A Novel Microwave Architecture for Passive Sensing Applications

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***Abstract*—The use of radio-frequency signals for passive indoor applications has gained significant interest over the last years. By leveraging ubiquitous Wi-Fi signals, the Doppler information of a target can be retrieved after the analysis of measurements associated with the received signal strength (RSS), the channel state information (CSI), or with passive Wi-Fi radar (PWR) techniques. However, RSS and CSI-based strategies require digital signal processing of high computational cost and/or special modifications to the Wi-Fi access point, while PWR-based approaches rely on a reference channel and interference removal algorithms to provide Doppler information. In this work, a novel microwave architecture for passive sensing applications is proposed. By taking advantage of the reflected RF signals and the direct signals from a non-cooperative transmitter, the proposed architecture can provide the Doppler information of a moving target. Experimental results confirm the effectiveness of the proposed scheme for the remote detection of small amplitude motion.**

Keywords—Doppler radar, passive radar, passive sensing, remote detection, spectrum sharing, wireless sensing.

I. Introduction

Passive sensing architectures are designed to exploit the electromagnetic waves emitted by a third-party transmitter to detect and localize targets [1]. The changes on the wireless signals are decoded by monitoring the strength of the received signals, by comparing the propagation characteristics of the communication channel over time, or by correlating the signals arriving after being reflected at a moving target and a reference signal, which is the time-delayed version of the transmitted signal [2]-[9]. Since Wi-Fi access points, Bluetooth signals, wireless power transfer, and the electromagnetic waves leaked from commercial microwave ovens are ubiquitously present in indoor scenarios, many efforts have been made to evaluate the feasibility of using passive sensing approaches to leverage these signals as illuminators.

Conventional passive sensing works have demonstrated human motion detection using captured wireless signals emitted from co-existing Wi-Fi devices. Received signal strength (RSS) and channel state information (CSI) are the main measurements used to enable passive detection using Wi-Fi signals. Wi-Fi-based RSS has been used for indoor occupancy sensing [3]. However, it suffers from unpredictable fluctuations in the communication link due to the existence of multiple reflections and scattering paths even in a static illumination scene. CSI-based systems extract fine-grained measurements obtained after the interaction between wireless signals and

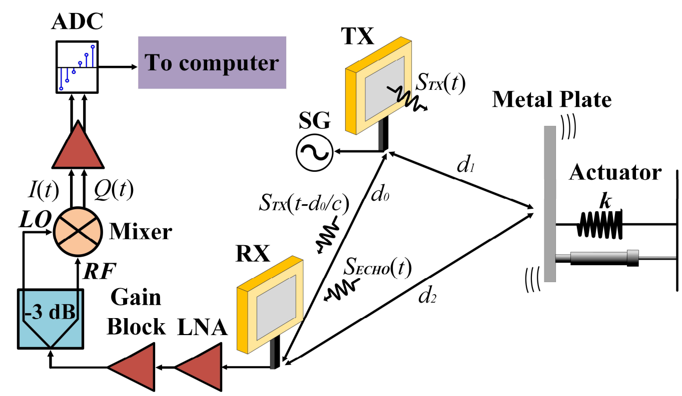

Fig. 1. Block diagram of the proposed microwave passive sensing technique.

surrounding moving objects/human subjects. For example, [4] employs CSI data to provide remote finger gesture recognition. In [5], CSI-based human activity recognition is studied. The major challenge for CSI systems is the constant changes in the surrounding environment, which considerably affects the communication channel requiring a training phase for each environment. In addition, they rely on a laptop or PC with a modified Wi-Fi network interface card to act as a receiver.

Passive Wi-Fi radars (PWR) have also been reported. In contrast to RSS and CSI-based systems, PWR systems allow the detection of moving targets through the cross-ambiguity function (CAF), which is evaluated by comparing the reference and the surveillance channels without any prior modification to existing Wi-Fi devices [7]-[8]. Nevertheless, a reference receiver is required in the same detection environment as the transmitter, and the reference and the surveillance channels' clocks must be synchronized. Also, PWR-based approaches are heavily affected by direct signal interference (DSI) and require DSI removal algorithms to obtain accurate Doppler information. Although the existing passive sensing techniques may accomplish the goal of taking advantage of pervasive Wi-Fi signals, they still require the use of customized RF transceivers and algorithms of relatively high computational cost to achieve robust detection.

In this work, a novel microwave architecture for passive sensing applications is proposed. The capability to simultaneously retrieve both the transmitted signal from a non-cooperative microwave source and the signals scattered by a target is the key to enable the identification of Doppler frequencies associated with the target of interest. Neither hardware modification nor synchronization to the signal source is needed, and a simple Fourier-based analysis of the baseband responses is used to extract the Doppler information of a moving target. The experimental results obtained in this paper demonstrate the feasibility of the proposed approach.

