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A Passive Multi-Static Radar Imaging System for Intruding Object Detection

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Abstract: **-** A Passive Multi-Static Radar Imaging System (PMSRIS) has been implemented for border surveillance, employing commercial Wi-Fi radios at 5GHz band. The radar array includes two transmitters and four receivers employing commercial Wi-Fi Radios. The radios were set at 5 GHz band at channel 42, and the frequency was selected between 5170 MHz and 5250 MHz. A sampling rate of 1 ms with a bandwidth of 40 MHz was considered in the receivers. The scanning detected targets were a human and a car. Firstly, some measurements were taken with no target in the area, then the changes in the signals were measured after a person and a car entered the area. An image reconstruction method has been developed based on the Synthetic Aperture Interferometric Radiometer (SAIR), obtains brightness temperature (BT) images by measuring the object's natural radiation in the microwave band. The proposed method employs a compact Variable Fiber Delay Line (VFDL) as the passive coding technique to encode the signal received by the antenna array. The BT image is reconstructed by decoding the coded signal and using the Fourier transform method. This method is capable of quickly detecting and imaging targets entering the area near land borders. The novelty of this project research includes implementing a new setup for the hardware of system and a new method for SAR image formation method to achieve higher-resolution images. The new MSRIS could be utilized for intruding target detection and border surveillance.

Keywords: Passive radar, Multi Static Radar, SAR, Tomography, Imagery, Transceivers, Wi-Fi

I. INTRODUCTION

A bistatic radar consists of a transmitter and a receiver to detect targets and extract target parameters [1]. Passive radars do not use a dedicated transmitter and mostly employ ambient signals at different frequencies to detect targets. This method has advantages such as reducing the dimensions of the radar, portability, lower construction cost, no need for a specific frequency band, and can be hidden from the enemy. The pitfall is that it cannot be controlled in terms of waveform and power [2, 3]. Passive radars generally operate in bistatic geometry. This means that the transmitter is in a different position than the receiver [3]. Passive radar can detect and locate desired targets with proper information processing, including clutter removal and signal processing [4].

In the long-wave range, high-power commercial transmitters such as FM, analog TV, DVB-T, and DAB can be used as signal source of passive radars. Also, GSM, WiMAX, LTE, and Wi-Fi are used in the short-wave range. Since these telecommunication signal types are not developed for radar target detection, it is a challenge to be employed for radar applications. There are several different standards for Wi-Fi signals; the most common are 802.11a, 802.11, and the third generation of the 802.11b standard. Wi-Fi waveform characteristics are complex and highly time-dependent, which affects their performance [4, 5]. These communication signals are not explicitly designed for target detection and are not ideal for radar applications [3]. However, with appropriate information processing, including clutter removal and signal processing, detecting, and locating the desired targets in a passive radar is possible. Foreign object detection is utilized to selectively transmit power to only the intended target to mitigate this issue. In this paper we employed Radar imaging techniques to detect and find images and type of targets. For just detection and alarming systems, it is feasible to analyze receiving or transmitting signals using machine learning and artificial intelligence techniques for performing foreign object detection [19].

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II. THE METHODOLOGY

A Passive Multi-Static Radar Imaging System (PMSRIS) has been implemented for border surveillance, employing commercial Wi-Fi radios at 5GHz band. The Passive Radar has been implemented that uses Wi-Fi signals as radar transmitters. Signal processing was performed using digital signal processing based on OFDM and employing reflections emitted from the targets. The received signals contain valuable information about the targets, and by applying radar signal processing techniques and specific imaging methods, such as Synthetic Aperture Radar (SAR), it would be possible to create high-resolution images of the targets. The article proposes using both SAR imaging and other image formation techniques to improve the overall image quality.

