Passive Multistatic Wireless Sensing Based on Discrete LNA/Mixer Co-Optimization and Fast-Startup Baseband Amplifier

Aaron B. Carman
Dept. of Electrical & Computer Engineering
Texas Tech University
Lubbock, TX, 79409, USA
https://orcid.org/0000-0003-2606-3977

Changzhi Li
Dept. of Electrical & Computer Engineering
Texas Tech University
Lubbock, TX, 79409, USA
https://orcid.org/0000-0003-2188-4506

***Abstract*—Passive radar has gained considerable interest as a mechanism of characterizing small motions using ambient electromagnetic (EM) energy. Compared to traditional Doppler radar, passive radar offers a means of motion detection leveraging existing signals such as Wi-Fi or Bluetooth to reduce crowding in the EM spectrum. Previous works have demonstrated an ability to detect periodic motions using passive radar but relied on bulky commercial building blocks that increase both size and power consumption of the overall device. Amplification of the low-frequency signals is often accomplished using baseband amplifiers with high-pass behavior, resulting in long startup times when detecting low-frequency motions. In this work, a board-level passive radar operating in the 5-GHz Wi-Fi band is presented as a method of detecting small motions created by human motion. The proposed system offers a compact, efficient method of detecting the Doppler information of a target. A fast-startup baseband amplifier is used as a method of quickly reaching the desired operating point, while keeping cost and complexity low. The radar is tested both in a controlled and experimental setting to verify its effectiveness in detecting small-amplitude motions. The results demonstrate that passive radar offers a low-power solution to detecting motion using ambient signals.**

Keywords—passive radar, motion detection, wireless sensors

I. Introduction

Recent trends in smart-home and Internet of Things (IoT) technology have enabled a considerable amount of integration and access to information within a user's home [1]. Advances in wearable and wireless health monitoring have also made users more aware of their own health [2]. With more wireless devices and sensors using IoT, spectrum allocation has become a concern [3]. As such, techniques to minimize the introduction of new frequencies is of paramount importance. Doppler radar has long been used as a method of wirelessly detecting human motion such as heartbeat and respiration [4], and advanced techniques have been used to monitor target beat-to-beat blood pressure and synthesize an EKG [5], [6]. Typically, these methods require the radar to transmit its own carrier frequency, reducing the available bandwidth for other IoT devices and further cluttering the spectrum. Passive radar has been used as a method of detecting motions using existing wireless signals such as Wi-Fi as shown in Fig. 1 [7]. Previous passive Doppler radar designs have used commercial RF building blocks, and as such have a large power consumption and relatively large size making it non-ideal for IoT applications.

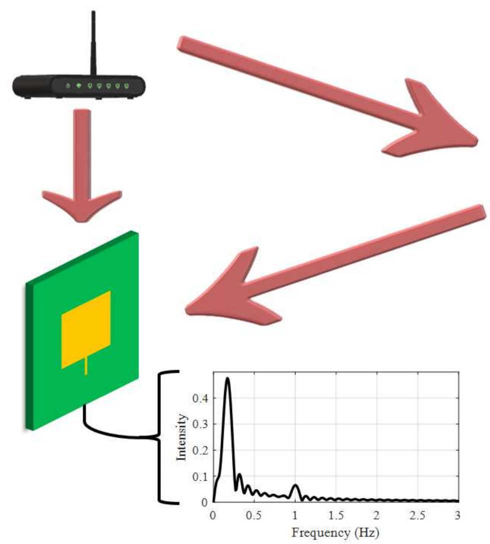

Figure 1. Passive radar motion detection utilizing ambient EM energy to detect human motion. Energy from the third-party transmitter is radiated directly to the receiver, as well as to the target. Energy reflected from the target carries the target's Doppler information.

In this paper, a novel passive radar design is proposed to utilize the 5-GHz Wi-Fi band for detection of small-amplitude motions. The radar is designed using discrete RF components to allow for maximum performance versus power consumption and utilizes an on-board fast-startup baseband amplifier. In addition, the integration of all active electronics on-board reduces the overall size of the system considerably, making it an ideal candidate for future wireless sensing or IoT applications.

