A Digital Beamforming Approach for Indoor Passive Sensing

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***Abstract*—Passive sensing leverages ambient electromagnetic energy to detect target metrics such as distance or motion, reducing the spectral footprint for sensor networks. Recent advancements have shown passive sensing's ability to sense sub-millimeter scale motions, highlighting the potential for passive sensing to be used in spectrally efficient sensor networks. This paper proposes a passive sensing beamforming technique to achieve direction estimation in passive motion sensors. By performing beamforming in the baseband domain, the direction of a target can be extracted without requiring complex beamforming architectures at the RF front end. A passive beamforming signal model is proposed based on wave propagation models and is simulated to verify its ability to detect angle-of-arrival. The model is then tested experimentally, with results showing the model matches experimental data to a high degree of accuracy and that the beamforming passive radar can accurately determine the position of moving targets to aid in robust sensing.**

***Keywords*—beamforming, passive radar, passive sensing.**

I. Introduction

Passive sensing has recently seen considerable advancement with new software techniques [1], [2] and hardware architectures [3]–[5] allowing for noncontact measurement of target distance, direction, and motion. New passive radar motion sensors leveraging single-diode mixers have demonstrated the ability to sense target motions on the sub-millimeter scale in a method resembling that of Doppler radar motion sensing [4], allowing for accurate measurement of small motions without requiring additional spectrum usage. This decrease in spectral footprint along with the reduction in power consumption due to the lack of a transmitter chain allows a higher number of sensors to be deployed in congested environments, making passive sensing a candidate for future distributed sensor networks.

The current state-of-the-art has seen passive sensing detect motions with peak-to-peak amplitudes below 1 mm [3], [5], as well as accurate detection of human vital signs [4]. These systems use only a single sensor, however, and as such cannot determine the direction of a moving target nor are they able to extract motions from multiple targets simultaneously. Since passive radar leverages third-party illuminators, the sensor cannot expect cooperation from the transmitter and as such should be able to isolate the angle-of-arrival internally to accomplish more robust sensing in realistic environments. Software-defined passive sensing approaches have shown the ability to detect human motions using two receive channels [1] as well as reference-free approaches [6], but require relatively large and complex systems compared to active motion sensors. Beamforming has been achieved in prior passive sensing systems [7], but has not been demonstrated with the small motions required for indoor human activity sensing.

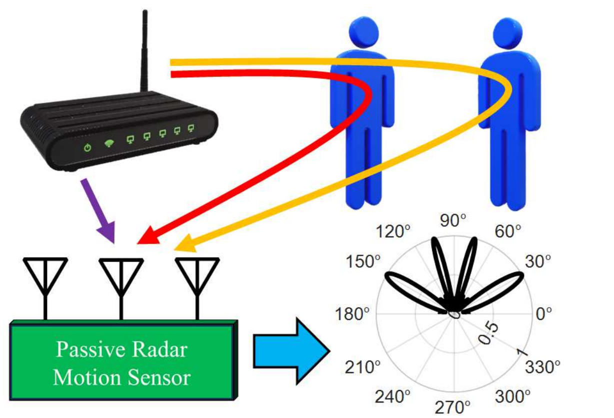

Fig. 1. Example passive radar beamforming system. By leveraging the relative phase between receiver elements, response vs. angle may be measured to provide multiple target localization and angle estimation.

This paper presents a novel passive radar beamforming technique as a method for providing angular resolution to passive indoor motion sensors. The proposed method utilizes multiple sensors along with a digital beamforming algorithm to extract target direction and ultimately allow for simultaneous sensing of multiple targets. The paper is organized as follows: Section II presents the theory of passive radar beamforming and develops the model to be used in Section III as a simulation study. Section IV discusses the experimental setup and results used to verify the accuracy of the model, and conclusions are drawn from the results in Section V.