Wi-Fi signal specifications of the passive radar system:

Wi-Fi signals surround the space. Telecom service providers, mobile phones, laptops, tablets, and smartphones typically include a Wi-Fi transmitter that works in the 2.4 GHz or 5 GHz band. In the 2.4 GHz band, there can be up to 14 overlapping channels (20 MHz bandwidth). The transmitter powers in the 2.4 GHz and 5 GHz bands (in the outdoor environment) are 50 mW and 1 W, respectively. The modulations used in Wi-Fi include OFDM, BPSK, and QPSK. Wi-Fi standard and commercial equipment are widely available and make it possible to establish a point-to-point wireless link from short distances of up to 30 Km, demonstrating that Wi-Fi can be used as a radar transmitting signal for longer distances, considering speed, modulation scheme, and type of preamble in a standard Wi-Fi transmission. For radio positioning applications, detecting the source of each frame is essential to find the source of the signal, and for this purpose, each recorded frame must be decoded. After the reference signal is divided into streams based on the source address, processing can be performed to find the target position [7,8].

In this project, we assume two fixed transmitters and four fixed receivers at specific distances from each other for OFDM Time Division Duplex (TDD). Each transmitter will send Downlink (DL) subframes based on Uplink (UL) requests from users in the network. In this context, the transmitter will have a fixed DL that treats DL subframes as a pulsed radar system with a constant pulse repetition frequency equal to the communication frame rate.

Reconstruction of SAR Structure:

Passive radar detection is based on calculating the cross-ambiguity function between the received and reference signal using (1).

$$(R,v_r) = \int_{t=0}^{t_i} x_R(t) * x_t\left(t - \frac{2R}{c}\right) * e^{\left(-j2\pi\left(-\frac{2v_rF}{c}\right)t\right)}dt \qquad (1)$$

Where, R: distance from the radar system, F: carrier frequency, v_r: radial velocity, C: speed of light, t: time, t_i: integration time, x_R : received signal, and x_t : transmitted signal [6]. Using a pair of transmitters and receivers allows tracking the target and estimating the range in a bistatic system. At least three receivers are necessary for accurate 3D imagery in a multi-static system. Each pair defines a bistatic elliptic system centered at the target.

The passive radar system supports a bandwidth of 20 MHz has an image resolution of 15 m in a bistatic system from (2), where c is the speed of light, and B is the bandwidth [6].

$$r = \frac{c}{B} \qquad (2)$$

The received signal is obtained by superimposing all the received signals and the echo signals scattered from the imaged scene captured by the transmitted signal. The coherent processing of the transmitted signal is usually performed through a matched filter for LFM Chirp radars. It is also possible to use a matched filter for reconstructing the reflected Fourier domain representation, known as the "phase history," for OFDM signals. Use, the received signal becomes as follows:

$$S_r(p,t) = \sum_{l=0}^{L-1} \sum_{n=-\frac{N}{2}}^{\frac{N}{2}-1} d_{l,n}\, e^{jn\Delta\omega(t-\tau_{l,p})} \int_{ua}^{ub} g(u)\, e^{-j(\omega 0+n\Delta\omega)\tau_{u,p}}du \qquad (3)$$

In its commercial model, OFDM signal utilizes features such as guard bands, synchronization, and enhancements to improve communication quality [9]. These features have also been employed here, and the following is a description of them:

Guard bands:

Guard bands are used in the frequency domain to reduce interference from adjacent frequency bands. The values of the carrier domain for OFDM subcarriers, along with the guard bands, will be equal to $d_{l,n} = 0$, which leads to a reduction in the effective bandwidth B_{eff} and, consequently, a decrease in the SAR image resolution.

Synchronization symbols:

Synchronization symbols are used in OFDM to synchronize and coordinate the transmission and reception of signals. These symbols are placed at the beginning or end of each OFDM signal and provide timing information, aiding in the proper alignment of transmitted and received signals. Synchronization symbols improve the robustness of signal transmission to the scene and enhance the process of information recovery. They also help mitigate the effects of temporal variations in the transmission channel. Preambles, Pilot Tones, and Sync Symbols. Preambles, pilot subcarriers, and sync symbols employ predefined values of $d_{l,n}$ given by the communications standard for a given signal type. Prior knowledge of symbol timing and subcarrier utilization allows for pulse-to-pulse phase coherence for radar imaging. Furthermore, knowledge of preambles, pilots, and sync symbols allows for generating noiseless reference signals for improved signal correlation. In this project, the communication radios do not exploit the preambles, pilot tones, or syncs exclusively, as it is assumed the receiver has access to the entire (noiseless) transmission data $d_{l,n}$, either via the cooperation of the transmitter or via processing the direct path signal.