II. Theory of Operation

Traditionally, motion detection with Doppler radar uses a co-located transmitter and receiver. The transmitter illuminates the target, while the receiver chain detects and down-converts the signal reflected by the target [4]. So long as the target is not a perfect absorber, the target may be modeled as a source radiating at the frequency of interest. When the target is stationary, no Doppler shift is created. Living targets, however, create microscopic motions from heartbeat, respiration, and tremors that may be detected with a sensitive receiver. In passive radar, although the transmitter and receiver are no longer co-located, the theory of operation remains the same. Any displacement in line from the target to the receiver will create a

Doppler shift that may be detected. One of the most beneficial features of passive radar is the ability to use third-party signals as a carrier frequency for Doppler information. If a simple example is considered, energy radiated by a third-party transmitter may take two paths to the receiver. The first path is the direct path to the receiver while the second has energy reflect from the target to the receiver. The unmodulated path carries no Doppler information but may act as the local oscillator (LO) for down-conversion. The energy reflected from the target carries the Doppler information and may be down-converted to baseband for digitization. It is worth noting, however, that the target may not always be radiating in the direction of the receiver. If, for example, the target is between the transmitter and receiver, very little of the reflected power will reach the receiver. In addition, since the geometry of this application is more complex compared to the monostatic case, new equations for received power must be derived. The two signals of interest are the unmodulated signal direct from the transmitter to receiver, and the modulated signal from transmitter to target, then to receiver. The received power for the unmodulated path can be expressed simply as the received power using the well-known Friis transmission equation. For the modulated path, the equation for received power is more complex. Primarily, since the target may be located at any point, there are two distances that impact the received power, so the radar range equation may not be used. In addition, since the transmitter and receiver are no longer co-located, the radar cross section (RCS) should describe the relationship between the power density at the target and the power radiated in the direction of the receiver. The reflected power may then be given using the standard radar formula, where the target's RCS is defined only for the specific arrangement of target, transmitter, and receiver locations Finally, applying the Friis transmission equation to the equation for reflected power gives the final equation for received power, given in (1) where P_{TX} and G_{TX} are the transmitter power and gain, G_{RX} is the receiver antenna gain, d_2 is the distance from transmitter to target and d_3 is the distance from the target to the receiver.

$$P_{RX2} = \frac{P_{TX}G_{TX}G_{RX}\sigma\lambda^2}{(4\pi)^3 d_2^2 d_3^2} \tag{1}$$

III. EXPERIMENTAL RESULTS

An experimental passive radar system is designed using discrete components in order to allow for optimization in the RF receiver chain while keeping the size and cost low. The system is shown in Fig. 2. A single transistor LNA is implemented using the BFP740ESD. Typically, the input and output of an LNA should be matched to 50Ω to minimize input/output reflection. However, since both the LNA and mixer design is performed as part of this work, the LNA output is not required to be matched to 50Ω, providing more versatility in the design. A single-diode mixer is implemented using the BAT24-02LS. The diode operating point must be chosen carefully in order to minimize the conversion loss, while also providing a reasonable impedance to the output of the LNA.

Before analysis of the baseband signal can be performed, the signal must first be digitized. In order to provide maximum resolution for the analog-digital converter (ADC), a baseband amplifier is needed to boost the baseband signal to an appropriate level. Typically, an AC-coupled amplifier is used to remove the DC voltage of the mixer and clutter reflections, giving the amplifier high-pass behavior. Since, however, the frequencies of human motion can be quite low, the cutoff frequency and startup times can be considerable. In order to alleviate this long startup time, a fast-start circuit is used. To achieve fast-startup, the amplifier should have a low resistance path to charge the input capacitor when power is first applied and switch to a high resistance path once the capacitor is charged to an acceptable level. This condition can be satisfied with a single diode, shown in Fig. 3. When forward biased, the diode presents a low resistance path in order to quickly charge the input capacitor to match V_{bias}. When the capacitor approaches its intended DC level, the diode will cease conducting and will act as an open circuit, allowing the amplifier to perform as designed. This considerably reduces the amplifier's startup time, allowing for accurate readings quickly after initially powering the device. The choice of diode is quite important and comes with tradeoffs. A typical PN diode, for example, has a larger

