi sensing applications. The survey groups CSI-based WiFi sensing applications into three categories: detection, recognition, and estimation, depending on whether the outputs are binary/multi-class classifications or numerical values. With the development and deployment of new WiFi technologies, there will be more WiFi sensing opportunities wherein the targets may go beyond from humans to environments, animals, and objects. The survey highlights three challenges for WiFi sensing: robustness and generalization, privacy and security, and coexistence of WiFi sensing and networking. Finally, the survey presents three future WiFi sensing trends, i.e., integrating cross-layer network information, multi-device cooperation, and fusion of different sensors, for enhancing existing WiFi sensing capabilities and enabling new WiFi sensing opportunities.

CCS Concepts: • **General and reference → Surveys and overviews**; • **Hardware → Wireless devices**.

Additional Key Words and Phrases: WiFi Sensing, Channel State Information, Activity Recognition, Gesture Recognition, Human Identification, Localization, Human Counting, Respiration Monitoring, WiFi Imaging.

ACM Reference Format:
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1 INTRODUCTION

WiFi has a very rapid growth with the increasing popularity of wireless devices. One important technology for the success of WiFi is Multiple-Input Multiple-Output (MIMO), which provides high throughput to meet the growing demands of wireless data traffic. Along with Orthogonal Frequency-Division Multiplexing (OFDM), MIMO provides Channel State Information (CSI) for each transmit and receive antenna pair at each carrier frequency. Recently, CSI measurements from WiFi systems are used for different sensing purposes. WiFi sensing reuses the infrastructure that is used for wireless communication, so it is easy to deploy and has low cost. Moreover, unlike sensor-based and video-based solutions, WiFi sensing is not intrusive or sensitive to lighting conditions.

CSI represents how wireless signals propagate from the transmitter to the receiver at certain carrier frequencies along multiple paths. For a WiFi system with MIMO-OFDM, CSI is a 3D matrix of complex values representing the amplitude attenuation and phase shift of multi-path WiFi channels.

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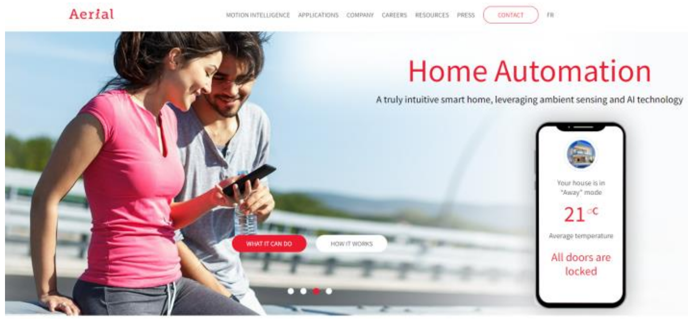
New Wi-Fi sensing solution keeps gentle ‘watchful eye’ on seniors – with Cognitive Systems

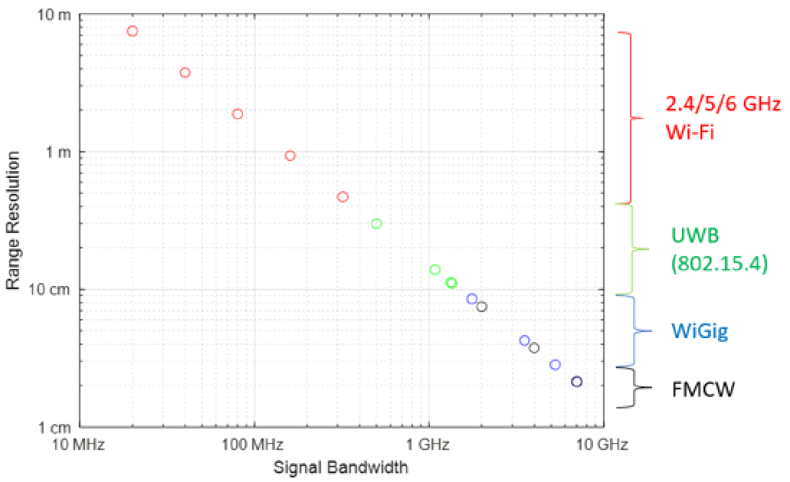
July 24, 2022 | Wi-Fi NOW TV | by Claus Hetting, Wi-Fi NOW CEO & Chairman

The world of Wi-Fi sensing is evolving fast – and leading sensing technology vendor Cognitive Systems is leading the charge when it comes to new use cases. Cognitive's 'Caregiver Aware' solutions lets caregivers – for example children or others – keep a gentle 'watchful eye' on seniors in their homes by analysing disturbances in Wi-Fi signals around the house.

