Recent Progress in Passive Sensing Leveraging Advanced Circuit Techniques

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***Abstract*—Passive sensing has seen considerable use as a method of detecting target distance and motion or imaging targets without requiring a cooperative transmitter. Traditionally, passive sensing has used high-power long-range illuminators of opportunity to accomplish detection at ranges on the order of hundreds of kilometers. As the proliferation of wirelessly connected devices in daily life continues, however, concerns about interference and spectrum usage have caused passive sensing to become a crucial technique to maintain the synergistic relationship between sensing and communications. Furthermore, the inherent security of passive sensing makes it a desirable choice for sensor networks. As a result, recent works have made considerable advances toward bringing passive sensing to new applications such as automotive sensing or home health monitoring. This paper reviews recent advances in passive sensing technology enabled by advanced circuit and system design techniques. New array design techniques have been shown to optimize detection ability using nonuniform linear arrays for automotive sensing, while novel passive sensing architectures have provided new techniques to extract small motions for high-sensitivity passive systems.**

Keywords—passive microwave sensing, passive radar, circuit design, radar system design.

I. Introduction

Passive microwave sensing has long been used as a mechanism for covert detection by utilizing ambient wireless signals versus dedicated cooperative transmitters. Historically, passive radar has relied on relatively high-power illuminators of opportunity to accomplish long-range detection of large moving objects at distances over 100 km [1], making the technology a valuable tool when the transmission of electromagnetic energy is not practical. Furthermore, the absence of an onboard transmitter for passive sensors makes them a natural candidate for the future of converged sensing and joint communication and sensing efforts as their operation relies solely on external signal sources and will not compete with communication networks for bandwidth. Traditionally, high-performance or high-sensitivity sensors rely on active systems that transmit their own illumination signal in order to detect metrics such as distance, velocity, or periodic motion [2], [3]. However, as more sensors and wireless devices are deployed, the finite electromagnetic spectrum ultimately limits the number of active devices that may transmit in a location at any given time. As a result, passive sensors will play an important role in continuing the deployment of sensing and communication networks to address areas such as home healthcare, smart infrastructure, and automotive radar. As such, recent years have seen considerable interest in passive sensing technology as a spectrally efficient method of performing environmental sensing. In addition, the increased prevalence of ambient

The authors wish to acknowledge the National Science Foundation (NSF) for funding support under Grant ECCS-2030094.

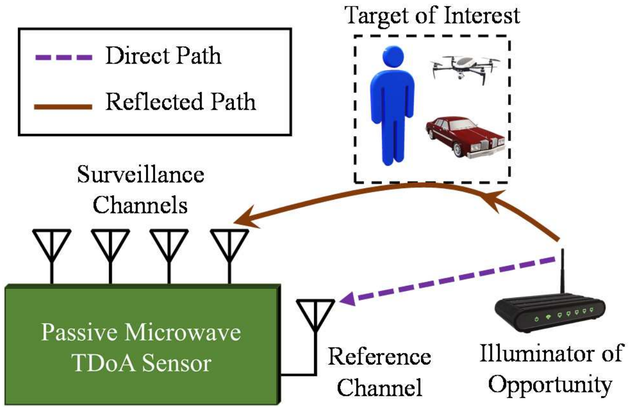

Fig. 1. Passive sensing block diagram. By comparing the time difference of arrival between the reference channel and the surveillance channels, the target's range can be extracted without requiring the radar to transmit.

electromagnetic energy combined with advanced circuit design techniques has allowed passive microwave sensing to be used in applications at much shorter distances with a considerably higher resolution. This paper investigates recent advances in passive sensing enabled by these techniques and gives context to their applications including automotive sensing, smart infrastructure, and home healthcare.

This paper is organized as follows: Section II provides the basic theory of passive microwave sensing in addition to the limitations of existing passive sensors for emerging applications. New antenna and array design techniques for performance improvement and size reduction are discussed in Section III. Section IV reviews novel passive sensing architectures to enable high-sensitivity motion detection using ambient wireless signals. Conclusions are drawn and a discussion is provided in Section V.

II. Passive Sensing Theory

Passive sensors sense their environment by leveraging ambient electromagnetic energy such as Wi-Fi, satellite audio/video, or FM radio signals as illuminators of opportunity. In a bistatic case like that in Fig. 1 where a single target is considered in the presence of a third-party illuminator, a passive sensor can extract the target's distance by measuring the time difference of arrival (TDoA) of two received signals: one following a direct path from the illuminator to the radar, and another that is reflected from the target then detected at the passive sensor. Due to the bistatic geometry, a single receiver using TDoA-based techniques can only determine the target's range and Doppler response in relation to the receiver-illuminator pair. As such, beamforming techniques, array optimization, and multistatic architectures are leveraged if more information is needed. In order to preserve the integrity of the unknown reference signal, many systems employ dedicated reference channels to isolate the reference signal, combined with multiple surveillance channels to measure the direction of arrival (DoA) of the reflected signal. As a result, typical passive radars are large due to the number of antennas required. In addition, many passive sensing paradigms rely on the demodulation and comparison in time of the received signals through the reference and surveillance channels, creating a fundamental limitation on the range resolution of the sensor and its ability to measure small motions. In order for passive sensing to be a viable solution for more applications, new circuit and system design techniques are necessary.

