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Modification of reconstruction threshold algorithm in two-dimensional LFMCW compressive radar

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Abstract

Nowadays, the Compressive Sensing theory has an important effect on many communication system's performances, and one of these applications is the radar system. Applying CS in the radar such as Linear Frequency Modulation Continuous Wave (LFMCW) radar signals has many advantages but suffers from the processing time in the two-dimensional processing. The performance of the LFMCW radar signals is achieved by using both conventional Complex Approximate Message Passing (CAMP) and adaptive recovery algorithms using a suitable reduction factor in both range and Doppler directions. In this paper, a modification is made to the adaptive CAMP algorithm to enhance the radar detection performance compared to both the conventional and adaptive algorithms under the same conditions. One of the main problems in radar detection is off-pin targets, which can be overcome using a certain filter in both range and Doppler directions. A comparison is achieved among these algorithms concerning detection performance using Receiver Operating Characteristic curves and the resolution performance in both range and Doppler directions. During the system analysis, it was found that an enhancement was achieved using the modified algorithm in the radar performance without any degradation in both range and Doppler resolution compared with the other algorithms.

Keywords: FMCW Radar, Range-Doppler processing, Compressive Sensing, Reconstruction CAMP algorithm, Adaptive CA-CFAR

Introduction

FMCW radar is a special type of radar system that radiates a modulated continuous signal to detect the target range. Target velocity can be determined by differences in phase or frequency between transmitted and received signals. The basic features of FMCW radar are [1]: the ability to measure very small ranges compared with pulsed radar; very high accuracy of range measurement; signal processing after mixing is performed at an Intermediate Frequency (IF), which simplifies the realization of the processing circuits; and safety from the absence of pulse radiation with high peak power.

Range and Doppler information can be extracted in the traditional FMCW radar using Range-Doppler processing unit based on Fast Fourier Transform (FFT) as shown in Fig. (1) [2, 3]. The two-dimensional information (Range and Doppler) can be

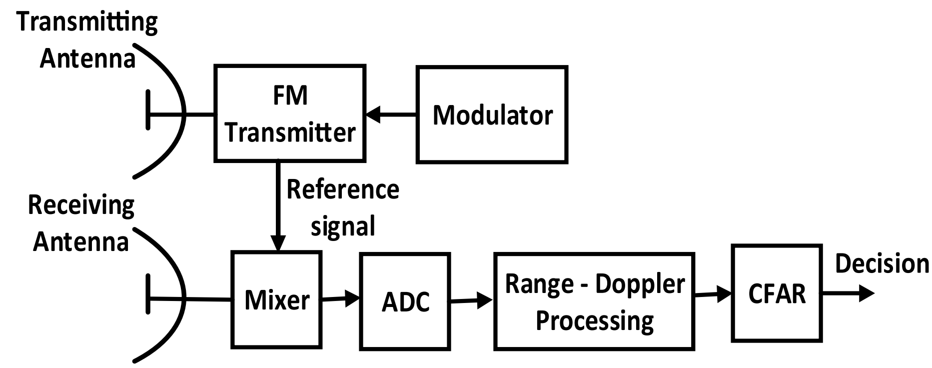

Fig. 1 General Block Diagram of LFMCW radar [2]

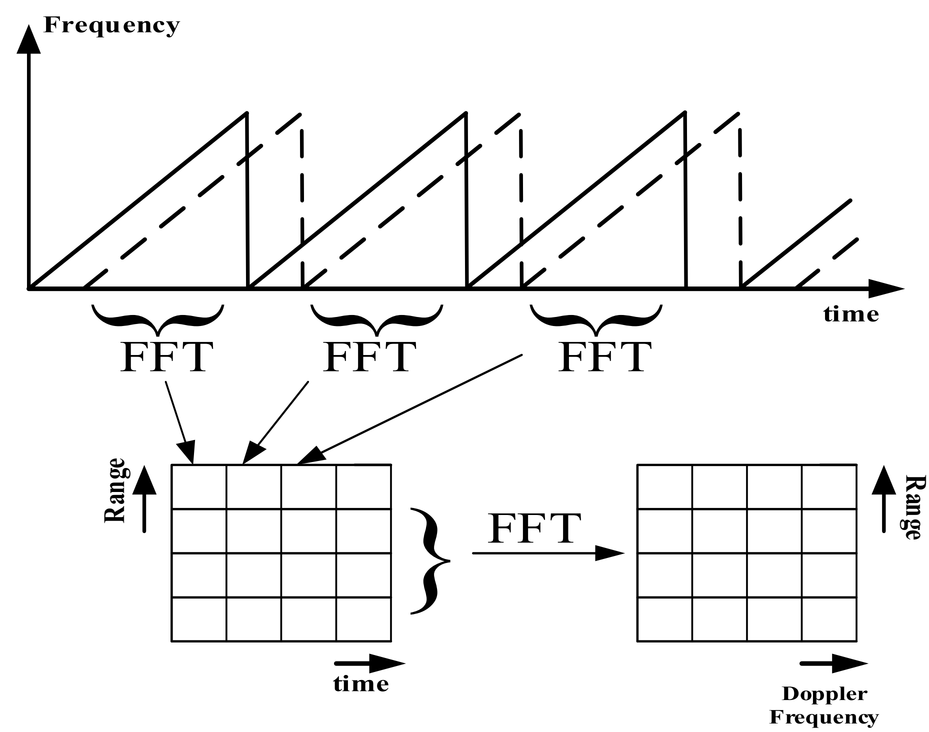

Fig. 2 Range-Doppler processing of FMCW radar using 2D-FFT [3]

processed in both directions using 2-D FFT. The first FFT is used to extract the target range by calculating the Fourier in the range direction only. The second one is used in the azimuth direction to extract the Doppler component, as shown in Fig. (2).

