Secure Occupancy Sensing with Passive Radar for Spectrally Congested Spaces

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***Abstract* — Room occupancy detection and people counting technologies, especially in a manner that is discrete and undetectable, have the potential for application in numerous scenarios, from healthcare to security. While various sensors, including Doppler and FMCW radars, have previously been used for these purposes, passive radar can achieve similar results without any additional spectrum requirements by leveraging their bistatic geometry and third-party transmitters. This work presents a study that uses passive radar to detect persons entering and exiting a room using simple processing techniques for a low-cost sensing system. Different orientations and locations for the radar and transmitter are tested, and time-domain and frequency-domain results are analyzed. The benefits of time-domain analysis are discussed, with the results demonstrating the capability of passive radar to distinguish between persons entering, exiting, and passing by the room and the potential for occupancy detection, people counting, and surveillance applications.**

Keywords—passive radar, passive sensing, occupancy detection

I. Introduction

Occupancy detection is useful in many areas of life, including in smart buildings to help control functions such as lighting and heating, healthcare, surveillance, and more. This may help improve working environments, living conditions, and security, as well as save energy and benefit inhabitants during pandemics such as COVID-19 [1]. For example, by monitoring the number of inhabitants within a room, occupancy detection systems can ensure proper social distancing protocols are followed by preventing overcrowding.

Current solutions for occupancy detection include cameras, infrared, and ultrasound sensors. These methods, while prevalent, are not ideal, as they face problems such as privacy concerns and various inaccuracies. For example, all three types of sensors would be unable to detect a human hidden by an obstacle such as furniture, and can return false readings when occupants do not make large movements for extended periods of time [2]. Additionally, methods such as wearables can be impractical and obtrusive.

Radar sensors have also been used for occupancy detection purposes, as they present the benefit of accuracy and are not limited by obstacles due to their ability to penetrate solid surfaces [3]. However, Doppler and FMCW radars have bandwidth requirements and thus contribute to spectrum congestion. Furthermore, their presence in the spectrum makes active radars susceptible to detection, tampering, and electronic countermeasures, which can pose security risks. These properties also make active radar detection systems unsuitable for large-scale implementation.

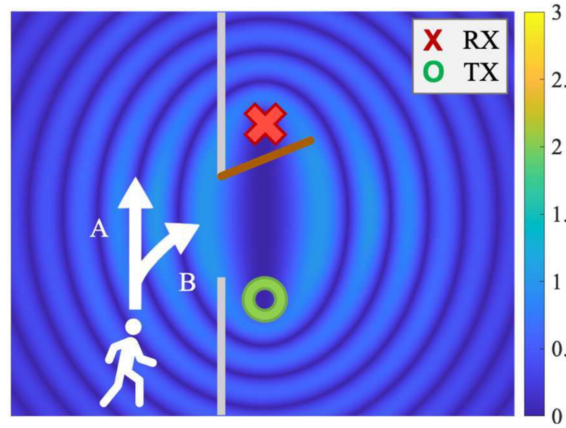

Fig. 1. Iso-range contours formed by radar and transmitter. Along Path A, few contours are crossed, creating a weak signal. However, along Path B, contours are crossed rapidly, creating a strong signal to perform occupancy monitoring.

Passive radar presents a viable alternative to existing solutions. The nature of passive radar, which receives signals from third-party transmitters rather than sending them itself, means that this method not only conserves power, but is also undetectable through spectrum sensing and other means of detection. Thus, passive radar can easily be integrated into the building environment or covert security systems. Previous studies have been performed using passive radars and local Wi-Fi networks to detect vital signs of occupants within a room [4]. Alternatively, this paper proposes the use of passive radar to monitor the entering and exiting of a room as a simpler way to monitoring the entirety of a room. This method provides the benefits of being unobtrusive, energy- and spectrum-conserving, and simple to implement at scale, while maintaining the capability of detecting the subjects' walking directions.

In this work, the theory of passive radar is discussed to provide background on the benefits of these systems as compared to active radars. Then, passive radar sensors and accompanying transmitters are tested in different orientations, locations, and angles. The sensor placement for optimal detection, maximizing the quality of the data collected without

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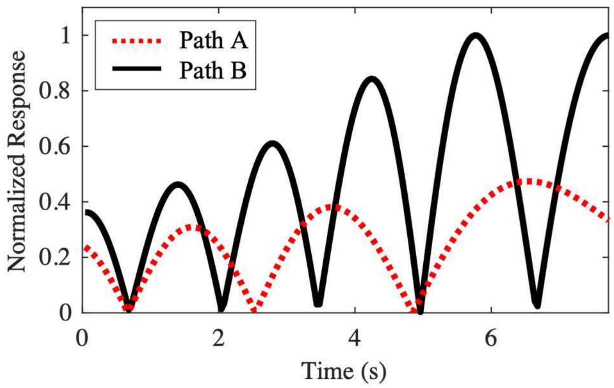

Fig. 2. Graph of the intensity of the iso-range contour graph along the respective paths shown in Fig. 1. Path A simulates a person passing by outside, while Path B simulates a person entering the room.

sacrificing the covertness of the system, is determined. The data collected from multiple subjects walking into, out of, and past the doorway is analyzed in both the time-domain and frequency-domain, with results showing that passive radar can clearly distinguish between these scenarios. These results ultimately demonstrate the potential for passive radar as an unobtrusive and undetectable solution for occupancy detection and people counting, especially in locations where a high number of connected devices may be present.

