Joint Design of Sensing and Communication Systems for Smart Homes

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ABSTRACT

With the recent advance of technologies, smart homes are no longer just the subjects of science fiction and are now becoming a reality. It is essential for a smart home to understand its residents and provide entertainment and healthcare services. Researchers have demonstrated the great potential of RF sensing in smart homes, including understanding the residents' gesture commands and monitoring the residents' health status unobtrusively. Although RF sensing has appealing properties, it brings congestion to wireless networks. To make the situation worse, there is an unprecedented amount of wireless traffic in smart homes. In this article, we investigate the joint design of sensing and communication systems to alleviate the strain on wireless resources. Instead of designing sensing and communication systems as separate objectives, we tend to address them jointly. We discuss this issue from two directions. The first is to empower the traditional sensing device with communication capability, so that the sensing device will become a dual-function apparatus; the second is to enhance the sensing capability of WiFi signals by redesigning the packet format so that the current communication infrastructure can also act as a sensing device. We believe that only with joint design can the sensing and communication system work harmoniously in smart homes, providing both unobtrusive sensing and ubiquitous connectivity.

INTRODUCTION

As we spend a large portion of our spare time at home, a comfortable, convenient and safe home is essential to our happiness and wellbeing. In order to provide better services, homes are expected to understand the residents both physically and physiologically. Traditional approaches for home sensing either rely on (near-infrared) cameras or dedicated ambient/on-body sensing devices. However, cameras are privacy invasive and dedicated sensors are location/user-dependent. To overcome these limitations, radio frequency sensing, as an unobtrusive and ubiquitous sensing approach, is gaining popularity.

Radio frequency, which traditionally serves as a communication medium, is now emerging as a sensing medium. When RF signals propagate in the air, they will get blocked, reflected and scattered by surrounding objects. By analyzing the physical signatures of RF signals (e.g., amplitude, phase, Doppler shift), we can infer the path that the signals traveled and understand what is going on in the surrounding environment. Compared with wearable technology, RF sensing does not require the users to wear any on-body sensors and thus is totally unobtrusive. Compared with vision-based approaches, RF sensing has no requirement on the lighting conditions and can work in non-line-of-sight scenarios. Given these appealing properties, RF sensing has demonstrated its great potential in smart homes. Existing works show that wireless signals can be used to detect the presence and location of residents at home [1] so that we can schedule HVAC and lighting systems accordingly [2]. Recently, researchers show that we can understand the gesture commands of residents using RF signals [3, 4], which could provide user-friendly control for numerous intelligent devices in homes. Existing works also demonstrate that RF sensing has great potential in healthcare services. Researchers show that we can monitor residents' heart rate and breathing rate [5] [6] unobtrusively using RF signals. RF signals can also understand residents' gait patterns [7] and sleep cycles [8], which is of vital importance to elderly care and health management.

As the wireless spectrum is the shared medium, when the sensing device is transmitting radio waves from time to time, it results in congested RF environments. To make the situation worse, there is an unprecedented number of intelligent devices (e.g., smart speakers, smart HVAC systems, security and surveillance systems) in a smart home, which all require wireless resources for data communication and control message exchange. Although there are existing works using WiFi signals for sensing [6, 9, 10], there is inherent confliction in the nature of sensing and communication. In wireless sensing, known signals are used to probe the ambient channel state, while in wireless communication, the goal is to decode the unknown transmitted signals.

In this article, we investigate the joint design of sensing and communication systems. Instead of designing sensing and communication systems as separate objectives, we tend to address them jointly. The goal is to improve the spectrum utilization and alleviate the uneasy coexistence between the sensing and communication systems. We study this subject from two directions. The first is to empower the traditional sensing device with communication capability so that the sensing device will become a dual-function apparatus, which can perform sensing and communication tasks simultaneously. To achieve this goal, we need to bridge the gap between wideband sensing signals and

Digital Object Identifier:
10.1109/MNET.011.2000107

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narrowband communication signals. The second is to enhance the sensing capability of traditional communication devices. The main challenge is to achieve the balance between communication efficiency and sensing performance. By redesigning the WiFi packet format, we can enhance the sensing capability of WiFi signals so that in the near future the WiFi access point at our homes will not only perform data communication but also has the sensing capability comparable to a radar.