Cyclic Prefix:

Cyclic Prefixes (CP) are copies of the end of a time-domain symbol that is appended to the beginning of the symbol transmission. The CP length is generally fixed and known from the communications standard. CP replication may result in multiple correlation peaks, yielding false target detection; the processing segment length Tseg should be greater than the CP time to mitigate false detections. Also, the matched-filter reference signal requires modification to include CP effects. An inverse Fourier Transform of the reference $d_{l,n}$ sequence, CP extension, and Fourier transform back to the frequency domain provides the proper reference to build to account for the CP. Omission of the CP in the reference signal results in segment averaging of pulses with varying range shifts, resulting in a corrupted image.

III. THE USE OF INTERFEROMETRIC RADIOMETER THEORY FOR IMAGE FORMATION BASED ON THE SYNTHETIC APERTURE RADAR (SAR) METHOD:

Synthetic Aperture Interferometric Radiometer (SAIR) is a promising passive imager that obtains brightness temperature (BT) images by measuring the object's natural radiation in the microwave band [10]. SAIR can realize high spatial resolution by using a thin array composed of numerous small aperture antennas to achieve a large aperture antenna and overcome the mechanical scan limitation of a traditional real aperture radiometer. Nevertheless, SAIR requires a large number of antennas and receivers to obtain as much information about the scene as possible, which results in increased system complexity and hardware cost and limits the applications of the SAIT in various domains.

Numerous types of research have been performed to reduce the high complexity of a SAIR system. These developed methods can be summarized into three categories: one based on the clock scanning technique, one based on the compressed sensing (CS) technique, and one based on the passive coding technique. For example, Zhang et al. proposed a clock scan microwave interferometric radiometer (CSMIR) to reduce the complexity of the SAIR [11]. However, the CSMIR requires rotation equipment and is suitable for observing slow-changing targets. The CS approach reconstructs the BT images by randomly selecting partial visibility samples from all visibility samples. The feasibility of the CS method is demonstrated for reducing the complexity of the SAIR system. Kpr´e and Decroze proposed a passive coding technique to reduce the hardware cost of the SAIR system. The BT image can be effectively recovered solely with a few receivers using an oversized microwave cavity as the passive coding device.

This project proposes a new passive coding imaging method for SAIR to reconstruct the BT image. Different from the competing methods, the proposed method employs a compact Variable Fiber Delay Line (VFDL) as the passive coding device to encode the signal received by the antenna array. Then the BT image can be reconstructed by decoding the coded signal and using the Fourier transform method.

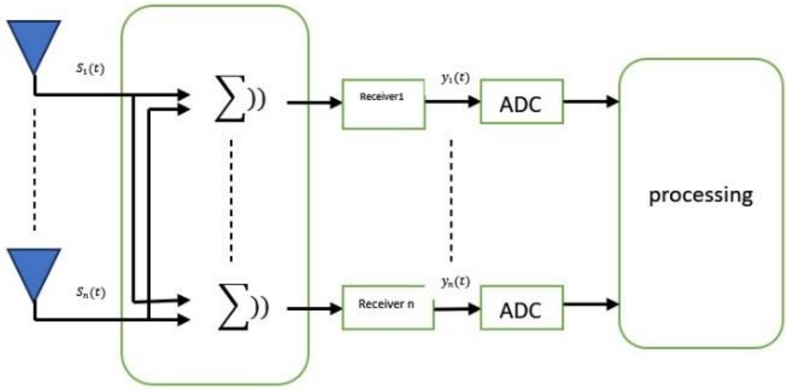


Fig. 1 *Diagram illustrating the Passive Radar system incorporating the new passive coding technique.*

This section describes the new passive coding imaging method for SAIR. Fig 1. shows the schematic of the SAIR system with a new passive coding device. The receiving antenna array with L elements is connected to an L×M (Input/Output) ports passive coding device. The passive coding device, which consists of variable fiber delay lines (VFDLs), delays and multiplexes the received L antenna signals into M (M <L) output signals, leading to architecture simplification. The data measured by receiver k in the frequency domain are expressed as follows:

$$y_k(f) = \sum_{l=1}^{l} h_{kl}(f)s_l(f) = \sum_{l=1}^{l} R_k(f)h'_{kl}(f)s_l(f) \qquad (4)$$

Where $S_l(f)$ denotes the signal of interest received by the lth antenna, and $h_{kl}(f)$ is the transfer function between the lth antenna and the kth receiver. $R_K(f)$ and h'_{kl} are the transfer functions of the RF receiver and the passive coding device, respectively.