II. THEORY

In a typical Doppler transceiver, a single-tone radio-frequency (RF) signal is divided in two paths. One is transmitted towards a moving target, while the other is sent to the local oscillator (LO) port of an RF mixer in the receiver chain. Part of the backscattered RF signals, which has the target's motion information modulated in phase, is captured by the receiving antenna. After amplification, the captured received signal is directly sent to the second input port of a RF mixer, namely the RF port, so it can be down-converted to baseband. In contrast, the proposed passive sensing device does not have an RF transmitter and does not use any dedicated reference signal path to recover the transmitted signal.

Fig. 1 details the block diagram for the proposed microwave passive sensing technique. The transmitted signals produced by an active microwave signal source such as Wi-Fi access points or a Bluetooth signal source can be leveraged. In this work, a signal generator (SG) operating at 2.4-GHz was employed as the active microwave signal source. Some of the transmitted signals ($S_{TX}(t)$) are phase-modulated by the target's motion, which is produced by a metal plate that moves periodically with the help of a mechanical actuator. The nominal distances between the TX and RX antennas, between the TX antenna and the metal plate, and between the RX antenna and the metal plate are d_0, d_1, and d_2, respectively. Part of the microwave signals ($S_{ECHO}(t)$) is backscattered towards the passive sensing device, where it is mixed with a delayed version of the transmitted signal ($S_{TX}(t-d_0/c)$) and with itself. The normalized baseband signals can be mathematically expressed as $I(t) = \cos(4\pi x(t)/\lambda + \theta)$ and $Q(t) = \sin(4\pi x(t)/\lambda + \theta)$, where $\theta = 4\pi(-d_0 + d_1 + d_2)/\lambda$ is the phase delay associated with the direct transmission path, and the phase delays due to the TX antenna-metal plate path and metal plate-RX antenna path. λ is the wavelength of the transmitted signal $S_{TX}(t)$, and $x(t) = m sin(\omega_0 t)$ is the mechanical motion of the metal plate with m and ω_0 being the motion's amplitude and frequency, respectively. Therefore, the metal plate's motion can be estimated by analyzing the recovered baseband I/Q responses in the time and frequency domains.

III. EXPERIMENTAL RESULTS

To validate the feasibility of the proposed application, experiments were conducted to measure the mechanical motion of an actuator (Zaber T-NAO8A50) using a 2.4-GHz microwave passive sensing device (MPSD) as depicted in Fig. 2. A rectangular metal place with dimensions of 10 cm $\times$ 10 cm was attached to the actuator. The distance between the MPSD and the metal plate was approximately 1.3 m. The distance between MPSD and the active microwave signal source, i.e., a signal generator (SG) operating at 2.4-GHz, was 1.3 m. A microwave cable connected the SG to a 2.4-GHz patch antenna (TX). The RF output power at the input of the TX antenna was measured as 8 dBm. The distance between the TX antenna and the metal plate was 1.3 m. The gain of the TX/RX patch antennas is 5.8 dBi. The actuator was programmed to produce a periodic sinusoidal movement of 1 Hz with a peak-to-peak amplitude of 1 mm to evaluate the proposed device's sensitivity.

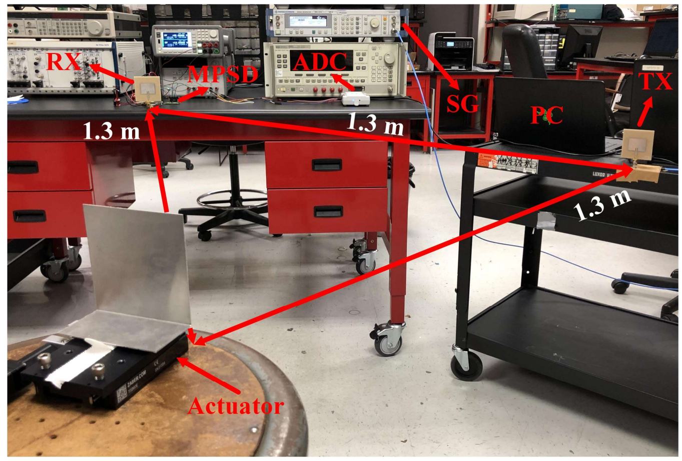

Fig. 2. Experimental setup.

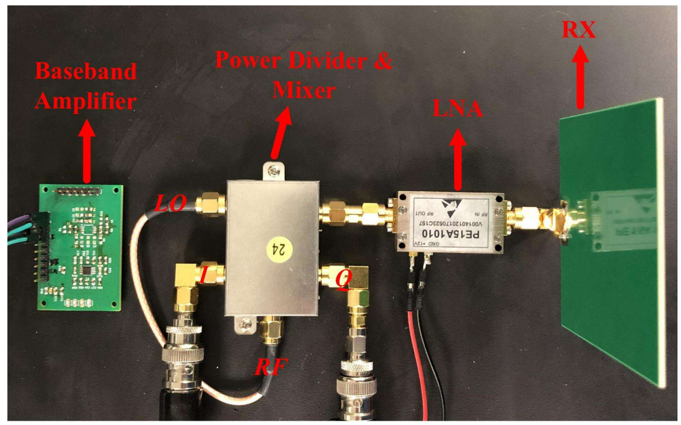

Fig. 3. Photograph of the proposed microwave passive sensing device.