Only with the joint design of sensing and communication, can we have efficient spectrum usage in smart homes. In this article, we first briefly review the working principle of RF sensing and introduce some representative work. Then we present our initial attempt along the two directions. Finally, we discuss the challenges and conclude this article.

PRIMER OF RF SENSING

Existing works on RF sensing mainly fall between two categories, either use a traditional sensing device (e.g., radar) or explore the sensing capability of a traditional communication device (e.g., WiFi access point).

RADAR SENSING

Radar, traditionally thought of as bulky, expensive and limited to military applications, now becomes a miniature device and are entering our homes with promising capabilities. Although there are many types of radar, here we introduce the working principle of FMCW radar as a representative.

FMCW is short for frequency-modulated continuous wave, where the frequency of the signal increases linearly with time, as shown in Fig. 1. The signal sweeps *BW* bandwidth in duration *T*.

The working principle of an FMCW radar is as follows. The radar transmits a linear frequency-modulated wave and the wave will get bounced off from objects. Each reflection from an object is a delayed copy of the transmitted signals. FMCW radar transforms time-of-flight measurement (τ) into measuring the frequency offset (Δf) between the transmitted wave and the reflected wave, as τ and Δf preserve the linear relationship $\Delta f = R \cdot \tau$, where R is the ramp rate of the linear chirp. At the receiving chain of radar, the received signal is mixed with the transmitted signal. The output from the mixer is the intermediate frequency (IF) signal, whose frequency is the difference of the two inputs, that is, Δf.

The ranging resolution depends on the radar's ability to distinguish two nearby locations, which depends on the frequency resolution of Δf. We calculate Δf by performing FFT on the baseband signal over a chirp duration T and thus, the frequency resolution τ_{res} is inversely proportional to T. Transforming it into distance resolution, we have that ranging resolution is inversely proportional to the signal bandwidth. For two objects that are separated by a distance larger than d_{res}, their reflections will fall into different FFT bins and thus their movements can be decoupled. It indicates that FMCW radar can track multiple targets-of-interest simultaneously.

Both industry and academia are designing miniature radar for home applications. Soli [4], a millimeter-wave radar designed by Google, is able to recognize ubiquitous hand gestures and thus can be used to understand residents' gesture commands for interacting with numerous intelligent devices in smart homes. The soli chip, incorporating the entire sensor and the antenna array, is only 8mm × 10mm. Researchers from MIT are also devoted to designing miniature radars for sensing purposes. WiTrack [3] and WiTrack2.0 [11] are both FMCW radars working on the 5.56–7.25GHz band. WiTrack [3] can localize the center of a human body in the 3D space with a median error of less than 20 cm in each dimension. It can also track the coarse direction of a pointing hand. WiTrack2.0 [11] is more powerful than WiTrack [3] as it can localize multiple users purely based on the signal reflections off users' bodies.

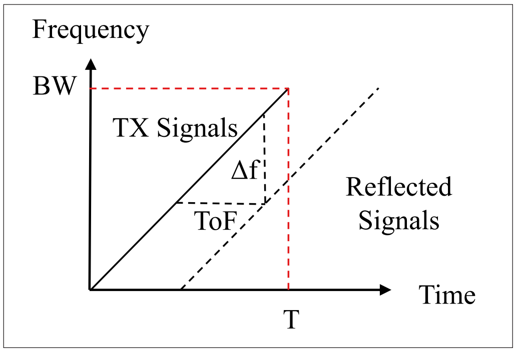

FIGURE 1. The working principle of FMCW. A linear frequency modulated signal is transmitted from the radar. When it gets reflected by objects, the radar will compare the frequency offset between the transmitted and reflected wave to estimate the time-of-flight parameter.