Watch the full interview above – and don't forget: Meet Taj Manku and Cognitive Systems at the Wi-Fi World Congress in Stockholm this September 26-28! *Click here for more information and registration.*



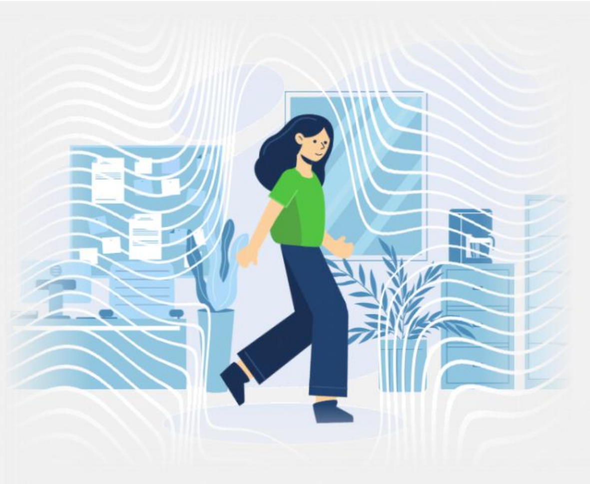
Wi-Fi sensing



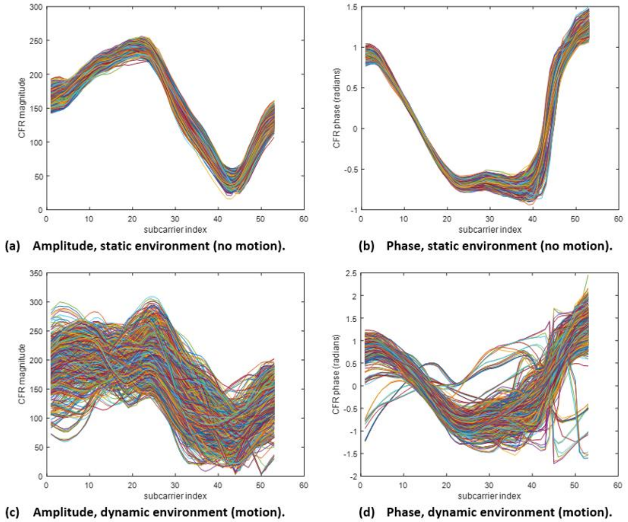
Linksys – Aware – Motion sensing and indoor localization

- The most basic metric of sensing/radar systems is range resolution, which is given by $c/2BW$, where c is the speed of light in vacuum and BW is the signal's bandwidth.
  - Resolution obtained with Wi-Fi is (much) lower than that of other technologies.
- Architecture: Bi/monostatic
  - To be discussed shortly
- Value proposition:
  - Wi-Fi is a relatively low-cost technology that has been widely deployed in various environments of interest, such as in home and enterprise environments.
  - Wi-Fi is a standardized technology that allows for multi-vendor interoperability and supports data communications, ranging, and sensing with a single chipset.
- Wi-Fi sensing resolution can be noticeably improved in certain scenarios by intelligently combining (low-resolution) measurements obtained with multiple spatially diverse devices.

CSI tracking



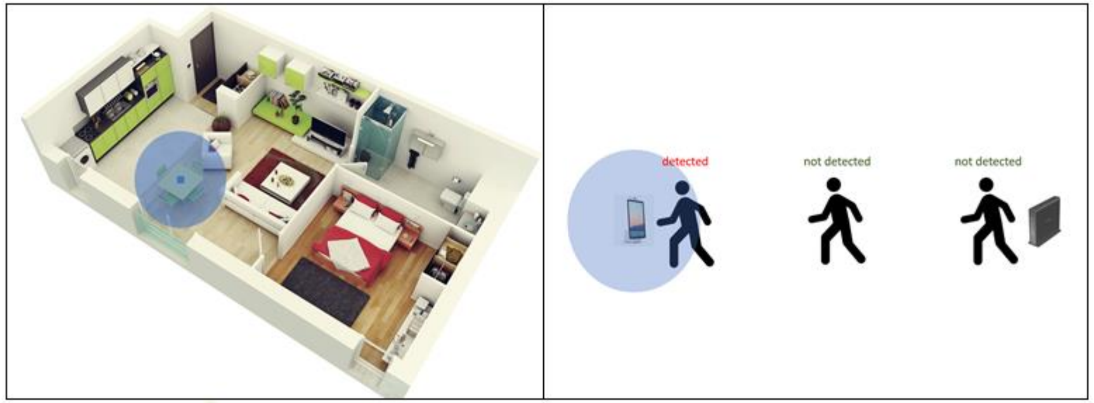
Source: https://www.originwirelessai.com/



Reference: "Wi-Fi sensing: Usages, requirements, technical feasibility and standards gaps," doc. IEEE 802.11-19/1293r0.