From the above theoretical analysis, the proposed method has two constraints: the received signals should satisfy the sparsity in the frequency domain, and the channels of the encoding device should satisfy the orthogonality constraint. Once these two conditions are met, the received signals s can be accurately estimated from the compressed data, and then the BT image of the scene can be reconstructed. Therefore, a key point of the proposed method in this paper is to design the time delay of the VFDLs to ensure that the channels of the encoding device satisfy the orthogonality constraint.

The proposed radar imaging algorithm:

Radar images can be created by solving an inverse problem, in which the spatial image of reflection density is reconstructed from measured scattered electric fields [12]. Hence, the direct scattering mode provides a general frame for the radar imagery problem. The relationship between image characteristics (pixel values) and measurement data is described in (3).

$$Y = (AX + r) \qquad (3)$$

Where X is a vector of length N that contains image characteristics coefficients, Y is a vector of length M that includes the measurement data, r is a vector of length M that represents residual effects (noise, interference, etc.) and A an M×N matrix that relates the vector X to the vector Y. These image details can point to scatter centers (simply representing individual pixels of the image) or could be a more complex electromagnetic mode. Fig. 2 shows a simple 2D representation of the direct scattering mode based on Equation (3).

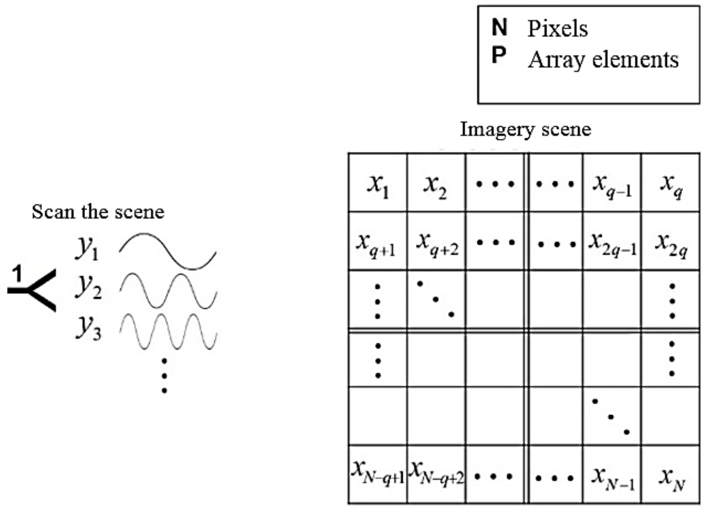


Fig. 2 A *direct scattering model placed in a 2D imagery scene.*

The vector X in the 2D example in Fig. 2 is divided into X/q rows, and q is the number of hypothetical columns based on the image scene and the range of pixels. In many 3D imageries, the number of unknown characteristics is much greater than that of measured values (in the given example, N≫M). Thus, there are infinite answers for Equation 3. In other words, Y is within A's dimensions, while A's empty spaces are large. When the image space is measured using a radar with a lower sampling density in more complex situations, it causes column dependence in matrix A. Therefore, the reduction of the rank of matrix A is necessary. The non-diagonal elements of A^A A, where A^H is the complex conjugate transpose of matrix A, represent the degree of linear dependence of the columns of the direct scattering matrix, which higher level of column dependence means that the effect of non-diagonal elements increases. So, the matrix A^A A can have unfavorable conditions, e.g., $K(A^A A) = \infty\ When\ N > M$), which often leads to an inaccurate solution or a solution with a high sensitivity to disturbances in the measurement data. Moreover, since typically N≫M, the imagery problem may have unfavorable conditions and lead to a non-unique solution.