Besides localization, the researchers go further to look at the minute movement of users. When the person inhales and exhales, his chest will expand and contract. Based on this observation, Vital-Radio [5] can monitor users' breathing and heart rate unobtrusively with 99 percent accuracy, even when users are 8 meters away from the radar or users are in a different room with the radar. WiGait [7] uses RF signals to continuously measure gait velocity and stride length, which are important health metrics among the senior population. In [8], the authors developed a deep learning model to predict sleep stages from radio signal measurements. The model is a modified adversarial training regime that can discard information in RF signals that are highly dependent on individuals and environments but are irrelevant to sleep stages. The accuracy for identifying four sleep stages is 80 percent, which is comparable to EEG-based sleep monitors. Zhao *et al.* [12] designed RF-Pose3D, which is the first system that can infer 3D human skeletons containing 14 key points, including head, neck, shoulders, elbows, wrists, hip, knees and feet. RF-Pose3D can track each key point with an average error below 5cm along the three axes and maintain this accuracy even in the presence of multiple people and new environments unseen in the training set, which will have a huge impact on both entertainment applications (e.g., gaming) and healthcare services (e.g., rehabilitation). Although works from this category demonstrate promising results, the radio signals are used only for sensing purposes and cannot carry information.

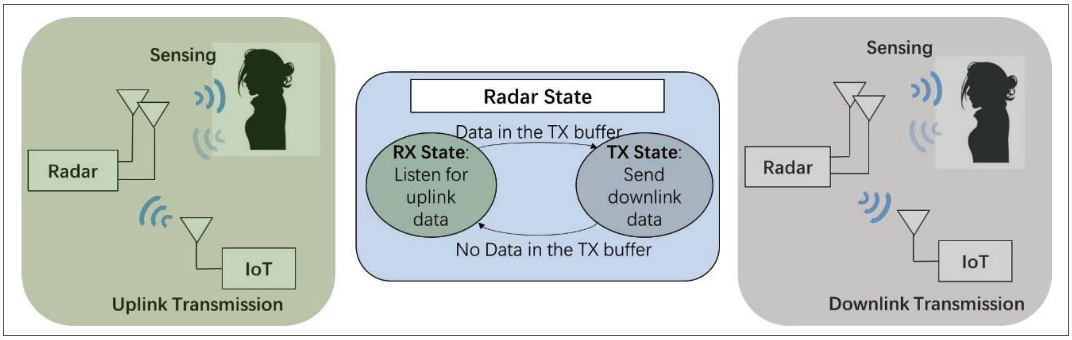

FIGURE 2. System overview.

WiFi Sensing

As for the second category, as WiFi signals are ubiquitous nowadays, WiFi sensing has shown growing popularity. We can obtain the channel state information (CSI) from commodity WiFi devices, which contain the physical signatures of the multipath profile. The channel state information H contains the integrated information from n propagation paths, where along each path, the signal is attenuated and delayed. When the target-of-interest moves, its movements will cause changes in the physical information at the corresponding path. This is the underlying principle for WiFi sensing.

The authors in [6] use WiFi signals not only to monitor users' breathing rate but also monitors heart rate. They work by monitoring the minute movement of users' chests to infer inhaling and exhaling. The authors in [13] track human position in the room with average error 0.75m. Guo *et al.* [10] proposed a WiFi based system to understand human dynamics, including crowd size, density distribution and moving patterns when multiple people are gathering.

As commodity WiFi devices are used, the sensing tasks are performed using ongoing data transmissions. Thus, the communication capability of RF signals is preserved. However, CSI is the integrated information from multiple propagation paths and it is not straightforward to extract the path corresponding to the target-of-interest. In order to achieve satisfactory sensing results, it usually requires the environment/surrounding objects to be static.

Empower Traditional Sensing Device with Communication Capability

In recent years, miniature radars are entering our homes with promising capabilities, such as understanding the gesture commands of the residents and fall detection for the elderly. However, radar signals are customized for the sensing purpose and are incompatible with legacy communication standards. Although there are existing works designing dual-function waveforms for sensing and communication, they work for radar-to-radar communication in military applications, where in home scenarios, we target radar-to-IoT communication.

Here is the dilemma for joint design. On one hand, radar signals are usually wideband signals as the sensing resolution is inversely proportional to the signal bandwidth, that is, the larger the bandwidth, the better the sensing resolution; on the other hand, legacy communication devices are usually narrowband transceivers (e.g., 20MHz for WiFi, 1MHz for Bluetooth, 500kHz for LoRa) and they cannot capture wideband radar signals.