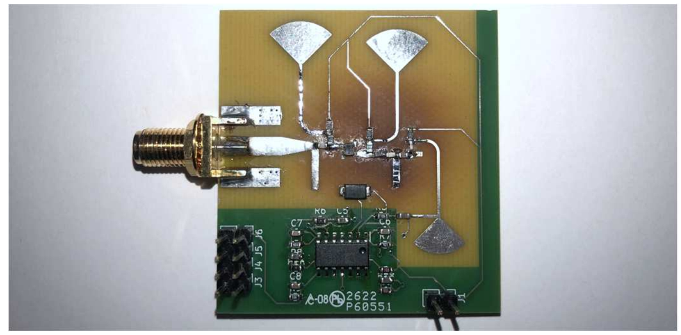

Figure 2. Experimental passive radar system. The signal present on the input is amplified and down-converted in the RF chain. The resulting baseband signal is amplified using an AC-coupled baseband amplifier with fast-start.

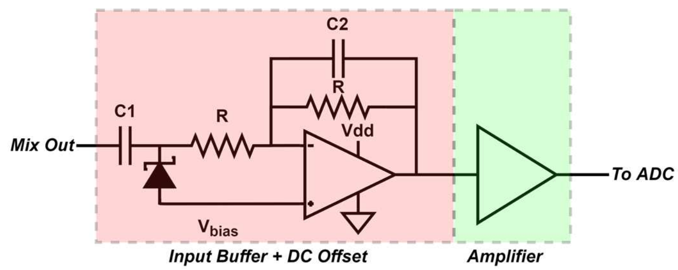

Figure 3. Baseband input buffer and DC offset with included fast-startup diode. When power is applied, C1 is charged through the diode. Once the capacitor voltage is within the forward voltage of the diode, the circuit operates normally.

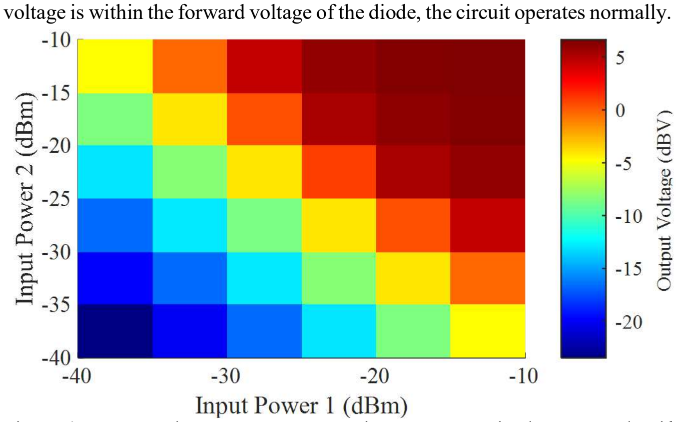

Figure 4. Output voltage versus two-tone input power. It is clear to see that if one tone is strong enough to drive the mixer, sufficient voltage is produced.

forward voltage drop and creates a longer startup time. A Schottky diode may shorten this startup time, but an increased reverse leakage current can unintentionally reduce the amplifier's gain. The RB058LAM was found to be an acceptable diode for the purposes of this work. To further improve the startup time, the input stage is configured as unity gain to minimize the input capacitance. C1 and C2 control the high-pass and low-pass cutoff frequencies, respectively, after a value for R is chosen. The large capacitors present in the remaining amplifier stages do not require a fast-start diode since the DC outputs of the preceding stages are close to the desired voltage, making their startup time small. The baseband amplifier has an overall gain of 60 dB with a passband from 0.2 Hz to 10 Hz.