II. Passive Beamforming Theory

Passive radar motion sensing leverages third-party illuminators in order to sense and characterize small motions. The architectures in [3]–[5] accomplish sensing using a single channel that receives a continuous-wave signal along two paths: one that is received directly from the transmitter, and another that is scattered from the moving target before being received. The received RF signal can be represented as

$$R(t) = A_D\cos(\omega_c t - kd_1) + A_M\cos(\omega_c t - kd_2(t)) \quad (1)$$

where k is the wave phase constant, d_1 is the path distance for the direct signal, and $d_2(t)$ is the distance for the scattered signal.

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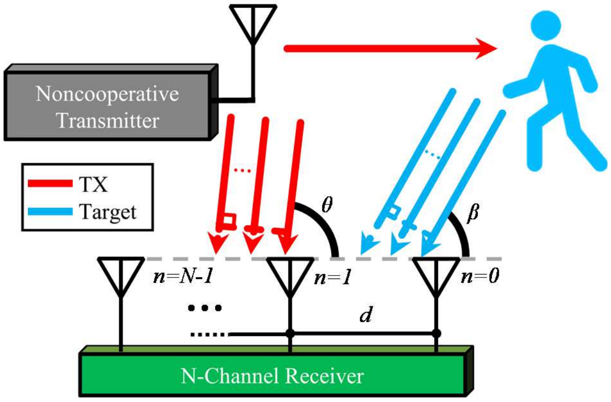

Fig. 2. Passive radar beamforming diagram. The overall phase shift between elements is dependent on both target and transmitter location, requiring the radar to know the position of the transmitter before beginning measurement.

To extract angle of arrival information, a system such as that shown in Fig. 1 can be used where multiple receive elements provide a known relative phase shift that can be used to extract target direction. The output of the radar may be used to synthesize a visual indication of target direction, shown by the output of the passive sensor in Fig. 1. If multiple receiver channels are collocated, (1) can be modified to account for the phase delay between channels. Since the direct and scattered signals can be located at arbitrary points, each of the received signal components will be subject to an independent phase shift. Using the diagram shown in Fig. 2, an expression for the received signal at the n^{th} receive channel can be represented as:

$$R_n(t) = A_D\cos(\omega_c t - kd_1 - knd\cos(\theta)) + A_M\cos(\omega_c t - kd_2(t) - knd\cos(\beta)) \qquad (2)$$

where θ is the incidence angle of the direct signal and β is the incidence angle of the scattered signal encoding the motion.

Using a nonlinear device to downconvert the two tones, the Taylor series expansion method in [8] can be used to find the baseband output from the nonlinear device to be:

$$\begin{aligned} x_n(t) &\approx \cos(k[d_2(t) - d_1 + nd(\cos(\beta) - \cos(\theta))]) \\ &= \cos(k[d_2(t) - d_1] - n\varphi) \end{aligned} \qquad (3)$$

where φ is the difference between the induced phase shifts in the direct and scattered signal paths. By leveraging baseband beamforming, the angle-of-arrival for a target can be resolved by employing digital signal processing techniques. Similar to traditional digital beamforming, (4) may be used to measure the response for a given φ using N independent receive channels.

$$x(t) = \sum_{n=0}^{N-1} e^{jn\varphi} x_n(t) \qquad (4)$$

It is worth noting that, since the employed passive radar architecture cannot perform quadrature demodulation, an additional ambiguity is introduced in the angle-of-arrival estimation created by the lack of *I/Q* data. In an intuitive sense, the even symmetry of the cosine function causes the rotation in the complex plane produced by $e^{jn\varphi}$ to create constructive interference both in the $+\varphi$ and $-\varphi$ cases. This "left/right" ambiguity will be evident in both simulation and experimental results, creating a "ghost target" in the sensing environment. However, these effects can be removed by properly choosing the installation location of the beamforming passive sensor such that the "ghost" target could not realistically be present in the sensing environment given the constraints of the room.