To bridge this gap, we observe that it is possible to create a narrowband signal by combining two wideband signals using RF nonlinearity [14, 15]. RF circuits are supposed to be linear, that is, the output signal is a linear function of the input signal. When the hardware is imperfect, the circuit will exhibit non-linear behavior. The output signal will become a non-linear function of the input signal. That is, the output signals will contain high-order harmonics of the input signals. When the input signal contains carrier frequencies f_1 and f_2, the output signal will contain not only the original frequencies f_1 and f_2, but also harmonics resulting from the non-linear behavior. Specifically, assume that the input signals are two sine waves, the second-order harmonics become

$$\lambda_2 S_{in}^2 = \frac{\lambda_2}{2}\Big[2 - \cos(2\pi 2 f_1 t) - \cos(2\pi f_2 t) + 2\cos(2\pi f_1 t - 2\pi f_2 t) - 2\cos(2\pi f_1 t + 2\pi f_2 t)\Big] \tag{1}$$

The output signal contains carrier frequency $2f_1$, $2f_2$, $f_1 - f_2$ and $f_1 + f_2$. It indicates that when two signals enter a non-linear circuit, there will be a harmonic whose frequency is the difference of the two input signals. Consider the case that the two input signals are both linear Frequency Modulated Continuous Wave (FMCW) chirp sequences. The two chirps can be the sensing signals transmitted by different antennas on a radar, as a radar usually has multiple TX-RX antenna pairs to handle multi-path reflections [11]. The first chirp starts from f_1 and its frequency increases linearly with time at a ramp rate R; the second chirp starts at f_2 and also increases with time at the same rate. As their frequency gap is constant, the second-order harmonics will contain a component, which is a constant wave at frequency $f_2 - f_1$. It can serve as the carrier wave for the data signal. It brings the feasibility that we can exploit this non-linearity phenomenon to convert two wideband sensing signals into a narrowband data signal.

Above is the high-level idea. Now we present the system overview and illustrate the design details for both downlink and uplink.

System Overview

Figure 2 shows the system overview. The radar is continuously performing sensing tasks. When there is data for downlink transmission, that is, from the radar to an IoT node, the radar will use the dual-function radar signals, which embed the

IoT data packets. For the remaining time, the radar will use the original linear chirp signal and listen for uplink transmission.

This radar has two key distinctions from a usual FMCW radar. First, we embed data packets into the sensing signals so that the sensing signals are no longer the standard FMCW signals. Second, we design a new receiving chain on the radar so that it not only can act as radar but also can decode uplink transmissions from IoT devices. We summarize the high-level operations of the radar as follows.

Sensing: Similar to other RF radars, the radar accomplishes the sensing task by transmitting wideband sensing signals. These signals propagate in the air and get reflected by obstacles. By analyzing the reflections, the radar can detect the presence and movement of objects and human bodies in the space. This functionality is the same as a normal radar.

Communication: Communication tasks are accomplished at the same time with the sensing tasks. For the downlink part, the sensing signals transmitted by the radar will resonate at the antenna on an IoT device. The signals will enter the non-linear circuit and create a narrowband harmonic, which turns out to be a legitimate IoT data packet and can be decoded by the IoT device. For the uplink part, the receiving chain in the radar is able to pick up both reflected sensing signals and uplink data transmissions simultaneously. The radar separates these two types of signals apart and carry out corresponding processing respectively.

Downlink Dual-Function Waveform Design

The goal for downlink design is to design the dual-function radar signals, where the sensing signals transmitted by the radar should preserve the sensing resolution while their joint harmonics is compatible with legacy communication devices. To achieve this goal, the desired harmonic should be a signal that fully complies with the communication standard of the legacy devices. In other words, it should be a signal at the legitimate frequency band with the right modulation scheme.

To achieve this goal, we first introduce a time offset between the sensing signals transmitted by the two TX antennas. When the two linear chirps sweep the same frequency band and their time offset is half the chirp duration, the desired harmonic (i.e., $|f_1 - f_2|$) will become a constant wave, as shown in Fig. 3. When $BW = 2f_L$, in the first half of the chirp ($0 < t < T/2$), we will have $f_1(t) - f_2(t) = f_L$, while in the second half of the chirp ($T/2 < t < T$), we will have $f_2(t) - f_1(t) = f_L$. In this way, we can create a carrier wave at the desired frequency f_L, while both original chirps sweep the full bandwidth and thus preserve the sensing resolution.

