Null/Optimum Point Optimization for Indoor Passive Radar Motion Sensing

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***Abstract*—Indoor passive radar has gained traction as a method for measuring small-amplitude motions without requiring a cooperative signal to be transmitted by the sensor. Ubiquitous signals such as Wi-Fi and Bluetooth may be used as illuminators of opportunity in order to measure the motion of various targets. Both the direct, unmodulated signal as well as the Doppler-shifted signal are received at the radar and are used for down-conversion to baseband. Since there is no cooperative local oscillator used in passive radar, it is not currently possible to effectively extract both the *I* and *Q* channel data making null-point detection a returning problem. In this work, the null-point detection problem is analyzed theoretically to develop a simulation model for passive radar sensing. Using this model, an in-depth analysis is undertaken in order to determine the effectiveness of methods such as channel selection, frequency tuning, or multi-band/multi-static sensing in removing or mitigating the null-point detection problem. The results demonstrate that despite the presence of the null-point issue, it is possible to reduce its impact on motion detection and optimize the detection sensitivity.**

Keywords—passive radar, passive sensing, multistatic radar, null-point detection

I. Introduction

New smart-home technologies and advances in wireless health monitoring have allowed consumers to easily obtain insight into their health as well as integrate their devices into their home's ecosystem [1], [2]. As the number of wireless sensors increases, the issue of bandwidth allocation becomes considerably more prominent and new transmitting devices may cause unwanted interference [3], [4]. Passive radar circumvents this issue by leveraging ubiquitous wireless signals such as Wi-Fi, Bluetooth, or DVB-S to accurately characterize motions without adding to the spectrum [5], [6]. Passive radar utilizes the direct, unmodulated signal that travels directly from a third-party transmitter to the receiver and the signal reflected from a moving target in order to characterize the target's motion by mixing the two signals [7]. Similar to Doppler radar, passive motion-sensing radar exhibits a null-point detection problem that can impact the sensor's ability to accurately characterize motion patterns. In traditional Doppler radar systems, the null-point detection problem can be removed entirely by using a quadrature mixer in order to generate both *I* and *Q* baseband signals, the combination of which can be used to detect motion without succumbing to the null-point problem present in single-channel systems [8], [9], [10]. Unlike traditional Doppler radar, passive radar does not have a cooperative local oscillator (LO), and relies on the direct, unmodulated path to act as the LO. Because of this and the finite directivity of the antenna, the Doppler-shifted and LO signals are superimposed at the receiver, and quadrature down-conversion cannot be accomplished, leaving the null-point problem intact.

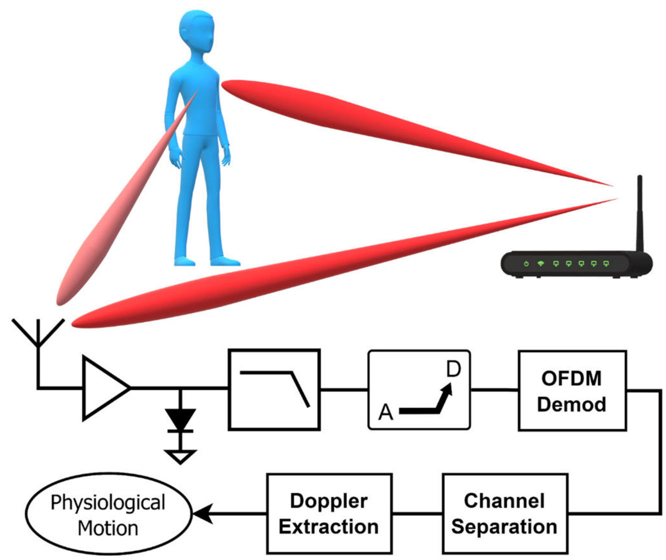

Figure 1. Passive radar architecture responsible for producing the null-point detection problem. Since there is no LO present, quadrature demodulation is currently not possible, causing detection problems in certain locations.