III. Simulation Study

In order to provide a basis for rapid evaluation and interpretation of the physical model for passive sensing beamforming, a simulation is developed to dynamically solve the received signals given parameters of the radar such as carrier frequency, antenna spacing, and number of channels and the physical layout of the sensing environment. The simulation will then construct a baseband signal for N channels and apply a scanning algorithm to visualize the target's direction. The results from this simulation study are shown in Fig. 3 for a variety of test cases using 16 receive elements. From the results, the ambiguity can be seen in the form of a "mirroring" around the direction of the transmitter. It is important to note that due to the off-board origination of the illuminator signal, the measured phase shift is relative to the progressive phase shift of the illumination signal between receiver channels. As such, the left/right ambiguity is observed with respect to the direction of arrival of the transmitter. In Fig. 3(a), the target at 60° can be seen alongside a mirrored image at 120°. When the target is moved to 75°, both the real and mirrored response are moved accordingly as is shown in Fig. 3(b). When the transmitter is moved to 60° with a target at 30°, it is observed in Fig. 3(c) that the ambiguous response is shifted such that the relative phase difference exactly matches that of the real target. Finally, Fig. 3(d) shows a case with two targets where both target responses are isolated, providing theoretical verification that passive sensing beamforming can be used to measure multiple target motions and angles for localization in 2D space.

IV. Experimental Results

In order to verify the models, an experimental setup is developed using two 5.8-GHz passive radars. The experiment leverages two radar receive channels to accomplish direction of arrival estimation in a lab environment along with two CW microwave signal sources to simulate the transmitter and target responses and to produce a known baseband response that can be readily compared with the proposed model. The distance between receiver channels is selected to be 75 mm to provide a larger overall aperture at the cost of introducing grating lobes to

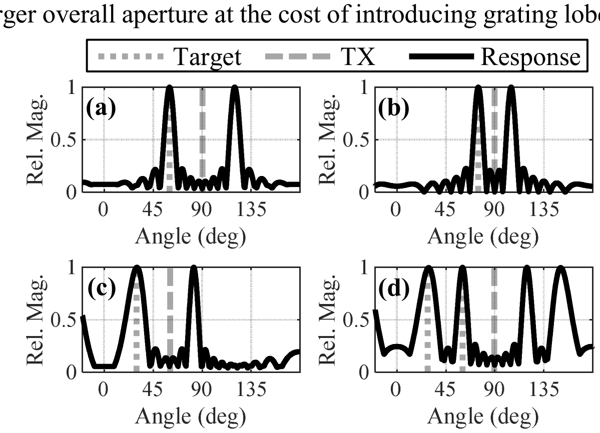

Fig. 3. Passive radar beamforming simulation study results. The graphs in (a) and (b) highlight the ability to track a single target while (c) shows the effects of moving the transmitter and (d) shows the potential for multi-target sensing.

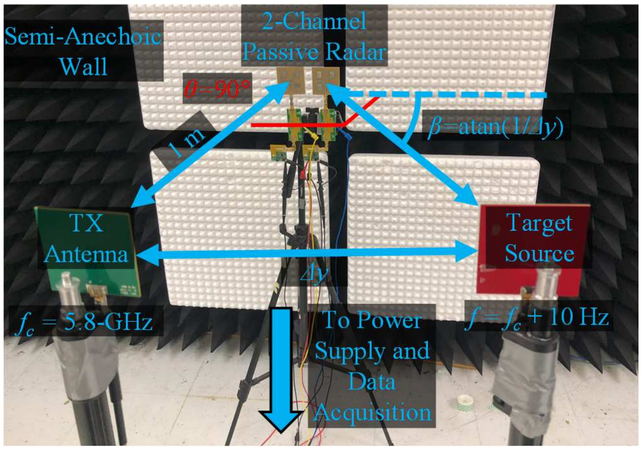

Fig. 4. Passive beamforming experimental setup. The target source creates a constant baseband output frequency and is moved parallel to the radar to allow for precise angle measurements and comparison with simulation.

the system. Each receiver channel utilizes the single-channel architecture discussed in [5]. The two 5.8-GHz microwave signal sources are operated at 10 dBm and are synchronized and offset by 10 Hz to produce a 10 Hz sinusoidal baseband response after downconversion.