Then we will embed data signals into the signal on one antenna. If we modulate signal $s(t)$ onto the wave on the first antenna, the received signal can be written as

$$\begin{aligned} RX &= TX_1 + TX_2 + (TX_1 + TX_2)^2 + \cdots \\ &= s(t)\sin f_1(t)t + \sin f_2(t)t + \\ &\quad [s(t)\sin f_1(t)t + \sin f_2(t)t]^2 + \cdots \\ &= \cdots - s(t)\cos[f_1(t) + f_2(t)]t + s(t)\cos f_L t + \cdots. \end{aligned} \tag{2}$$

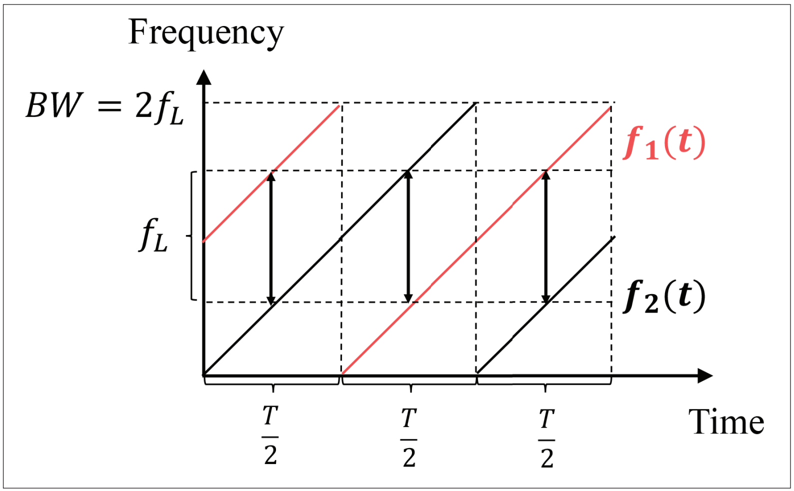

FIGURE 3. Two unsynchronized FMCW chirps, with half chirp duration offset. In this way, the two chirps can create a harmonic at frequency BW/2, while both chirps sweep the full sensing band.

We can see that in these harmonics, there is one term that we desire, which contains the signal $s(t)$ at frequency f_L.

We can determine the value of f_L and the modulation scheme of $s(t)$ to make the signal compatible with the communication interfaces of legacy devices, so that the radar can transmit data directly to legacy devices such as Bluetooth/ZigBee/LoRa nodes in a smart home. In an experiment, we test with LoRa nodes. The radar chirp signal sweeps an 866MHz bandwidth where the center frequency is 900MHz, thus $f_L = 433$MHz. The receiver, SX1278, is configured to work at 433MHz. The LoRa data rate is 3.4 kb/s. In order to amplify the nonlinear phenomenon, we add a diode between the antenna and the RF circuit, which is a non-linear component. This LoRa node can successfully decode the harmonics generated by the Radar device. The received signal strength drops from −98dB at 1.6m to −118dB at 16m in the line-of-sight scenario. It shows that we can generate a legacy LoRa signal from the wideband radar signals.

Uplink Receiver Design

The goal of uplink design is to enable the radar to decode uplink transmission. The receiving chain in the FMCW radar is designed for the sensing task but not for data communication. To serve both as a sensing and communication device, the radar needs to collect targets' reflected signals and decode uplink transmission simultaneously. To achieve this goal, we propose a new design for the radar receiving chain.