There are three challenges in this problem: (i) a large number of conditions, (ii) replacing the matrix with unfavorable conditions with a matrix with correct conditions (derived from the original matrix with unfavorable conditions); it does not always lead to a helpful solution, and (iii) applying to limit constraints (which lead to a reasonable solution), which strongly depends on the problem type and problem definition.

Several imagery methods using different mathematical concepts have been developed to deal with the challenges of reconstructing the reflection density (finding the value of X in (3)), including brute-force search, matrix inversion, tomographic algorithms, regularization, greedy algorithms, subspace methods, time reversal processing, principal component analysis (PCA) and compressive sensing) [13]. Some of these methods, such as matrix inversion, are based on geometry (back-projection), and some, such as tomographic algorithms, are based on wave equations (back-propagation). Greedy algorithms are usually fast and effective for certain types of optimization problems. Greedy algorithms work on scattering phases to select the best outcome of each phase without considering future effects. The main idea of this algorithm is to obtain the optimal response by determining the optimal local value in each step. These algorithms are usually quick and easy to implement but can only provide the expected solution in exceptional cases. The CLEAN algorithm (such as the Matching-Pursuit algorithm or the Orthogonal-CLEAN algorithm) is one of the most well-known examples of the Greedy algorithm [14]. By repeating the search for the brightest image points (the largest size), the CLEAN algorithm finds these points in a scene, then the point spread function (PDF) images of these points are removed from the original image, and this process continues until all bright points are found. The point spread function can be the system's response to an ideal scattering point at a random location in the image space. O-CLEAN is a modified version of CLEAN. In each iteration of the CLEAN algorithm, the vectors of the bright points of the original image are orthogonalized before reducing their PSF. After the orthogonalization process, all extracted PSFs are linearly independent of other PSFs, making O-CLEAN more efficient than the CLEAN algorithm and guaranteeing convergence.

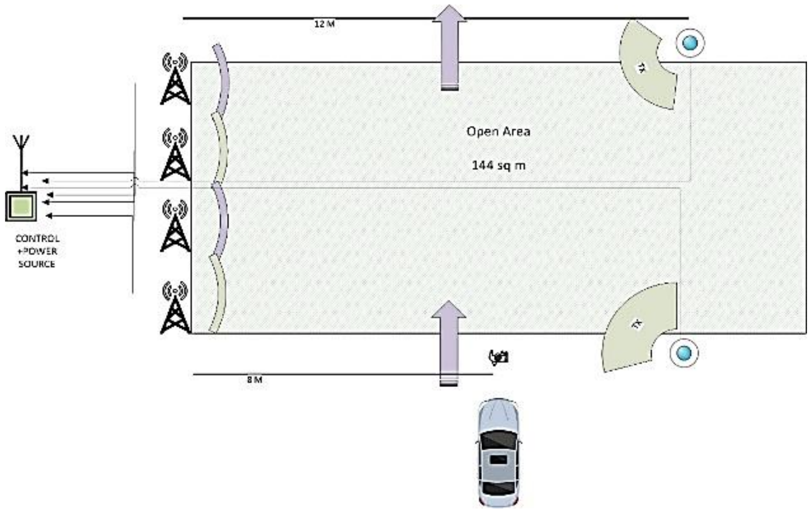
Using subspace methods is another approach to solving inverse imagery problems. These methods are performed using the decomposition of the scattering matrix based on the Eigen Values or Eigen Vector. The main idea of subspace methods is to divide the scattering matrix into two orthogonal subspaces consisting of signal and noise spaces (noise is an unwanted signal). The signal space matrix rank indicates the number of significant features (bright points) in the image. These methods, such as the Multiple Signal Classification (MUSIC) method, can produce high-resolution images, especially when combined with other methods (like Beam space MUSIC, time-reversal imaging/MUSIC, and TOPS). Due to the increased efficiency and convergence of the solution under most conditions, there has been a recent interest in compressive sensing (CS) method research. In short, CS can store and display a compressible signal at a sampling rate lower than Nyquist, and then the signal is reconstructed through an optimization process [16, 17,18].

In this project the imagery has performed based on a simple linear method like back-projection (BP), as the methods can give results quickly and efficiently. Then with combination to a complex linear method which is based on the wave equation, tomographic methods, the final images of targets were created.