An experimental setup is used to determine the passive radar's effectiveness with known input powers. Two signal generators are used to create 5.5-GHz tones, one of which with a 5-Hz offset to simulate the RF energy modulated by motion. These tones are joined using a power combiner, then fed into a circulator to ensure that any reflections on the input of the radar do not damage the measurement devices. Each of the two tones are swept from -40 dBm to -10 dBm, and the corresponding output voltage is measured at the output of the baseband amplifier. The results from this input power sweep are shown in Fig. 4. From the results, a semi-linear relationship between input power and output voltage may be seen. Much like conventional mixer design, a strong LO drive is required to ensure optimal performance. In the case of passive radar, the LO would be the direct path from transmitter to receiver. Since the unmodulated path undergoes no reflection and is only attenuated by free-space path loss, it is expected to be higher power compared to the modulated signal, providing the required drive.

In order to determine the radar's ability to detect physical motions, a realistic experimental setup is used. The experimental setup consists of a transmitter operating at 5.5-GHz, an actuator creating small periodic motions, and the passive radar. This setup is shown in Fig. 5. The transmitter is positioned such that both the passive radar and the target receive radiation. The transmitter's output power is 5 dBm. The actuator creates 1.5 mm motion at user-defined frequencies. The output of the passive radar is digitized using an NI-6210 and a fast Fourier transform (FFT) is applied to the time-domain signal. The spectrum after applying FFT is shown in Fig. 6 for various frequencies of motion created by the actuator. The results of the FFT show the small motions created by the actuator can in fact be detected using ambient EM energy and the proposed passive radar, all while only consuming 85 mW of power.

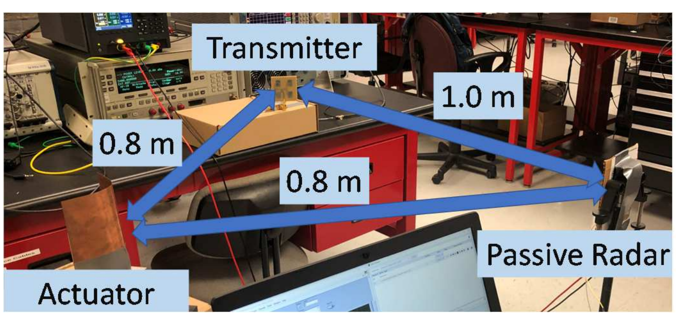

Figure 5. Experimental test setup used to verify passive radar's motion detection capabilities. The actuator creates small motions at specified frequencies which may be detected by the passive radar.

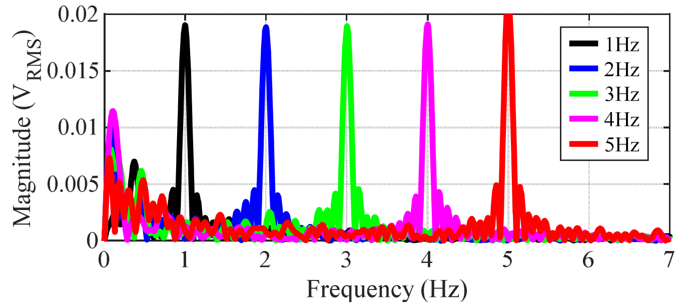

Figure 6. Experimental results using passive radar to detect motion. Using the resulting spectrum, the motion can be isolated using the proposed passive radar.

IV. Conclusion

In this paper, a novel passive radar design operating in the 5-GHz Wi-Fi band is presented using discrete RF components in a board-level design. The design relies on ambient wireless signals to provide an unmodulated path acting as the LO, and a modulated path which contains the target's Doppler information. In addition to the RF components, a fast-startup baseband amplifier is implemented on-board. The fast-startup circuit uses a single diode and a unity-gain buffer to provide the DC offset required for the amplifier to function as intended. Experimental results demonstrate the radar's ability to accurately detect low-frequency, small-amplitude motion. Future works should focus on characterizing the limits of passive radar in realistic scenarios, such as when the target is placed between the transmitter and receiver or when the transmitter radiates in an omni-directional pattern. In addition, work should be performed to determine the feasibility of passive radar when modulation is present on the transmitted signal such as orthogonal frequency division multiplexing or quadrature phase-shift keying in the case of Wi-Fi.

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