In order to separate data signals and sensing signals, we observe that when the sensing signal is down-converted, its maximum frequency f_{max} is dependent on the slope of the FMCW chirp and the maximum detectable range. In other words, the sensing signals will fall within the frequency range $[0, f_{max}]$. Thus, we can separate data signals and sensing signals on the frequency domain by ensuring that $f_{DATA\text{-}IF} \geq f_{max} + \Delta F$, where $f(_{DATA\text{-}IF})$ is the intermediate frequency of data signals and ΔF is the guard band between the sensing signals and data signals. In this way, we can separate data signals and sensing signals in the frequency domain and they will not interfere with each other. In the

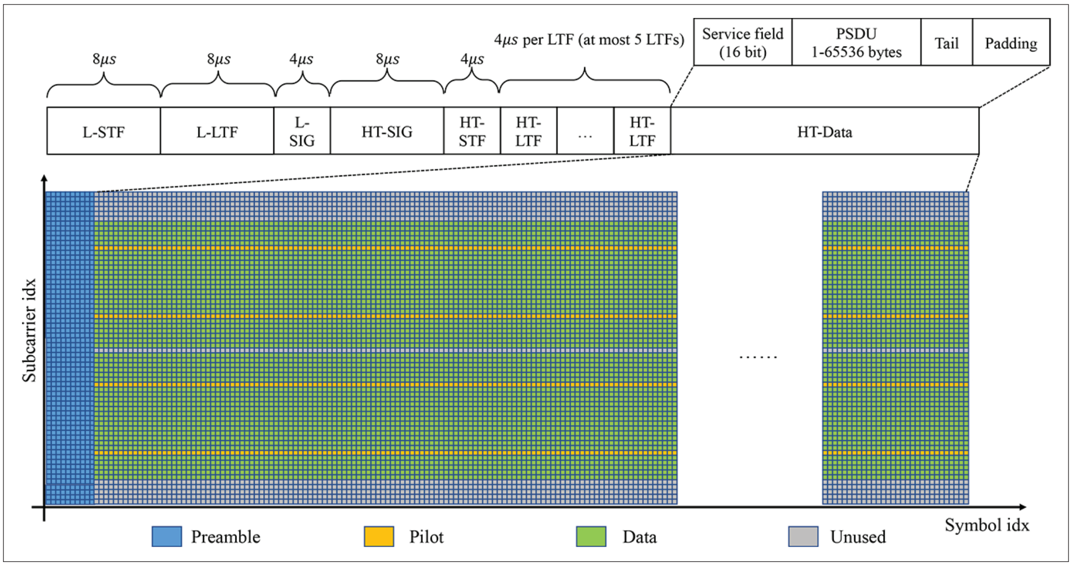

FIGURE 4. Frame format of an 802.11n (HT) packet.

implementation, we estimate f_{max} to be 0.5MHz according to the chirp rate and the maximum detectable range. ΔF is set to be 0.5MHz. Thus, $f_{DATA\text{-}IF}$ is set at 1MHz. Uplink LoRa signals is down-converted to 1MHz while the down-converted sensing signal is within DC and 0.5MHz. Evaluation results show that we can successfully decode the uplink data signals and the sensing performance is not affected by the data signals.

Enhancing the Sensing Capability of Traditional Communication Devices

WiFi sensing has its unique advantages owing to the widespread WiFi infrastructure. However, the current WiFi sensing methods mainly rely on CSI information extracted from the packet preamble which occupies a small portion of the WiFi packet. In other words, we can get only one measurement per packet. This hinders the sensing capability in time-critical cases and highly dynamic scenarios. This intensifies the inherent conflict between communication and sensing, as sensing prefers short packets (i.e., more packets, more CSIs) but communication prefers aggregated long packets (i.e., less packets, less overhead). Our goal is to enhance the sensing capability of WiFi signals and the idea is to exploit pilot subcarriers.

Our design rationale relies on the signal persistence of pilot subcarriers and its interleaving structure with data subcarriers in the frequency domain. Figure 4 shows the frame format of a typical WiFi packet. HT-LTF fields in the preamble that are used to derive CSI for each spatial stream, generally occupy several microseconds. Pilot subcarriers, however, spread over the whole HT-Data fields and may occupy several milliseconds, especially when data fields contain aggregated-MSDUs. This creates more opportunities for sensing in time-critical cases and rapidly changing scenarios.

WiFi specifications adopt OFDM modulations to combat frequency-selective fading. Figure 4 also presents the interleaving structure of pilot and data subcarriers in the frequency domain. This structure provides opportunities for enhancing sensing capability without degrading communication efficiency.