IV. EXPERIMENTAL IMPLEMENTATION OF A PASSIVE MULTI-STATIC RADAR SYSTEM:

In most passive radar systems, the receivers, the data collection, and measurement strategies are designed in advance, and based on it, the systems are developed, constructed, and synchronized. For this project, four modules of the commercial radio of the 4ipnet model [15] were used for receivers, and two sets of the LigoWave model [16] were used as transmitters.

The experimental Passive radar systems were arranged in the University of Sistan and Baluchestan open area based on SAR (so the target area should be illuminated). In the setup for this project include two transmitters and four receivers that used in a 5 GHz band, and their arrangement was based on the point-and-strip lighting of SAR. On the receiver side, a computer was used to control and receive information. A spectrum analyzer was also used to check and collect data. Then, the transmitters and the receiver were connected, and the transmission speed was set to 6 Mbps. All signal processing was done in MATLAB using specially developed codes. Fig. 1 shows the Experimental setup of passive multi-static radar for target detection. The scanning detected targets were a human and a car. Firstly, some measurements were taken with no target in the area, then the changes in the signals were measured after a person and a car entered the area.



(a)

(b)

Fig. 3 *Experimental setup of passive multi-static radar for target detection (a) proposed experimental model (b) placement of equipment in the university area.*

Input data to the image detection algorithm:

The signal used in the transmitter was calibrated and set to a 5 GHz band on channel 42, and the frequency was selected between 5170 MHz and 5250 MHz. A sampling rate of 1 ms with a bandwidth of 40 MHz was considered in the receivers. Firstly, the signals were measured and stored in the absence of targets, and after the arrival of the targets, the signals were measured again and stored. During the experiment, the signals were recorded by a storage system and kept for further processing. To perform the imagery, the processed data is used in the FBP algorithm, then the CLEAN algorithm is used to remove noise and clutter, and the ambiguity function is used to vivid the image.

Based on the provided explanation and raw data collected from both OFDM and Radio-Frequency (RF) methods, the image fusion approach has been used in this article to improve image quality by applying the mentioned filters for noise reduction and enhancement.

Non-linear optimization is utilized to adjust image acquisition and achieve exceptional resolution compared to simple linear image reconstruction solutions such as BP or CF-BP, which require more resources (time and memory). Improving the resolution between two scattering centers (separating scatter centers) using non-linear adjustment is generally associated with significant resource costs, mainly when used in non-stationary or insensitive temporal locations. The time it takes to obtain the data and estimate the image is often crucial, and linear imaging methods based on reflected compression are adequate for rapid image formation.

Increasing the data acquisition angles in the scene or the system's bandwidth is necessary to enhance linear methods. An efficient and fast approach to improving data acquisition angles and cross-sectional resolution is using an image fusion process called "Image Fusion." Image Fusion combines coherent images in specific scene angles and integrates them incoherently to create a fused image. It is an alternative to the SAR method, resulting in significant time savings and reduced image distortion without needing higher coherence between antenna locations.

Image Fusion can be performed using various techniques, including multiplicative fusion, additive fusion, direct level fusion, and statistical methods (such as the generalized likelihood ratio test (GLRT). The statistical techniques generally assume Gaussian distribution for the underlying data and noise. Therefore, focusing on easy implementation and stable solutions, emphasis is placed on multiplicative, additive, and direct-level fusion methods.

In this project, image formation from non-active radar targets was accomplished by combining two algorithms: OFDM and the Radio Frequency (RF) method. The final image was improved, and noise reduction was achieved by applying the mentioned filters. The image reconstruction is performed based on the described algorithm, using data from experiments with a human and a car targets. The results indicate the successful detection of the desired targets as shown in Fig 4. Although scattered points and noise can be seen in the final imagery, this application helps detect targets entering a region near land borders. It should be noted that for border security the fast detection of targets is crucial. So, implementing a fast imagery algorithm is necessary while having some artifacts in the image.