III. Passive Sensing Array Design

A critical limitation of traditional passive sensors is the size of the antenna array required for effective operation. For passive sensing to be a practical solution for a wider variety of applications, it is necessary to efficiently design the surveillance antenna elements and array to maintain both the required angular resolution and moving object detection.

A. Nonuniform Array Design Method

In order to provide improved performance with few antenna elements, nonuniform arrays can be employed to provide optimal performance given the design requirements. The design process in [4] details a method through which a nonuniform linear array (NULA) may be designed in order to meet the performance requirements of a passive sensing system, specifically in the context of automotive sensing where size constraints limit the maximum array size. Typically, NULA design comes with inherent tradeoffs such as angular resolution and unambiguous sensing that demand opposing array geometries. By leveraging the design method in [4], however, it is possible to effectively design a passive sensing receive array that satisfies the specified peak-to-sidelobe ratio for the desired angular resolution and ambiguity performance. The performance of NULAs were analyzed in [5] against simulated datasets using DVB-T signals as illuminators, where it was found that NULAs demonstrated better preservation of both fast- and slow-moving targets compared to ULA systems, as well as better DoA accuracy. However, the forward-looking array presents a new issue for automotive passive sensors caused by the symmetry of the range and Doppler information creating left/right ambiguity and a new limitation to be addressed in a practical system.

B. NULA Performance for Automotive Sensing

In order to evaluate the effectiveness of NULAs in the context of automotive passive radar, simulation studies were conducted to both develop an algorithm for target localization and remove the left/right ambiguity problem. In [6], it was found that stationary scatterers were able to be localized in 2D space due to the relative Doppler shift produced at the passive radar receiver under a known vehicle velocity. Through a Doppler beam-sharpening approach, the range-Doppler map can be converted to a 2D image of scatterer locations with left/right ambiguity shown in Fig. 2(a). In order to address the ambiguity, the simulation study in [7] showed that a NULA could successfully remove ambiguities and effectively localize targets in 2D space with no left/right ambiguity present, illustrated by the results in Fig. 2(b).

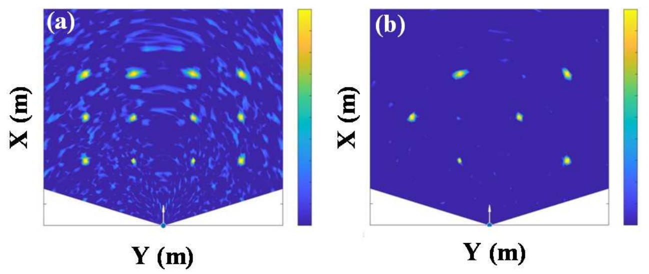

Fig. 2. Comparison of automotive passive radar target detection of 6 targets from [8]. The results in (a) show the left/right ambiguity, while the results in (b) negate the effects of ambiguity and provide accurate localization.

C. Polarimetric Passive Radar

In order to further improve the performance of passive systems, unifying novel array designs with polarization diverse systems could assist in providing more target information for robust sensing and classification as is shown in [8]. By measuring both the co- and cross-polarized components of the reflected signal, it is possible to extract unique information about the target that could be used for classification (e.g., stationary vehicles versus pedestrians). When considering that illuminators of opportunity are noncooperative and therefore cannot be modified to meet sensor needs, a full polarimetric system employing small automotive radar antennas such as those in [9] allows the sensor to gather more information and improve detection.

IV. Novel Passive Sensing Architectures

While traditional passive sensors can extract target distances by measuring the TDoA of the reference and surveillance signals, the range resolution for these sensors is generally too poor to extract small motions with amplitudes on the order of millimeters. In many applications such as structural health monitoring, healthcare, or gesture recognition, motions on a sub-millimeter scale must be accurately measured by the sensor. Traditionally active radars have been used as a method of measuring these motions, however, recent works have demonstrated passive radar architectures that can be used to detect small motions.