Pilot-Based Sensing

To illustrate the working principle of pilot-based sensing, we consider a basic scenario where two WiFi devices behave similarly as a bi-static radar system to detect a nearby object. The transmitted signals from a WiFi transmitter are reflected by the object, and then a WiFi receiver infers the relative distance and velocity of the object from the physical properties of the received signals. It is assumed that the relative distance between the object and WiFi transceivers bring τ_p delay in the time domain, and the relative velocity between them brings f_D^p Doppler shift in the frequency domain. Assume that the transmitted signals $x(t)$ contain K packets, and each has M OFDM symbols. There are N_{pl} pilot subcarriers within N subcarriers in an OFDM symbol. T_k is the time duration of a packet. The reflected signal from the object can be represented as:

$$\begin{aligned} y_p(t) &= x(t-\tau_p)\exp(j2\pi f_D^p t) \\ &= \sum_{k=0}^{K-1}\sum_{n=0}^{N-1} s[n]\exp\big(j2\pi f_n(t-kT_k)\big) \\ &\qquad \exp(j2\pi f_n\tau_p)\exp(j2\pi f_D^p t) \end{aligned} \tag{3}$$

where $s[n]$ is the modulation symbol on the n-th subcarrier. For pilot subcarriers, they are defined in advance. In general, there are several (say P) multi-paths reflected/scattered by other objects besides the target object. Thus, the received signal at the WiFi receiver is $y(t) = \Sigma_{p=1}^{P} y_p(t)$.

The goal of sensing is to derive the relative distance and velocity of the object buried in the received signal $y(t)$. This can be achieved by performing DFT and IDFT along the frequency and time axes of the pilot subcarriers to get a delay-doppler map. Then we can estimate the target's distance and velocity from the delay-doppler map.

Pilot Pattern and Waveform Design

Pilot pattern and waveform have effects on the sensing performance. Given fixed bandwidth, the frequency resolution is inversely proportional to the number of pilot subcarriers N_{pl}. According to

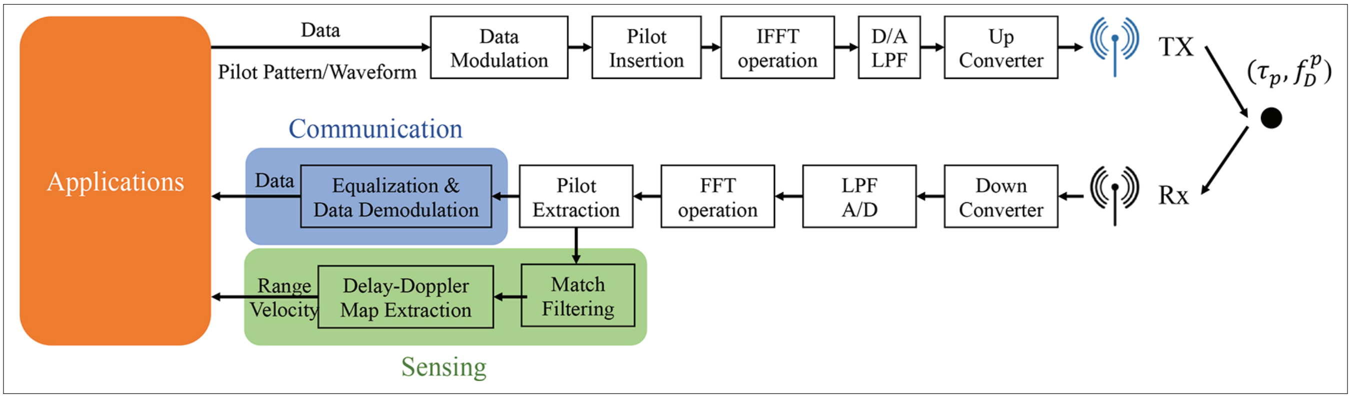

FIGURE 5. System overview.

the operation of IDFT, the maximum time limit is inversely proportional to the frequency resolution, which in term is proportional to N_{pl}. Thus, the maximum unambiguous distance is proportional to N_{pl}. In terms of choosing a proper pilot pattern, we need to jointly consider the trade-offs between sensing and communication requirements in specific applications and adjust patterns in a dynamic manner. For example, when the communication load is small, we can temporally adopt a denser pilot pattern, that is, more subcarriers are used as pilot subcarriers, so that we can improve the maximum unambiguous distance for sensing.