In this paper, an analysis of the null-point problem for passive radar is undertaken to construct a model to accurately represent a passive radar's ability to detect small-amplitude motions in a variety of situations. In addition, null-point removal and optimization techniques such as frequency tuning, channel selection, and multi-band/multi-static sensing are proposed and validated for future works using passive radar in a realistic setting where multiple options may be present. The results from simulation verify that despite the difficulty to separate the LO and Doppler signals, the null-point problem may have its impact reduced using the presented techniques.

II. Theoretical Background

Passive radar relies on two correlated signals in order to detect motion, both of which originate from a third-party, noncontact transmitter often called an illuminator of opportunity. Domestic illuminators typically radiate in an

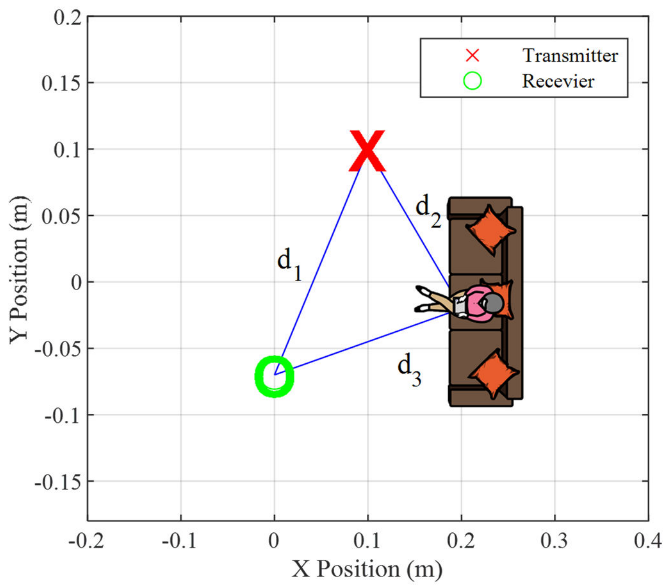

Figure 2. Example passive radar setup used to formulate received signal for null-point detection modeling. Two signal paths exist: one directly from the source represented by d_1, and the other following the path of d_2 and d_3 that is modulated with target motion.

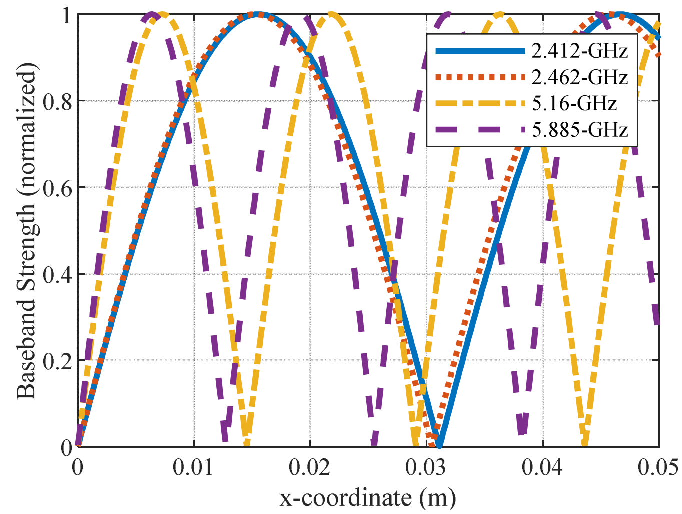

Figure 3. Motion strength vs distance from radar for single-channel Doppler motion detection at various frequencies.

omnidirectional pattern in order to provide service in a wide range. In the presence of a moving target, a passive radar will receive two signals: an unmodulated signal directly from the illuminator of opportunity and a signal reflected from the target whose frequency is Doppler-shifted proportional to the target's velocity. For both signals, their phase will be shifted according to the distance that each wave must travel in order to reach the receiver. An example passive radar setup is shown in Fig. 2 to assist with the formulation of a passive radar model. At the input of the passive radar, the received signal may be represented by:

$$\mathrm{x_R(t) = A_D\cos(\omega_c t - kd_1) + \cdots} \\ \mathrm{A_M\cos(\omega_c t - k[d_2(t) + d_3(t)])} \quad (1)$$

where k is the propagation phase constant, d_1 represents the distance from illuminator to radar, d_2 is the distance from illuminator to target, d_3 is the distance from target to radar, and A_D and A_M are the direct and modulated received signal amplitudes, respectively.