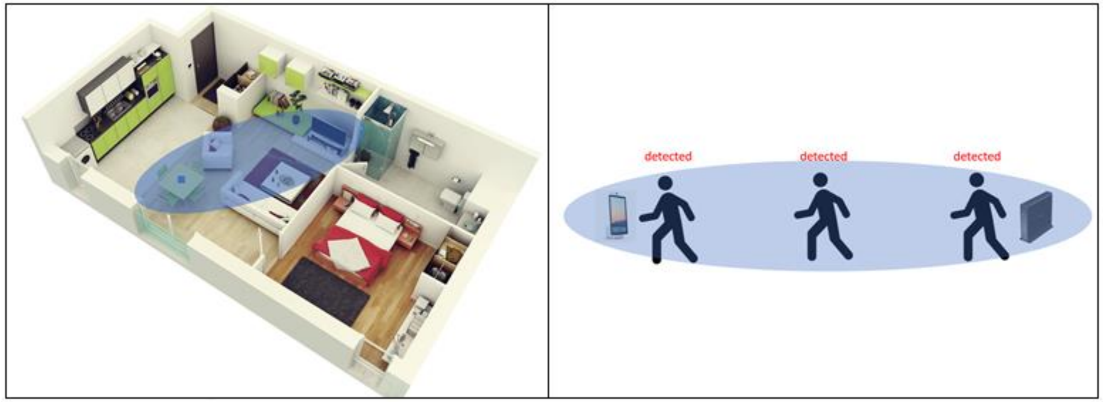
- Sub-7 GHz Wi-Fi sensing applications typically make use of “CSI tracking”.
  - Note: Channel State Information (CSI) is the 802.11 term used, most of the time, to the estimate of the channel (that is, the channel frequency response) between two devices.
- Rationale:
  - As a person or object moves, it impacts how wireless signals propagate in that location. Propagation paths are created and cancelled generating time-varying multipath fading that mirrors changes in the target location.
  - Thus, if the CSI of a given radio link is captured with a certain regularity over time and/or space, it may be possible to identify patterns that may correspond to an event of interest.

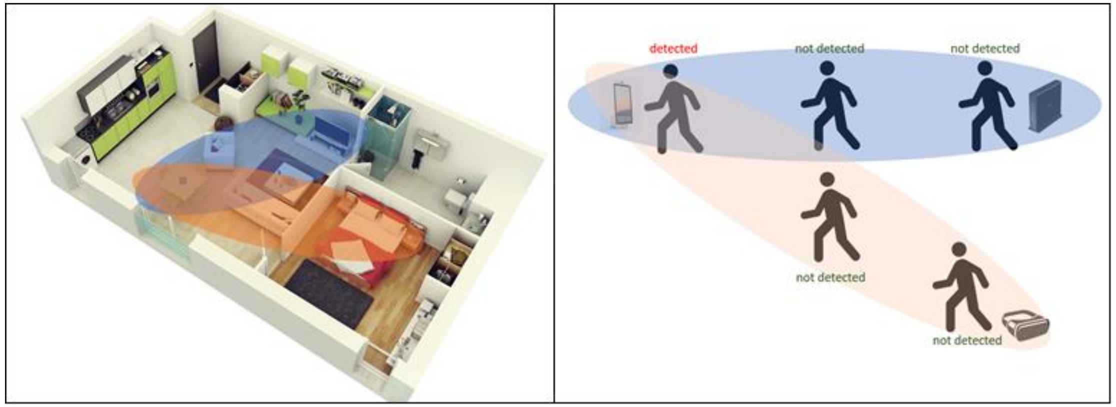
Sensing architectures



Monostatic – Transmitter and receiver of the signal used for sensing are collocated

Bistatic – Transmitter and receiver of the signal used for sensing are different devices





Multistatic – Multiple (spatially diverse) bistatic radar devices with a shared area of coverage

Intro to IEEE 802.11bf

IEEE 802.11bf

- While Wi-Fi sensing has been successfully demonstrated and commercialized for several years, the range of applications that is currently supported is limited because the IEEE 802 standard does not currently define sensing-specific features.
- For this reason, Task Group IEEE 802.11bf was formed in September 2020 to develop an amendment to the IEEE 802.11 standard that will enhance its ability to support WLAN sensing.
- The sensing-specific amendment will:
  - Allow for sensing applications to use devices by multiple vendors
  - Define an interface for sensing applications to request and obtain sensing measurements
  - Lower the overhead associated with obtaining sensing measurements
  - Allow for sensing applications to obtain sensing measurements with greater consistency and control

IEEE P802.11bf™/D0.3, September 2022
(Revision of IEEE P802.11REVme™/D1.1,
as amended by IEEE P802.11be™/D1.5)

IEEE P802.11bf™/D0.3

Draft Standard for Information technology— Telecommunications and information exchange between systems Local and metropolitan area networks— Specific requirements

Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications

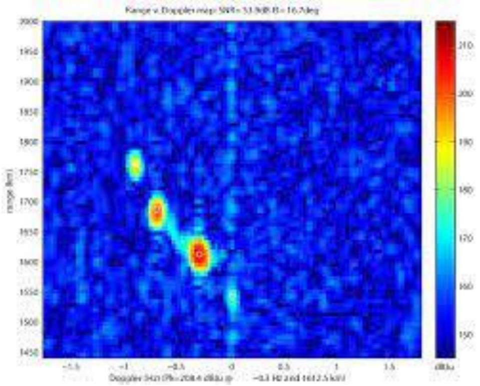
Amendment 2: Enhancements for Wireless LAN Sensing

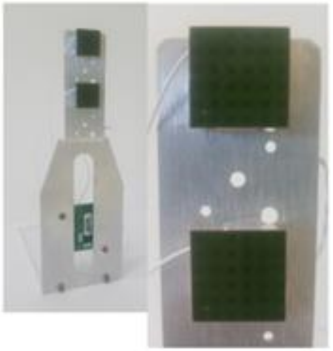
Prepared by the 802.11 Working Group of the

LAN/MAN Standards Committee
of the
IEEE Computer Society

IEEE 802.11bf

- The IEEE 802.11bf task group is developing specification for both (sub-7 GHz) Wi-Fi and 60 GHz Wi-Fi (WiGig).
  - Our focus in today's presentation is the protocol being developed to enhance sub-7 GHz sensing, which is termed WLAN sensing protocol.
  - While the protocol being developed for 60 GHz sensing, termed Directional Multi Gigabit (DMG) sensing protocol, has similarities to the sub-7 GHz one, it also has features/differences needed to support unique characteristics of millimeter-wave channel/hardware/protocol.