Fig. 3 depicts the proposed MPSD. A 41-dB low-noise amplifier (LNA) designed by Pasternack (PE15A1010) was placed at the RF front end of the proposed device. Its noise figure and its input referred P1dB are -25 dBm and 0.9 dB at 2.4-GHz, respectively. Although the relatively high-gain LNA boosted the weak signals reflected by the moving target, its wideband input matching (2 – 6 GHz) also allowed the coupling of other undesired signals, which contributes a possible increase in the noise floor. The received signal is then sent to a demodulator module, which consists of a power divider and a RF mixer. The power divider immediately follows the LNA and allows the separation of the received signals in the *LO* and *RF* signals, which are the inputs of the RF mixer. The RF mixer used in this work is a passive quadrature mixer optimized to operate at 2.4-GHz. A signal of at least 1 dBm should be applied to the *LO* port of the passive mixer, which also explains the use

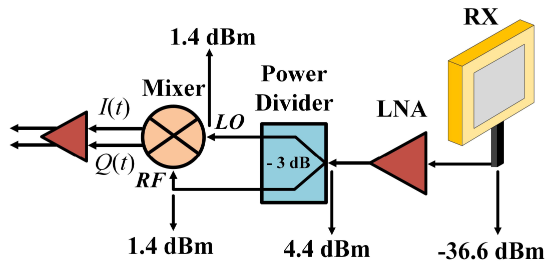

Fig. 4. Power level of the received microwave signals at the input of each RF component for the proposed passive sensing microwave architecture

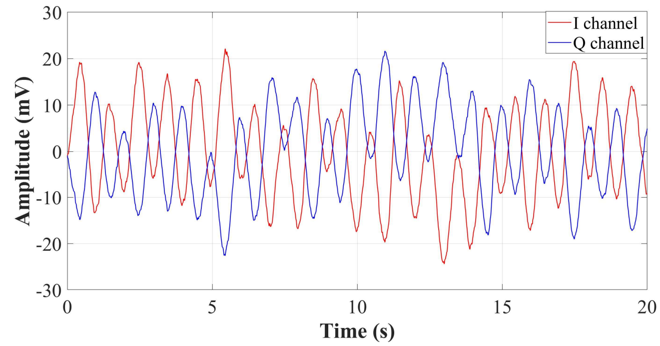

Fig. 5. Experimental results. Recovered I/Q baseband signals.

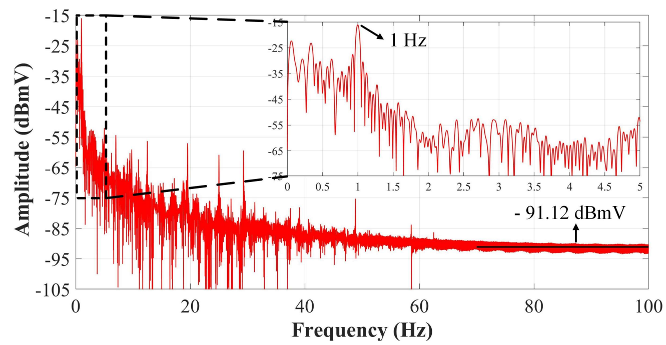

Fig. 6. Experimental results. Spectra of the recovered I/Q baseband signals.

of the high-gain LNA. The power level of the received microwave signals at the input of each RF component of the proposed passive sensing device is exhibited on Fig. 4. Finally, the quadrature I/Q baseband signals are further amplified by a baseband amplifier with a baseband gain of 100 V/V. The baseband outputs were digitized using a 16-bit analog-to-digital converter (ADC) DI-2108 designed by DATAQ. The sampling frequency was 200-Hz.

Fig. 5 details the recovered I/Q baseband signals, after applying a moving-average approach along each channel. Each mean is calculated over a sliding window of length 100 elements across neighboring elements of each baseband channel. This smooths the received signal and eliminates high-frequency random interferences coupled to the passive microwave system. It should be noted that the proposed device was able to successfully detect the moving metal plate as shown in Fig. 5. In Fig. 6, the corresponding spectra of the recovered I/Q baseband signals is illustrated. The fundamental frequency of the target's motion (1 Hz) is highlighted. The noise floor level was obtained by averaging the spectral power over frequencies higher than 70 Hz. It was estimated as -91.12 dBmV as highlighted on Fig. 6, while the power level of the fundamental tone was estimated as -16 dBmV, which confirms the effectiveness of the proposed fully passive microwave architecture for the detection of low-amplitude motions.

IV. Conclusion

This paper investigated the feasibility of using a novel microwave architecture for passive sensing applications. By simultaneously injecting the delayed version of the transmitted signals of an RF illuminator and the corresponding phase-modulated signals into the RF and LO ports of the RF mixer, the detection of a 1 mm amplitude motion was successfully achieved, when the proposed device was placed 1.3 m away from the active microwave source and a vibrating target. Also, no reference channels or high complexity digital signal processing techniques were used in this work. Future research will focus on the study of the limitations of the proposed approach for indoor applications, and the extension of the proposed strategy for range-Doppler capability.

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