To enhance the sensing capability, the pilot waveforms along the time axis can adopt waveforms with a good auto-correlation property so that match filtering can be applied to enhance the sensing function. Barker code is a viable option for two reasons. First, Barker codes imply the use of the same modulation scheme, BPSK, as in pilot subcarriers of existing WiFi protocols. Second, Barker codes are −1/1 alternating sequences, satisfying the power masking requirement for pilot subcarriers in WiFi. Thus, it is compatible with phase and frequency tracking for communication.

SYSTEM OVERVIEW

Figure 5 shows the system overview. The system consists of two roles, WiFi transmitter (Tx) and WiFi receiver (Rx). On one hand, Tx and Rx exchange data via WiFi packets. On the other hand, Tx and Rx behave as a bi-static radar system to detect a nearby object. We summarize the high-level operations of the system as follows.

Communication: Similar to existing WiFi devices, our system conducts the transmission task by transmitting WiFi packets. Specifically, WiFi Rx demodulates signals on data subcarriers to retrieve the transmitted information. The only difference here is that WiFi Tx should indicate the pilot pattern in the header part of the packet so that WiFi Rx can find the positions of data subcarriers for demodulation.

Sensing: The system accomplishes the sensing task by transmitting WiFi signals. The transmitted signals from a WiFi Tx propagate in the air and get reflected by the object, and then a WiFi Rx infers the relative distance and velocity of the object via processing pilot signals. WiFi Rx knows the pilot waveform adopted by Tx through indicators in the packet header or prepositive communication. Then Rx performs corresponding match filtering and DFT/IDFT processing to get a delay-doppler map. Then Rx estimates the relative distance and velocity of the object from the delay-doppler map.

OPEN CHALLENGES

In this section, we discuss several challenges related to the joint design of sensing and communication.

COEXISTENCE OF RADAR AND HETEROGENEOUS IOT DEVICES

Although the dual-function apparatus can be used for both sensing and communication, it only complies with one specific type of device (e.g., WiFi). In other words, the radar can perform the sensing task and communicate with WiFi devices simultaneously. However, there are other devices working at the same band as WiFi, such as Bluetooth and ZigBee devices. The dual-function device is not able to recognize these signals, neither can communicate with these devices. As sensing tasks usually require generating persistent sensing signals, which may occupy the channel continuously and leave other devices less opportunity for transmission.

Given that there are various types of IoT devices in a smart home which may talk in different protocols, the joint design needs to consider not only a specific protocol, but also all possible protocols that may exist in a smart home scenario, so that the sensing and communication system can work harmoniously.

PERSISTENCE NATURE OF SENSING AND RANDOMNESS NATURE OF COMMUNICATION

Sensing signals and communication signals are different in their nature. A sensing application usually requires generating persistent sensing signals, while communication signals are transmitted only when there is a need for data communication. When we reuse the data signal for sensing, the measurement that we obtained may not be strictly periodic and may be insufficient in terms of sampling rate. To address this challenge, we may use interpolation techniques to transform uneven observations into periodic ones. The dual-function AP may also generate dummy packets that are purely intended for sensing purposes, when there is insufficient traffic.

CONCLUSION

In this article, we discuss the joint design of sensing and communication in smart homes. As we take sensing and communication as an integrated

Sensing signals and communication signals are different in their nature. A sensing application usually requires generating persistent sensing signals, while communication signals are transmitted only when there is a need for data communication.

system, we can alleviate the uneasy coexistence between them and make them work harmoniously. We discuss this issue from two directions: empower the traditional sensing device with communication capability, and enhance the sensing capability of the traditional communication device. We also discuss the open challenges and hope that this article can intrigue research interests in this subject.

ACKOWLEDGMENT

This work is partially supported by the RGC under Contract CERG 16204418, FP909, R8015; the National Natural Science Foundation of China (No. 61872420); the Guangdong Natural Science Foundation (No. 2017A030312008); the Guangdong Key Research and Development Program (No.2019B121204009); and the project of "FANet: PCL Future Greater-Bay Area Network Facilities for Large-scale Experiments and Applications (No. LZC0019)."

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BIOGRAPHIES

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