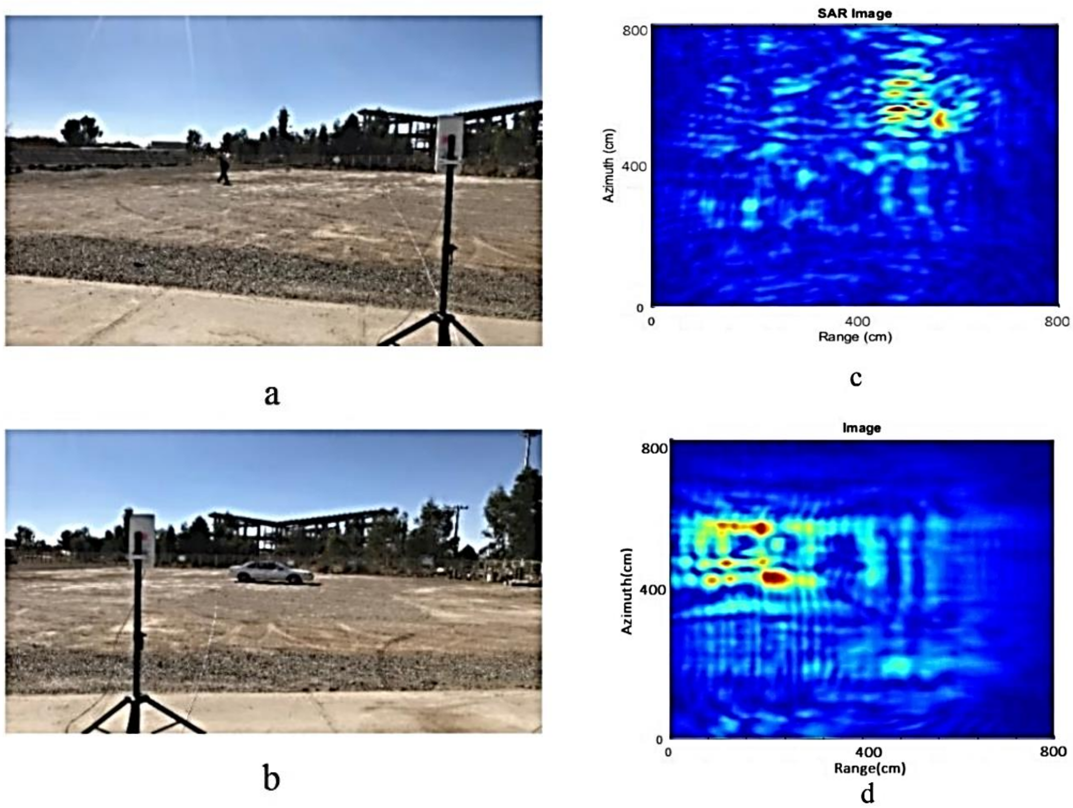


Fig.4 *The images of detected targets (a) Real image of the human target, (b) actual image of car target, (c) detected human image, and (d) detected car image.*

The new Multi Static Radar detects targets and determines their image boundaries using Wi-Fi as reference signals. The experiment demonstrated that the received noise and harmonics from commercial transmitters and environmental noise from the university's wireless network severely impacted the image quality and data cleaning obtained from target scattering. Since the receivers used in this experiment were also commercial, controlling the bandwidth and receiver gain and removing noise was impossible in the implemented system.

Declaration of Competing Interest

The authors declare no financial interests. Any financial related issues can be referred to the corresponding author.

Funding Statement

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Data availability

No Data has been used in this project. A hardware has been implemented, some measurements were taken, and image reconstruction programming Code has been developed.

Using generative AI in scientific writing

The authors did not use generative artificial intelligence (AI) and AI-assisted technologies in the research or writing process of this paper.

V. CONCLUSIONS:

A Passive Multi-Static Radar Imaging System (PMSRIS) has been implemented for border surveillance, employing commercial Wi-Fi radios at 5GHz band. PMSRIS has been implemented that uses Wi-Fi signals as radar transmitters. Signal processing was performed using digital signal processing based on OFDM and employing reflections emitted from the targets. The received signals contain valuable information about the targets, and by applying radar signal processing techniques and specific imaging methods, such as Synthetic Aperture Radar (SAR), high-resolution images of the targets were reconstructed. This experiment verifies the feasibility of using commercial Wi-Fi signals for RADAR applications. The project is continuing to implement a more accurate detection system by designing a precise receiver with better signal-to-noise rates to detect smaller targets.

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