II. Theory

Due to the bistatic nature of passive radar, elliptical iso-range contours are formed with the radar and the transmitters at the foci [5]. These contours, shown in Fig. 1, provide distinct advantages that make differentiating between people entering and exiting a room or passing by the doorway much simpler, as the radar produces a response as the subject crosses the contour lines. As the subject passes by the room, they walk nearly along the contours, resulting in weak or non-existent signals at the output of the radar. However, if the subject enters or exits the room, they would rapidly cross many of these contours, resulting in a larger bistatic velocity and a larger, higher-frequency signal response that reflects as a peak in the time-domain and frequency-domain graphs. Two such curves are shown in Fig. 2 where it is seen that Path B creates greater fluctuation in the baseband signal. This property makes passive radar optimal for this type of detection and eliminates the need for time-consuming and complicated analysis.

III. Experiments and Results

A. Experimental Setup

This study uses the passive radar architecture detailed in [6] and a 5.7-GHz transmitter powered at 10 dBm to emulate a simplified, single-tone version of a third-party signal source, such as a Wi-Fi router. The time-domain baseband signal was sampled at 5000 Hz and later plotted along the time-domain and frequency-domain to demonstrate how the baseband frequency detected by the radar changed depending on the actions of the subjects.

Experiments were initially performed multiple times with the radar and transmitter arranged at various positions and a smaller test group to find the optimal configuration of the radar and transmitter to maximize the detection ability while remaining unobtrusive. After analyzing the data, the results showed that the arrangement in Fig. 3, with the radar concealed behind the door and the transmitter located on the opposite side, both at hip height and pointed towards the room, achieved the best balance between the quality of the data collected and the concealment of the radar. This angle of the radar and transmitter allows for the detection of the direction of the subject passing through the doorway, as more signal will be received while the subject is inside the room as compared to when they are outside. Furthermore, the angle of the radar and transmitter creates asymmetry in the resulting time-domain results, making it possible to determine whether the subject was entering or exiting the room. This arrangement presents the benefit of covertness while still being capable of detecting the movements of the subject into and out of the room. In future implementations, the transmitter could be placed on the wall or above the doorway and the radar attached behind the door to be even more discrete.

After determining the ideal experimental setup, three subjects of differing heights walked past the doorway, both inside and outside of the room, and entered and exited the room from various directions to simulate realistic situations. Data was collected for all cases.

B. Results

The results collected were graphed as a function of time for each experiment as shown in Fig. 4. The column of Fig. 4(a) shows the time-domain graph for subjects walking back and forth once by the doorway from outside the room, the column of Fig. 4(b) shows the results from a subject walking back and forth once by the doorway from inside the room, and the column of Fig. 4(c) shows the subjects entering, pausing, and then exiting the room. The graphs for every subject exhibited similar features that allowed for characterization of the movement of the subject.

As the subject enters or exits the room, a peak occurs in the data due to their proximity to the sensors and the large number of iso-range contour lines crossed rapidly. As the subject passes by the sensors in the hallway or room, very weak signals are detected if any at all, as the subjects' distance from the sensor and movement direction result in low-frequency, low-amplitude signals. These graphs show an evident difference in data when subjects are entering or exiting the room, as compared to when they are just passing by. This suggests that passive radar may be

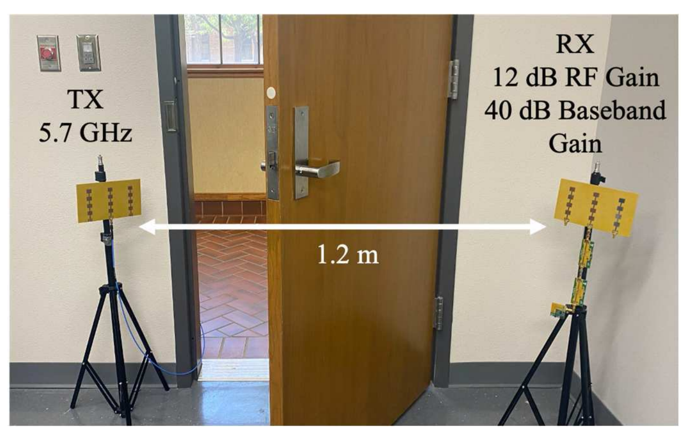

Fig. 3. Optimal experimental setup to maximize detection ability and provide directionality while preserving covertness.