The signal in (1) is the superposition of two sinusoidal functions, one of which has a time-varying phase term. Since two tones are present, the signal may be sent to the input of a nonlinear device in order to effectively down-convert (1) into a low-frequency, baseband signal for digitization. The output of the nonlinear device is typically dependent on the received signa amplitudes A_D and A_M. If either of the becomes too weak, the conversion gain, and therefore sensitivity of the passive radar will be reduced. For this work, it will be assumed that the received signal amplitudes are sufficient for down-conversion, but more discussion regarding the impacts of A_D and A_M may be found in [7]. The baseband signal may be represented by (2) after low-pass filtering to remove higher-order harmonics.

$$\mathrm{x_{BB}(t) \approx I_S e^{\frac{qx_{RF}(t)}{nkT}}}$$

$$\mathrm{x_{BB}(t) \propto A_D A_M \cos(k[d_2(t) + d_3(t) - d_1])} \quad (2)$$

Both d_2 and d_3 consist of a large unchanging component and a relatively small periodic motion. It may be observed that when the argument of (2) approaches even multiples of one-quarter wavelength, the derivative of (2) approaches zero (i.e. small motions create nearly zero change in signal). This is illustrated in Fig. 3 for various frequencies. On the other hand, when approaching odd multiples of one-quarter wavelength, the associated derivative reaches a maximum which corresponds to optimum motion detection. Because of this dependence on distance, the received and digitized signal may vary wildly for similar motions creating uncertainty in the measured motion.

In order to verify this model for the baseband signal, the model may be compared against well-known Doppler null-point detection. In this case, the distance d_1 is set to be zero since the illumination signal is generated on-board, while d_2 and d_3 are both equal to the target distance. Doppler null-point detection occurs when the target distance is any multiple of one-quarter wavelength away from the radar, and as such there are expected to be four null-points per wavelength of distance away from the radar. A simple simulation is used to verify this using a transmit frequency of 2.4-GHz (λ=125 mm). In the simulation, the

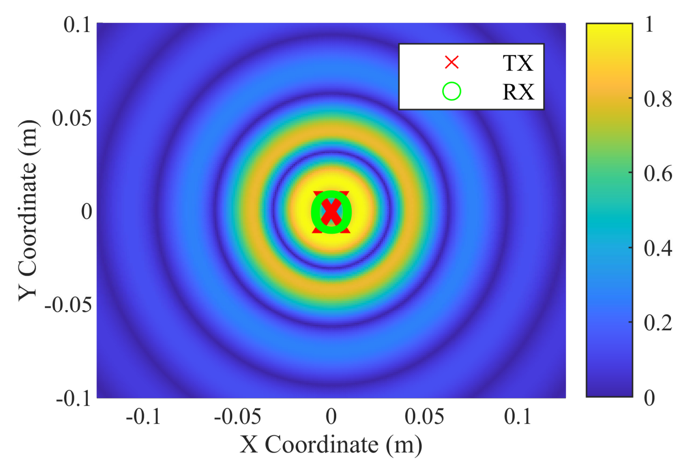

Figure 4. Doppler radar test for passive radar model using a 2.4-GHz radar (λ=125 mm). For traditional Doppler radar, there is expected to be 4 null-points within one wavelength, which can be observed in the model results.