Reference: "Wi-Fi sensing in 60 GHz band," doc. IEEE 802.11-19/1551r1.

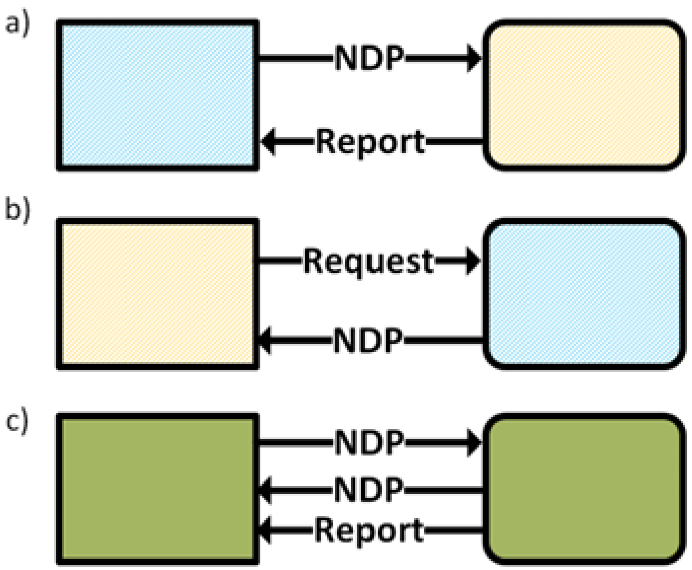
- Algorithms that process and combine channel measurements obtained with a WLAN/DMG sensing procedure and support a sensing application are our-of-scope for IEEE 802.11bf.

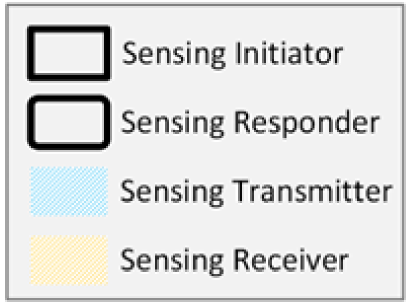
Key IEEE 802.11bf definitions

- Roles – Part 1:
  - Sensing initiator: A station (STA) that initiates a WLAN sensing procedure.
    - STA: Loosely speaking, a “Wi-Fi-enabled device”.
    - Note 1: A sensing initiator can be an AP or a non-AP STA (client).
    - Note 2: Different “flows” are defined depending on whether the sensing initiator is an AP or a client.
  - Sensing responder: A STA that participates in a WLAN sensing procedure initiated by a sensing initiator.
    - Note: Similarly, a sensing responder can be an AP or a client.

- Roles – Part 2:
  - Sensing transmitter: A STA that transmits PPDUs used for sensing measurements in a WLAN sensing procedure.
    - Note: PPDU (PHY protocol data unit) is “(t)he unit of data exchanged between two peer PHY entities to provide the PHY data service”.
    - Note: PPDUs are often referred to as “packets”
  - Sensing receiver: A STA that receives PPDUs sent by a sensing transmitter and performs sensing measurements in a WLAN sensing procedure.

Sensing configurations





- Null data PPDU (NDP) is a PPDU that carries no Data field
  - Already used for measurements (beamforming and ranging) in sub-7 GHz 802.11.
- Reporting is optional. Sensing receiver may send (possibly processed) measurement results as data/payload, or in any other form, to the sensing initiator or to a different entity (e.g., “cloud”).