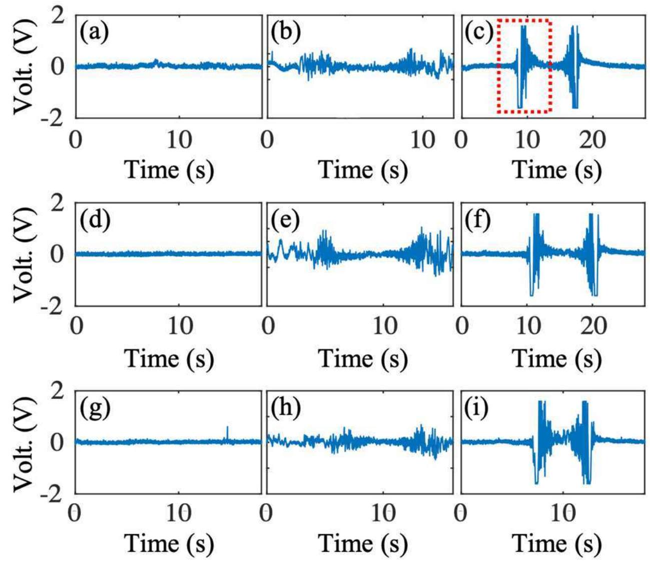

Fig. 4. Time-domain graphs of subjects passing by outside the room are shown in (a), (d), and (g). Graphs of subjects passing by the doorway inside the room are shown in (b), (e), and (h). Graphs of subjects entering and exiting the room are shown in (c), (f), and (i).

a valuable tool in occupancy sensing due to its unique ability to distinguish between these situations.

Furthermore, as subjects enter the room, there is an identifiable asymmetry as marked in Fig. 4(c). As the subject reaches the doorway, there is a distinct dip in the data before the signal peaks sharply, and as the subject exits the room, the graph is mirrored, with the large peak occurring before the dip. This makes it possible to identify whether the subject is entering or exiting the room and demonstrates the potential of this system for automated people counting in future works.

The respective frequency-domain graphs of each situation can also be seen in Fig. 5. In each spectrogram, the movements of the subject can be observed in more detail. The dip as the subject crosses the doorway can also be identified in the marked box (Fig. 5(c)), as aligned with the time-domain graphs. Additionally, peaks corresponding to the footsteps of the subjects are visible as well. A possible consideration for data processing is time-domain versus the frequency-domain analysis. While frequency-domain graphs may yield more information in future works, spectrograms are resource-consuming for low-power portable devices. On the other hand, time-domain analysis has more potential for future applications, as the time-domain graphs shown are simpler and less costly to generate and provide sufficient information to distinguish between subjects passing into, out of, and by the doorway.

IV. Conclusion

This study demonstrates the effectiveness of passive radar sensors when applied to occupancy detection and people counting by monitoring doorways. Due to the iso-range contours formed by the passive radar and transmitter, the bistatic velocity of subjects passing through or by the doorway varies greatly. This characteristic makes passive radar well-suited for occupancy detection. This study tested the optimal configuration of the passive radar and transmitter for this purpose, determining

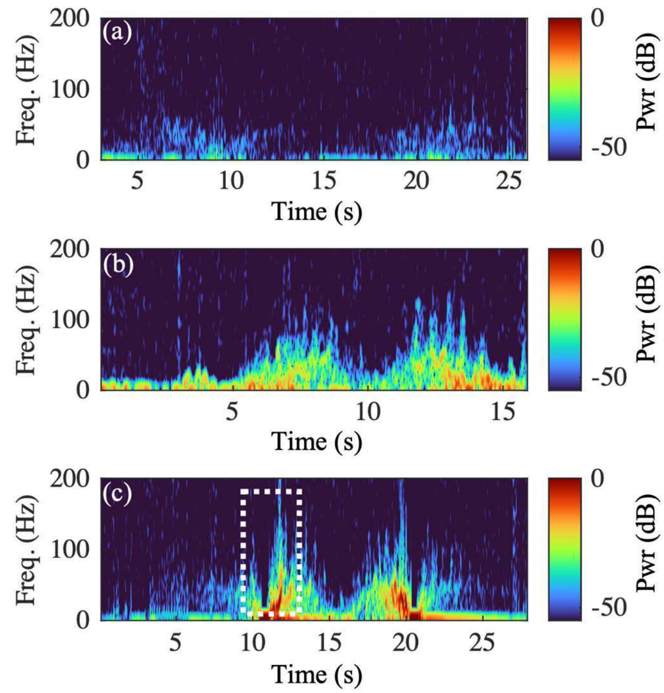

Fig. 5. (a) Spectrogram of subject walking past doorway from outside the room. (b) Spectrogram of subject walking past doorway from inside the room. (c) Spectrogram of subject entering and exiting the room.

suitable placement to collect high-quality data while remaining inconspicuous. Experimental results were collected for the movements of three subjects passing through and by the doorway. With minimal data processing, the radar system used can distinguish between subjects entering, exiting, and passing by the doorway. The data for multiple subjects, when analyzed in the time-domain, show identifiable and consistent features for classifying the subjects' movements. These findings demonstrate that passive radar systems hold potential for future people-counting applications and imperceptible security systems. Future works may utilize more robust systems with multiple sensors and realistic transmitters to optimize results.

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