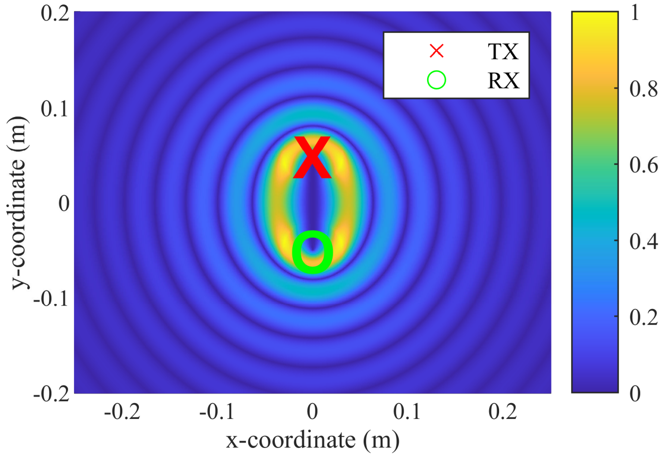

Figure 5. Passive radar test using a 2.4-GHz single-channel receiver. The null/optimum points are distributed around the radar elliptically.

response produced by a small motion is evaluated at each point in the plane. The results of the simulation are shown in Fig. 4. In the figure, the dark rings surrounding the radar located at the origin represent "blind spots" where the sensor is unable to detect motion. As is expected, at one-wavelength away from the radar, a total of 4 unique null-points are encountered, verifying the validity of the model.

Since passive radar uses a third-party transmitter located away from the radar, the transmitter and receiver may be placed at arbitrary locations to begin analysis of the null-point detection problem for passive radar. For this analysis, both the transmitter and receiver will be placed along the y-axis with a spacing of 0.1 m. The results of this analysis are shown in Fig. 5. In the bistatic passive radar case, the null/optimum points are no longer distributed around the system circularly, but rather elliptically. It is also important to note that, for the bistatic case, any system of transmitter, receiver, and target may be represented on a single plane, making the 2D analysis quite versatile.

III. Analysis and Optimization Results

In order to evaluate different methods' abilities to remove null-points, a new metric is developed to relate a practical

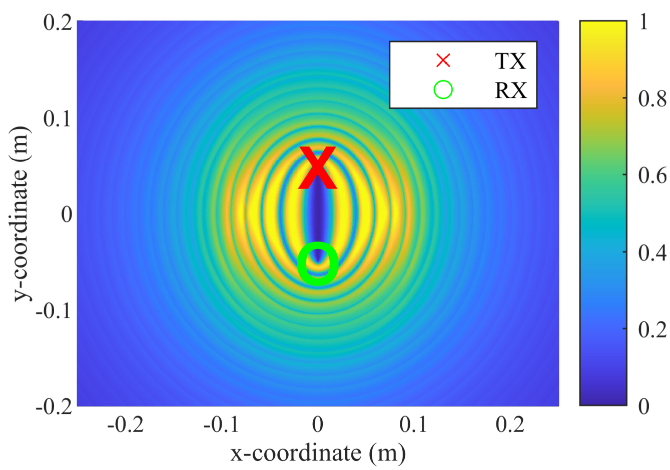

Figure 6. Results showing detection capabilities using a 5-GHz SBMC passive radar. If all channels in the 5-GHz band may be used, then a much smaller portion of the plane produces a null response.

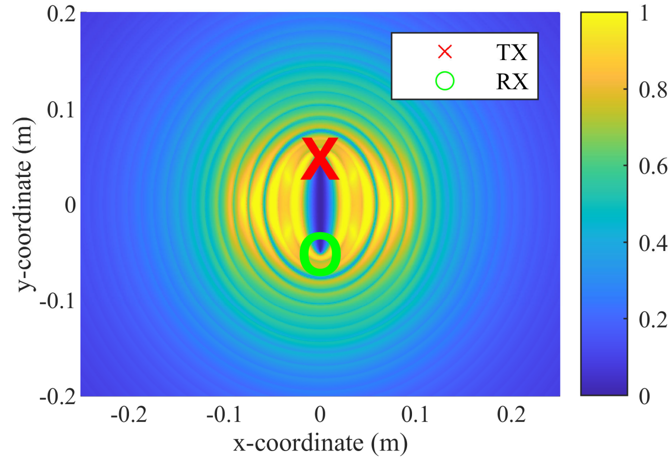

Figure 7. Results showing detection capabilities using a MBMC passive radar. The addition of more channels using the 2.4-GHz band improves detection.