WLAN sensing procedure

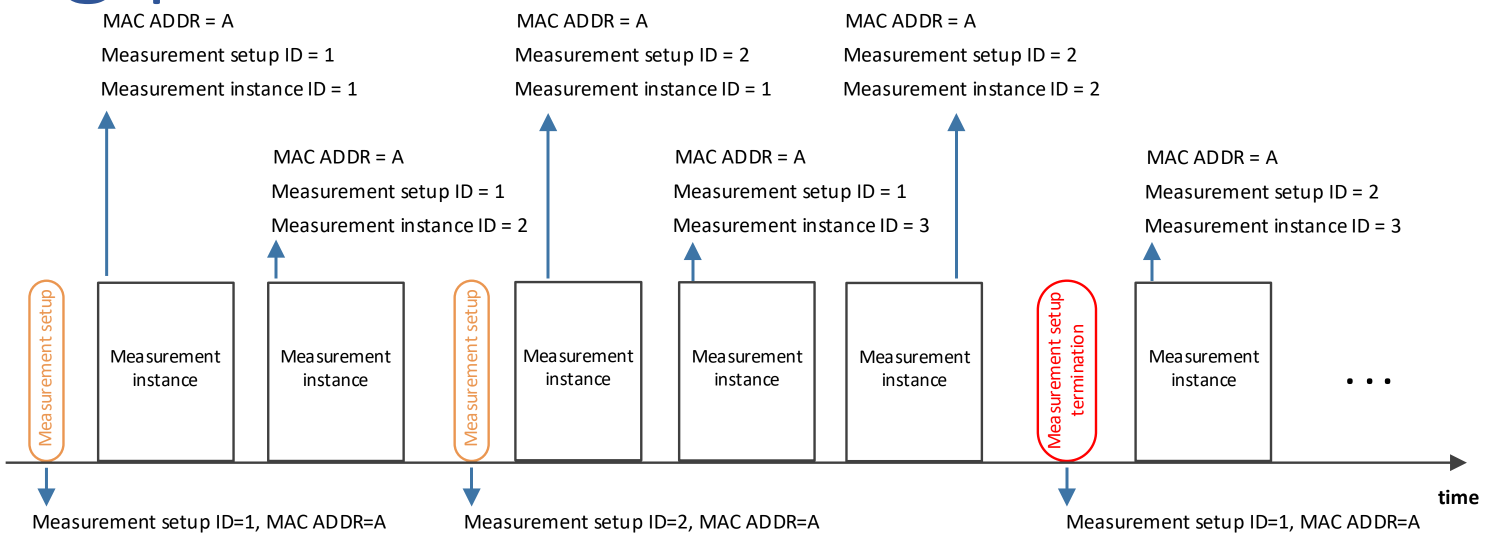
- A WLAN sensing procedure allows a STA to perform WLAN sensing.
  - WLAN sensing: The use of PHY and MAC features of stations to obtain measurements that may be useful to estimate features such as range, velocity, and motion of objects in an area of interest.

- A WLAN sensing procedure is composed of one or more of the following:
  - Sensing session setup
  - Sensing measurement setup
  - Sensing measurement instance(s)
    - This is when sensing measurements are obtained
  - Sensing measurement setup termination
  - Sensing session termination

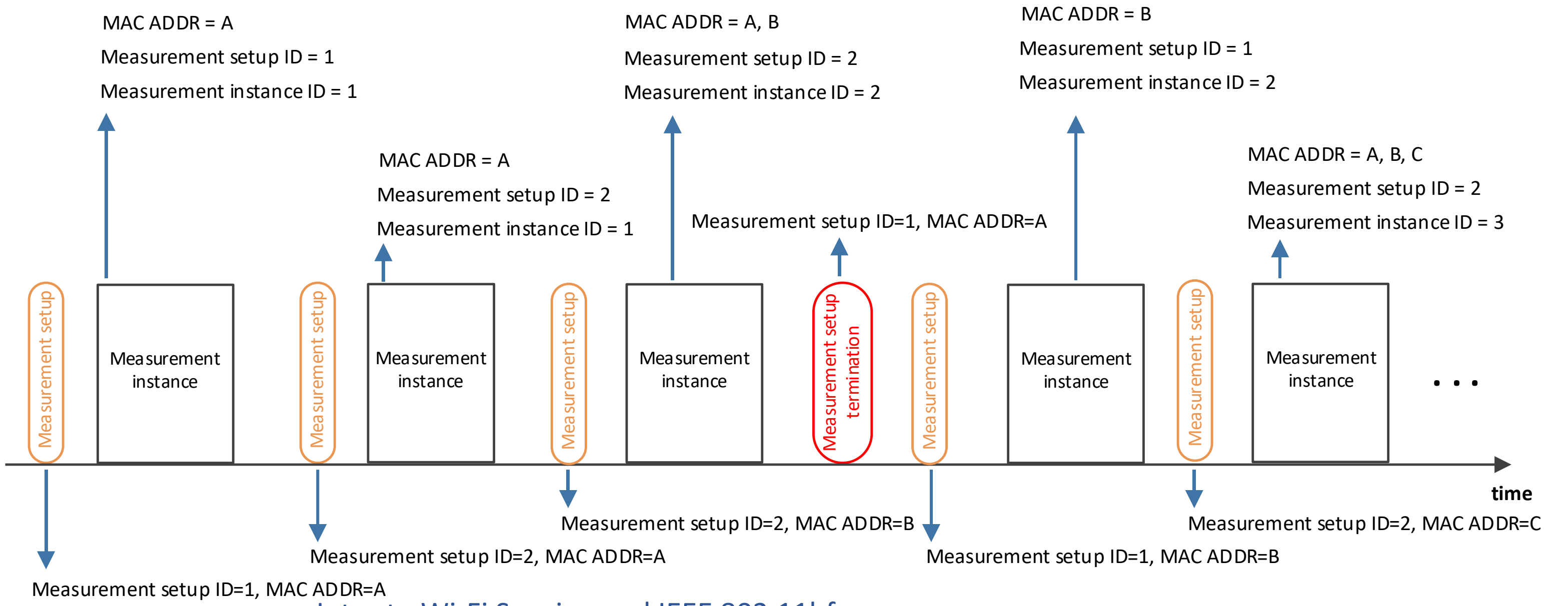
- Sensing session setup
  - Capabilities exchange.
- Sensing measurement setup
  - Pair of stations (initiator and responder) agree on operational attributes associated with a sensing measurement instance.
  - To identify a specific set of operational attributes, the sensing initiator associates a measurement setup ID to it.