The time difference of arrival at the two sensors will induce a relative phase shift between the baseband signals, which is used to extract angle information using the scanning technique discussed in Section III. The signal sources begin at the same location broadside to the sensors, and the output of the passive radar is digitized and stored for later processing. Measurements are repeated as the target source is moved parallel to the plane of the sensor, allowing for precise measurement of the ground truth angle of arrival. The overall experimental setup is illustrated in Fig. 4. For each measurement, the collected data is compared to simulated results using the same radar parameters to evaluate the accuracy of the proposed beamforming models.

A. *Results Comparison*

The results from the 2-channel experiment alongside accompanying simulation results are illustrated in Fig. 5. The resulting experimental and simulated spectra for a target at 90°, 108°, 120°, and 135° are shown in Fig. 5(a)-(d), respectively. From the results, a clear correspondence between the simulated

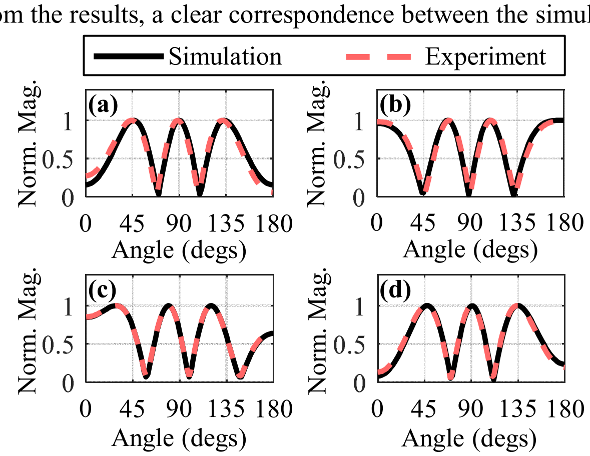

Fig. 5. Passive beamforming results. From the results, a target at 90° is seen in (a), and progressively moves to 108° in (b), 120° in (c), and 135° in (d). The results in (d) match those in (a) due to the grating lobes present in the system.

and experimental results can be observed, demonstrating the accuracy of the proposed beamforming model and the ability for the architecture to extract angle-of-arrival information. In addition, it can be seen that the results in Fig. 5(a) almost exactly match those in Fig. 5(d) due to the presence of grating lobes. In this case, it is not possible to distinguish between a target at 135° versus a target at 90°. Furthermore, the relatively small number of channels limits the accuracy of the sensor due to the interactions between the real and "ghost" targets. However, adding additional channels and reducing the antenna distance will remove the grating lobes and improve angular resolution, as was shown in Section III, while proper placement of the sensors can mitigate the impact of "ghost" targets. Additionally, it is important to note that the proposed model relies on the precise angle of the transmitter to extract the direction of the target. If the transmitter angle is unknown, an additional calibration step would be needed to remove the measurement error.

V. Conclusion

This paper presented a novel beamforming model for indoor passive motion sensing and localization using advanced circuit architectures. The proposed beamforming model leverages fundamental characteristics of passive motion sensing to extract the direction of a scatterer using multiple independent radar receivers and is verified through simulation to be capable of accurate angle estimation. In addition, a new ambiguity introduced due to the lack of quadrature data is discussed from a theoretical perspective and is verified through simulation and experimental tests. A 2-channel beamforming passive radar leveraging two independent receiver channels is used to detect the angle of arrival in an experimental demonstration, verifying the ability for passive radar beamforming to detect the direction of scatterers when the transmitter direction is known. Future works should further develop the system to include more receive channels to provide higher angular resolution and perform more rigorous experimentation with small motions and realistic wireless signals. In addition, work should be performed toward a novel architecture capable of quadrature demodulation to accomplish more robust sensing and remove the introduced left/right ambiguity.

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