sensor's ability to detect small motion versus an ideal sensor with no null-points. This metric, termed detection coefficient, is given in (3), where N_x and N_y represent the number of x and y nodes in the analysis, and R_N represents the normalized response at the desired node, such that the received signal strength is decoupled from the distance from the transmitter and receiver. Using the normalized response, for an ideal case with no null-points (e.g. a Doppler system with quadrature demodulation), the detection coefficient is unity.

$$C_D = \frac{1}{N_x N_y} \sum_{i=1}^{N_x} \sum_{j=1}^{N_y} R_N(i,j) \tag{3}$$

Using a single channel in the 2.4- or 5-GHz band, the detection coefficient is approximately 63%. However, each Wi-Fi band has multiple channels that may be used, each with their own carrier frequency. For this work, the 11 2.4-GHz channels and the 56 5-GHz channels for North American use will be considered in the analysis.

A. Multi-Channel Passive Radar Sensing

A single-band multi-channel (SBMC) system is first considered due to its simplicity compared to a dual-band design. Both 2.4-GHz and 5-GHz bands are considered. The 2.4-GHz band consists of 11 channels, each with 5-MHz spacing and an overall bandwidth of 50-MHz. The 5-GHz band, on the other hand, has 57 channels, most of which with 10-MHz spacing and an overall bandwidth of 725-MHz. The greater selection of channels and higher bandwidth of the 5-GHz band make it a more desirable candidate for an SBMC system, which is further confirmed by the results of the analysis. A 2.4-GHz SBMC system has a detection coefficient of 71.2%, while a 5-GHz SBMC system achieves a detection coefficient of 96.7%. The results from the 5-GHz SBMC system are shown in Fig. 6 after being recoupled to distance. It is expected that the 5-GHz SBMC system would achieve a higher detection coefficient due to its wider overall bandwidth and greater selection of channels when compared to the 2.4-GHz band.

In order to make better use of the available Wi-Fi signals, a dual-band system may also be analyzed. Such a system can make use of the channels in both the 2.4- and 5-GHz bands to further maximize the detection capabilities of a passive radar system. The results from a multi-band multi-channel (MBMC) system are shown in Fig. 7, with a corresponding detection coefficient of 97.5%. Compared to the 5-GHz SBMC system, the MBMC system exhibits a marginally improved detection coefficient but a marked increase in system complexity, making it a beneficial option if maximum performance is necessary but a potential drawback if the SBMC solution is sufficient.

B. *Single-Channel Passive Radar Sensing*

Since no LO is generated onboard the passive radar sensor, frequency selectivity is crucial to ensure that down-conversion only occurs with the signals of interest. For a 5-GHz system, this may increase the complexity since the 5-GHz Wi-Fi band has a large bandwidth and relatively small spacing between channels, imposing considerable design challenges for a selective RF tuning circuit that may be dynamically adjusted to select the appropriate channel. To ease the design constraints, a multi-band single channel (MBSC) system may be used. Since Wi-Fi channels are at discrete locations, an optimization may be performed to find the best combination of channels in the 2.4- and 5-GHz bands, the results of which are shown in Fig. 8. The best scenario occurs when using the 2.462- and 5.16-GHz channels and produces a detection coefficient of 81.2%. In the worst case, however, a detection coefficient of 80.4% is still achieved, demonstrating that a lengthy optimization is not necessary for designing a MBSC system and that a MBSC system is capable of motion detection while using a single channel in each band.