WLAN sensing procedure

- Example 1:



- Example 2:



Sensing measurement instance

- A sensing measurement instance has the following variants:
  - Trigger-based (TB) sensing measurement instance
    - AP is the sensing initiator and one or more non-AP STAs are the sensing responders
  - Non-Trigger-based (Non-TB) sensing measurement instance
    - Non-AP STA is the sensing initiator and an AP is the sensing responder

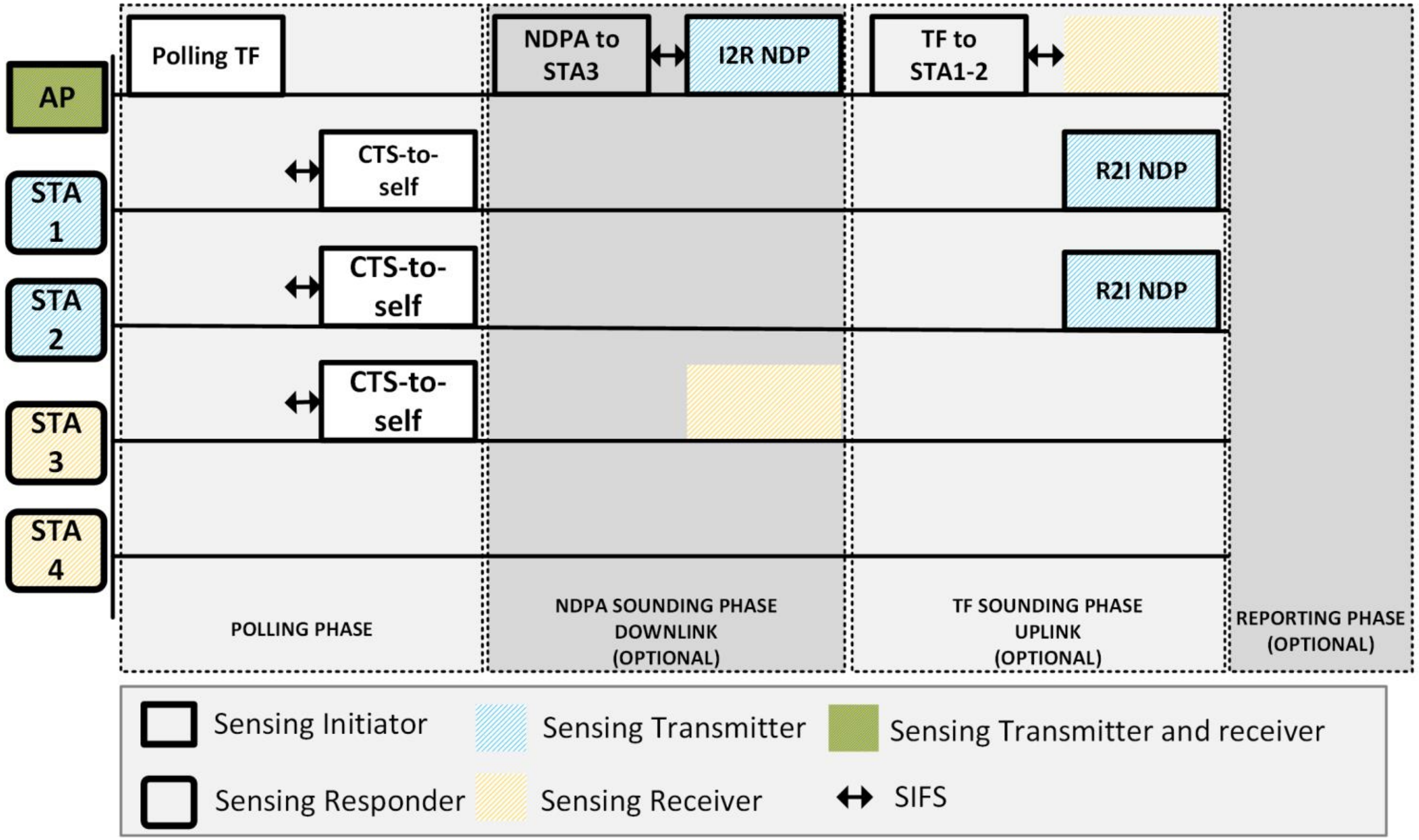
Sensing measurement instance: TB

- Recall: In trigger-based (TB) sensing measurement instances, the AP is the sensing initiator, and one or more non-AP STAs are sensing responders.

- It may include the following phases:
  - Polling phase
    - AP sends a Sensing Polling Trigger frame to one or more STAs that are assigned to be polled in the TB sensing measurement instance and expected to participate during the sensing availability window
  - NDPA sounding phase
    - AP is the sensing transmitter
    - AP sends NDP to one or more STAs to perform sensing measurement
    - Only present if downlink sensing is setup
  - Trigger frame (TF) sounding phase
    - AP is the sensing receiver
    - AP solicits NDP transmissions from one or more STAs to perform sensing measurement
    - Only present if uplink sounding is setup
  - Reporting phase
    - Sensing measurement reporting can be either immediate or delayed

- Note: The order of TF sounding and NDPA sounding is yet to be defined.