A. Passive Doppler Radar

In a manner similar to traditional Doppler motion sensing, several works have highlighted a new architecture that allows a passive sensor to detect small motions in the presence of a CW illumination signal. The architecture was first demonstrated using commercial RF modules in [10], where it was shown that the bench-level system was able to isolate a 1 Hz motion produced by an actuator. The passive architecture was then further tested in [11], where a 2.4-GHz board-level system was able to measure the vital signs of a subject in the presence of an illumination signal in the 2.4-GHz Wi-Fi band. These results measuring heart and respiration rates are shown in Fig. 3(a) and Fig. 3(b), respectively. In an effort to improve the sensitivity of the system, the architecture was then tested at the 5-GHz Wi-Fi band in [12] using custom RF components to realize the amplifier and mixer. For each of the sensors above, the

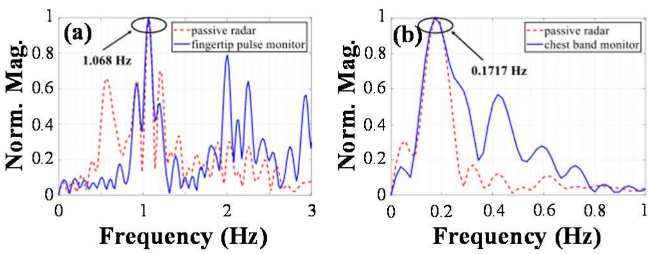

Fig. 3. Vital sign detection results from [12] using passive motion sensing radar. The extracted heart rate in (a) and respiration rate in (b) exactly match the ground truth values, proving the ability to measure small motions.

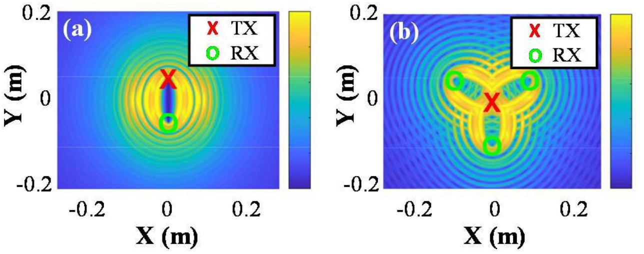

Fig. 4. Null-point analysis with mitigation techniques. The bistatic system (a) shows the optimum (yellow) and null (blue) points using multiple channels. The 3-sensor system (b) mitigates null points with spatial diversity.

baseband output can be expressed as $x(t) \approx \cos[2\pi/\lambda(d_2(t) - d_1)]$, where λ is the wavelength of the transmitted signal in free space, $d_2(t)$ is the time-varying transmitter-target-radar distance that includes periodic motion, and d_1 is the transmitter-radar distance. It is worthy of note that, despite the mention of *I/Q* baseband data in the literature, it is currently unknown if complex baseband signals can be extracted using the above architectures. As such, the passive Doppler architecture exhibits the null-point problem that is prevalent for single-channel Doppler motion sensing. In order to fully understand the impacts of null points on detection abilities for passive Doppler radar and to propose mitigation techniques, the study in [13] developed a simulation platform to evaluate the impacts of frequency- and spatially-diverse systems. It was found that, despite the limitations of the passive Doppler architecture, detection can be improved by leveraging the scalability of passive Doppler radar by employing systems working in the entirety of the Wi-Fi bands, shown in Fig. 4(a), or by using multistatic sensing, illustrated by Fig. 4(b).

B. *Injection-Locking Injection-Pulling Passive Sensing*

Injection-locking/injection-pulling (ILIP) methods have been proposed in [14] as a passive method of extracting target motion information. In the ILIP architecture, the received signal from an illuminator drives an injection-locked oscillator. As the target moves, the motion encoded in the phase of the reflected signal modulates the oscillator frequency due to injection-locking and injection-pulling effects, creating two tones in the RF spectrum. These tones are then downconverted to baseband, where they are digitized and processed to extract motion characteristics. The results in [14] show that the architecture can effectively isolate human vital signs and other small motions, establishing a second novel architecture for passive radar motion detection.

V. Conclusion

As more of the electromagnetic spectrum becomes occupied to accommodate high-bandwidth communications and sensing technologies, new techniques must be developed to continue trends toward a greater number of sensors in daily life. Passive radar techniques have allowed for spectrally efficient detection, and recent works have allowed passive sensing to be used in a wider range of applications. New array technologies leveraging NULAs for automotive passive radar have shown promising performance in simulated case studies and have succeeded in removing the left/right ambiguity for automotive passive sensors. Furthermore, sensor fusion with full polarimetric passive sensors allow for more information to be gathered on the targets, further improving the performance of passive sensing systems. Novel passive sensing architectures have circumvented the range resolution issues of traditional passive sensors, providing new low-power techniques that can be used to detect motions on a submillimeter scale using ambient energy.

Future works can further integrate passive sensing systems in spectrally congested environments such as roadways, homes with dense sensor networks, or smart cities with smart infrastructure. In addition, more research in passive Doppler and ILIP radars is necessary to develop robust models for the systems. Studies focusing on waveform design may open new possibilities for passive sensors by employing chirp or communications signals to extract target range and perform localization in an indoor environment. Beamforming for the new architectures can be explored and may provide methods to be used to monitor multiple motions with a single sensor array. In addition, more complex architectures leveraging injection-locked oscillators could provide a method of performing quadrature demodulation to improve the sensing performance of passive Doppler radars.

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