C. *Multi-Static Passive Radar Sensing*

A major detriment of bistatic passive radar motion sensing is the large null point located between the transmitter and receiver. In each result reported at this point, there is a relatively large blind spot at the center of the figure where no motion may be detected. This point is due to the relatively small difference in path length between the unmodulated and modulated signals, producing little phase shift. In order to circumvent this problem, a multi-static system may be used. A two- and three-sensor

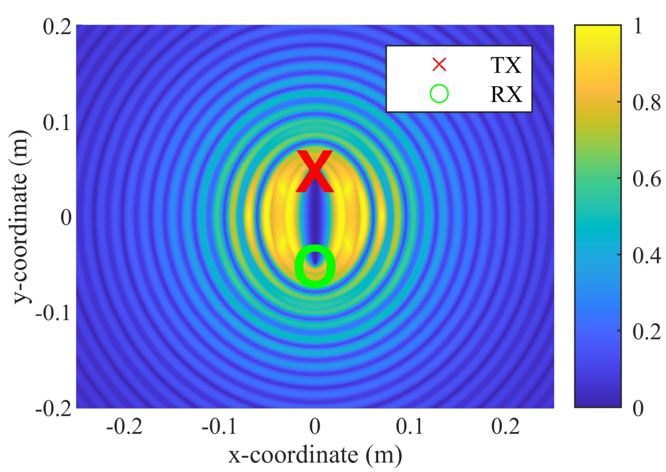

Figure 8. Results showing detection capabilities using a MBSC system. Selecting frequencies in different bands improves detection coefficient while keeping the architecture simpler.

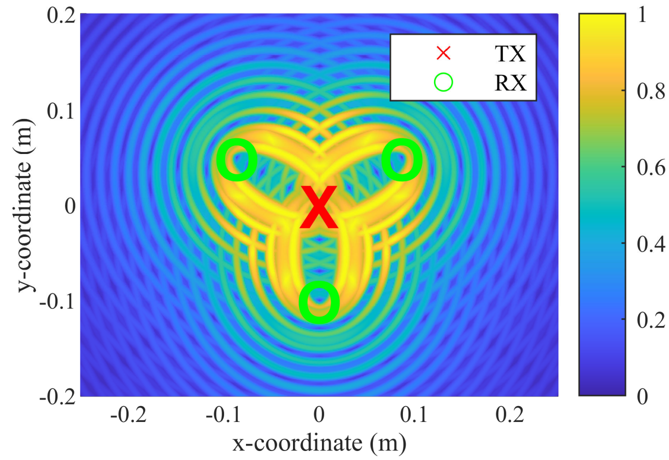

Figure 9. Results showing detection capabilities using a multi-static MBSC passive radar system. The null-points located between the transmitter and receiver are eliminated since the cooperative radars may provide motion detection when one radar is at a null-point.

system is examined in this work, but the results may be scaled to any number of sensors to further increase the performance.

The multi-static analysis assumes SBSC and MBSC sensors are used since the MBMC system already presents a high detection coefficient and any improvements would be marginal. For an SBSC system, the detection coefficient increases to 81% in a two-sensor system and 88% in a three-sensor system. The MBSC two-sensor system produces a 92% detection coefficient and the MBSC three-sensor system produces a 95% detection coefficient. The results of the three-sensor MBSC system are shown in Fig. 9, demonstrating that in a multi-static system, the large null-point between the third-party transmitter and the passive radar receiver may be reduced by the cooperation of other passive radars. The overall results of this study are summarized in Table I.

TABLE I. NULL-POINT ANALYSIS SUMMARY

Passive Radar Architecture	Frequencies	Detection Coefficient
2.4-GHz SBSC	2.432-GHz	63.4%
5-GHz SBSC	5.16-GHz	63.2%
2.4-GHz SBMC	2.412-2.462 GHz	71.2%
5-GHz SBMC	5.160-5.885 GHz	96.7%
MBSC	2.462 & 5.160 GHz	81.2%
MBMC	2.412-2.462 GHz 5.160-5.885 GHz	97.5%
Multi-static MBSC	2.462 & 5.160 GHz	95.4%