Sensing measurement instance: TB

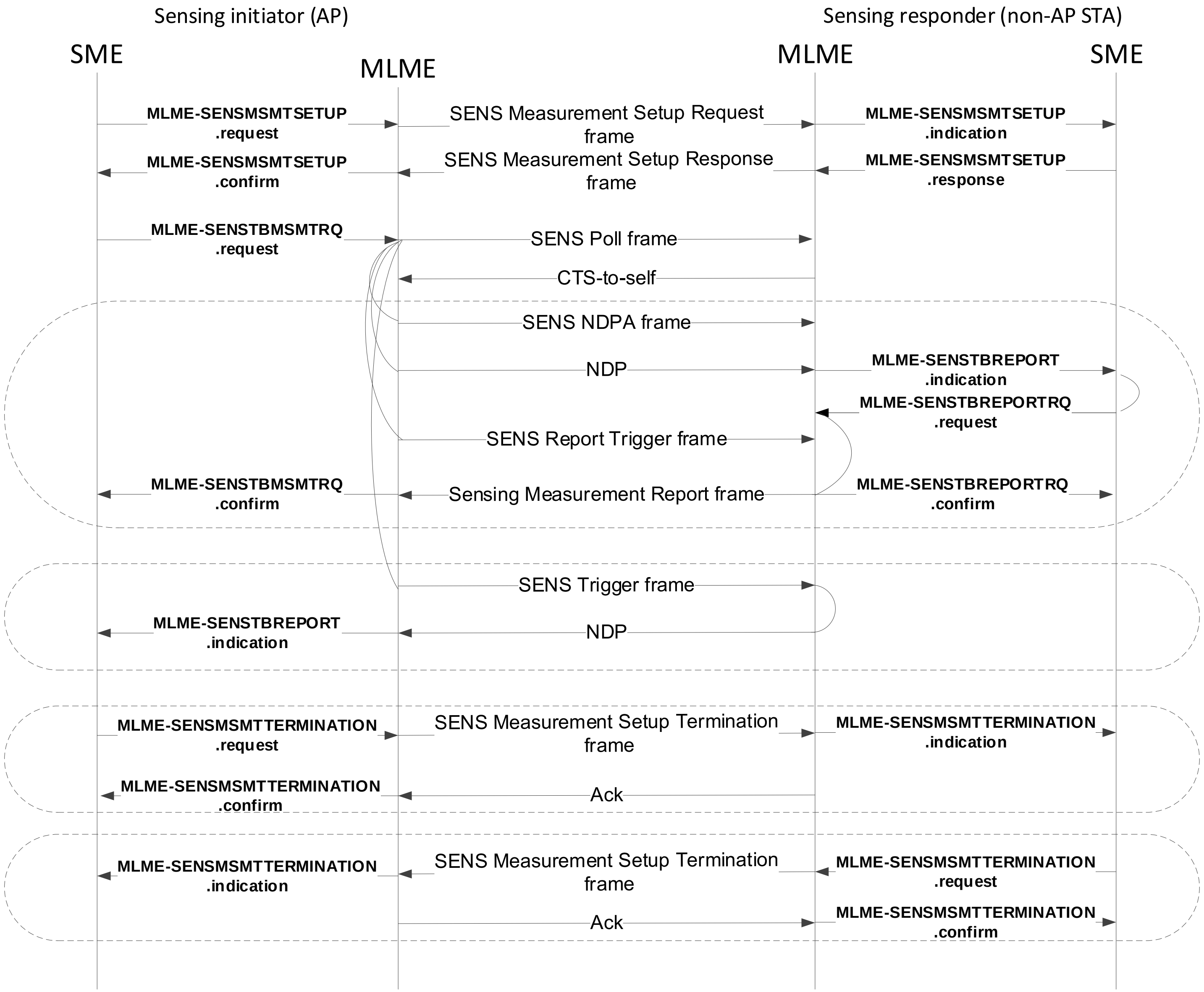


Example of TB sensing measurement instance

SIFS: Short Inter-Frame Space (10/16 µs for sub-7 GHz systems)

- Once a station has gained access to the medium, it maintains control of the medium by keeping a minimum gap (SIFS) between frames in a sequence. Another station will not gain access to the medium during that sequence since it must defer for a fixed duration that is longer than SIFS

Sensing measurement instance: TB



Station Management Entity (SME)

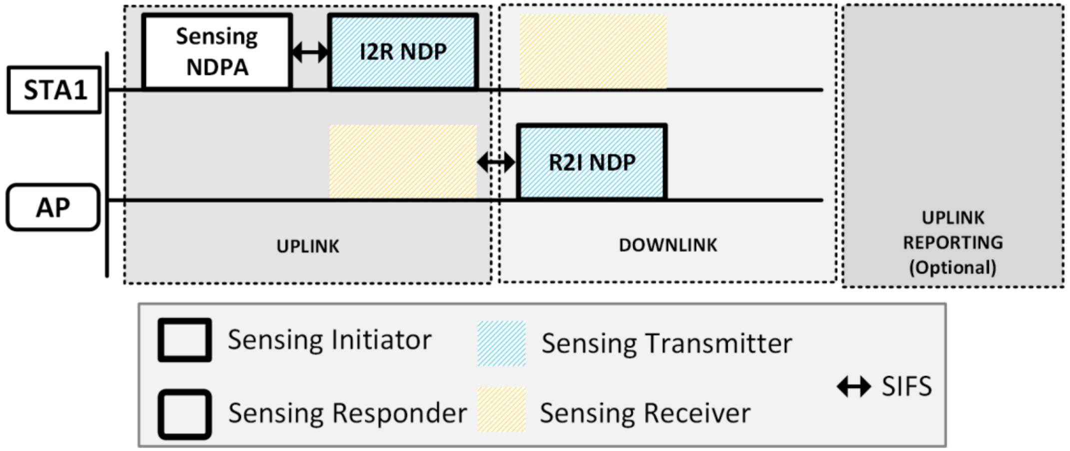
- "… regarded as responsible for functions such as the gathering of layer-dependent status from the various layer management entities and setting the value of layer-specific parameters. An SME would typically perform such functions on behalf of general system management entities and would implement standard management protocols."