IV. CONCLUSION AND FUTURE WORK

In this work, an in-depth analysis of the null-point detection problem for passive motion-sensing radar is presented alongside methods of removing null-points using channel selection, band selection, and multi-static sensing. Passive radar may be used as a detection method using signals of opportunity without requiring a cooperative transmitter. Since no RF signal is generated on-board the passive radar, however, the Doppler information cannot be separated from the unmodulated signal, creating a null-point at certain distances where motion may not be accurately detected. In order to characterize and mitigate the null-points, a model for passive radar motion sensing is generated and tested in the well-known Doppler radar case. After verification of the model, it is shown that null-points circumvent the transmitter/radar system elliptically. Multiple passive radar systems leveraging the North American Wi-Fi bands are considered, and the results from the simulation show that, although the null-point problem cannot be removed entirely, its effects can be lessened through appropriate selection of Wi-Fi band and channel, as well as the inclusion of multiple passive radars in a multi-static sensing system. Future works may verify the validity of this model using an experimental setup leveraging a known motion or may further develop the model to include support for multiple subcarriers in addition to a single carrier frequency to better mimic the OFDM modulation used with 802.11 Wi-Fi signals. Finally, a gradient descent optimization may be performed in order to maximize the detection coefficient for a multi-static setup to determine the best system layout for maximum detection in a defined area to allow for better practical implementation of passive radar motion detection.

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REFERENCES

[1] S. Li, D. X. Li and S. Zhao, "The internet of things: a survey," *Information Systems Frontiers*, vol. 17, no. 2, pp. 243-259, 2015.

[2] S. Majumder, T. Mondal and M. J. Deen, "Wearable Sensors for Remote Health Monitoring," *Sensors,* vol. 17, no. 1, p. 130, 2017.

[3] D. Tarek, A. Benslimane, M. Darwish and A. M. Kotb, "Survey on spectrum sharing/allocation for cognitive radio networks Internet of Things," *Egyptian Informatics Journal,* vol. 21, no. 4, pp. 231-239, 2020.

[4] G. P. Blasone, F. Colone and P. Lombardo, "Passive radar concept for automotive applications," *2022 IEEE Radar Conference (RadarConf22)*, 2022, pp. 1-5.

[5] D. V. Q. Rodrigues, D. Tang and C. Li, "A Novel Microwave Architecture for Passive Sensing Applications," *2022 IEEE Radio and Wireless Symposium (RWS)*, 2022, pp. 57-59.

[6] F. Santi, I. Pisciottano, D. Pastina and D. Cristallini, "Impact of Motion Estimation Errors on DVB-S Based Passive ISAR Imaging," *2022 IEEE Radar Conference (RadarConf22)*, 2022, pp. 1-6.

[7] D. Tang, V. G. R. Varela, D. V. Q. Rodrigues, D. Rodriguez and C. Li, "A Wi-Fi Frequency Band Passive Biomedical Doppler Radar Sensor," *IEEE Transactions on Microwave Theory and Techniques*, 2022.

[8] C. Li, V. M. Lubecke, O. Boric-Lubecke and J. Lin, "A Review on Recent Advances in Doppler Radar Sensors for Noncontact Healthcare Monitoring," *IEEE Transactions on Microwave Theory and Techniques*, vol. 61, no. 5, pp. 2046-2060, May 2013.

[9] A. D. Droitcour, O. Boric-Lubecke, V. M. Lubecke, J. Lin and G. T. A. Kovacs, "Range correlation and I/Q performance benefits in single-chip silicon Doppler radars for noncontact cardiopulmonary monitoring," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 52, no. 3, pp. 838-848, March 2004.

[10] B.-K. Park, O. Boric-Lubecke and V. M. Lubecke, "Arctangent Demodulation With DC Offset Compensation in Quadrature Doppler Radar Receiver Systems," *IEEE Transactions on Microwave Theory and Techniques,* vol. 55, no. 5, pp. 1073-1079, 2007.