MAC sublayer management entity (MLME)

- The MLME handles higher MAC functions such as synchronization, power management, and connection management, which include association and authentication.

Sensing measurement instance: Non-TB

- Non-AP STA is the sensing initiator and an AP is the sensing responder.
- Phases:
  - Sensing initiator initiates a non-TB sensing measurement instance by transmitting a Sensing NDP Announcement frame addressed to the AP, followed by an Initiator-to-Responder (I2R) NDP after SIFS
  - SIFS after the I2R NDP, the AP transmits a Responder-to-Initiator (R2I) NDP to the non-AP STA

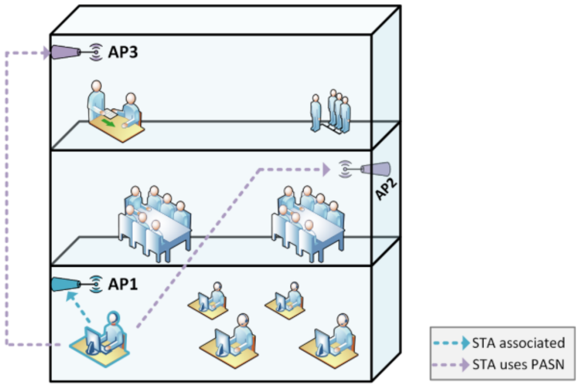


- The non-AP STA may initiate a non-TB sensing measurement instance whenever the medium is available.
- Different from the TB variant, for ease of implementation, the packet exchange defined for non-TB sensing measurement instances is the same independent of whether measurements are obtained in the uplink only, downlink only, or both uplink and downlink.

Enhancing client-based sensing

How can a client perform multistatic sensing?

1. It could use APs to which it is not associated with.
   - In principle, this case will be supported automatically by 11bf with the use of a feature termed Preassociation Security Negotiation (PASN).
   - Example: Enterprise environment.
   - While this option may be viable in an enterprise environment, unfortunately, viability in home environments is questionable in the near future.
2. Enabling a client to request an AP to serve as a “proxy”.
   - Client asks an AP to obtain measurements on its behalf.
3. Perform sensing with another client (that is, client-to-client sensing).
   - Break from a traditional AP-client architecture.



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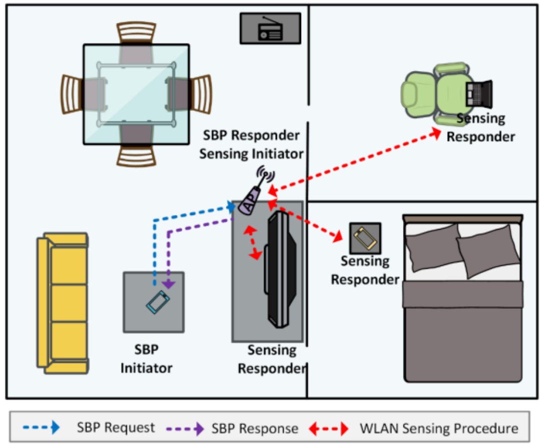

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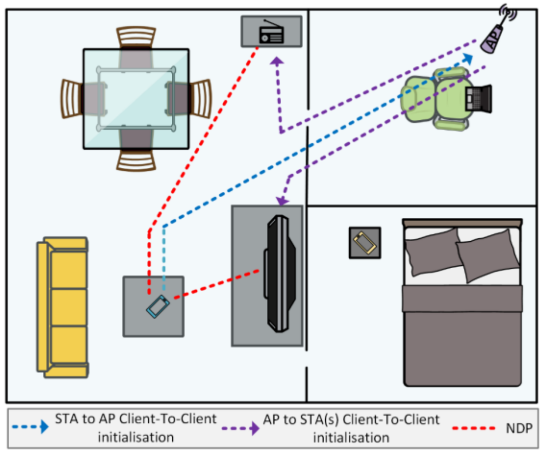

c)

Conclusions

- Significant progress on the development of sensing applications, both in academia and industry

- Market interest in Wi-Fi sensing is very strong and growing
- A Wi-Fi sensing standard will spur further innovation and market development by defining key features specific to Wi-Fi sensing
  - Interoperability, enhanced reliability, lower overhead, new application areas

- Interested in learning more?
  - 2022 IEEE ICC tutorial
  - IEEE 802.11bf tutorial papers
  - IEEE 802.11bf webpage: https://www.ieee802.org/11/