In [4–6], authors have proposed the compressive sensing theory, which is mainly dependent on random linear measurements to acquire efficient representations of compressible signals. Many applications in radar, communication systems, remote sensing, and other fields are mainly dependent on this theory. Many reconstruction algorithms are used for signal recovery based on CS, such as the Orthogonal Matching Pursuit (OMP) algorithm, which is illustrated in [7]. In [8], the detection of a compressive constant false alarm rate (CFAR) is achieved using the CAMP algorithm depending on the iteration process to evaluate good performance.

In [9], the authors provide an algorithm to analyze SAR data via (2-D) random sparse sampling beyond the Nyquist theorem to construct the target range and Doppler. Detection of FMCW radar signals is enhanced in the azimuth direction only based on the CAMP algorithm. The signal recovery using the proposed reconstruction algorithm is compared to that of the traditional FMCW radar as illustrated in [10].

In [11, 12], enhancement of LFMCW radar is introduced using an adaptive CAMP algorithm based on an adaptive threshold which is calculated according to the smallest window noise value. From this research, it has been found that the recovery process of the estimated signal is successfully reconstructed depending on the presence of a sparse dictionary. This research mainly improved the detection performance of the radar systems to ignore the effect of off-pin target detection. In [13], the authors suggested a new method for windowing to separate the target data into near and far distances. Detection of off-pin targets for FMCW radar is illustrated in [14], which uses a filter to enhance the target detection in the range direction only.

Two contributions can be obtained from this work. Firstly, the enhancement of the detection performance of 2D-LFMCW radar using an improvement detector based on CA-CFAR in the adaptive CAMP algorithm. The second one is the enhancement of off-pin target detection using a proposed filter in both range and Doppler direction. Receiver Operation Characteristics (ROC) curves are used to evaluate the detection performance compared with that of the conventional adaptive CAMP algorithm. Another aspect that is being evaluated is the resolution in both range and Doppler. The organization of this paper is achieved as follows: after the introduction, "Compressive sensing and camp reconstruction algorithm" section represents the operation of Compressive sensing in LFMCW radar and the reconstruction process using the adaptive CAMP algorithm. "CA_CFAR modification in the adaptive camp algorithm illustrates the modification in the CA-CFAR threshold of the CAMP algorithm. The proposed filter structure to enhance off-pin target detection is presented in "Off-pin filter structure" section. Computer simulation results using MATLAB are introduced in "Computer simulation" section. Finally, the conclusion is presented in "Conclusion" section.

Compressive sensing and camp reconstruction algorithm

Introduction to CS theory

CS plays an important part in the radar system, which acts as an encoding and decoding process. A transformation of high-dimensional signals into lower dimensional ones is performed based on a sensing matrix. Many advantages are acquired when applying the CS in radar systems, such as the reduction of the redundant signals, compression of large signals, perfect original signal recovery through different recovery algorithms, and a reduction in processing time, in addition to improving the radar performance.

The signal recovery process using the reconstruction algorithm is mainly dependent on some conditions on the radar signal. One of these conditions to deal with CS in radar application is sparsity. The FMCW radar signal is considered to be sparse when using a transformation domain such as, Fourier which can be represented in the sensing matrix as shown in Fig. (3).

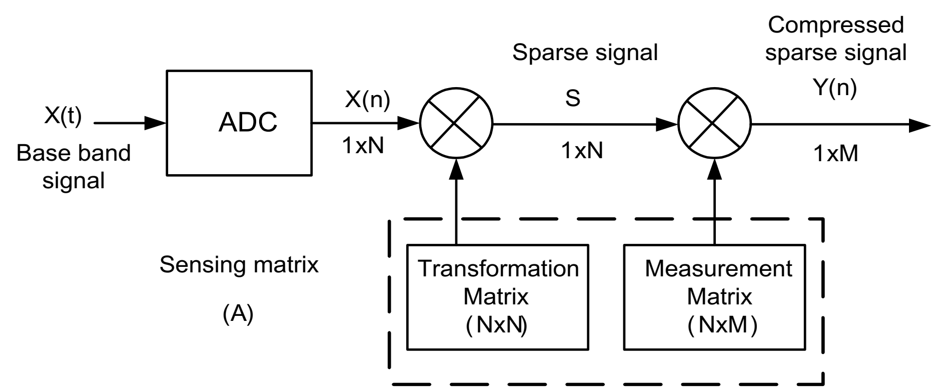

Fig. 3 Application of CS in LFMCW radar [10]

If the radar signal samples with dimension, *N*, are transformed into under-sampled signals or measurements, *M*, with a linear operator where the measurement vector, y, is given by:

$$y = Ax \tag{1}$$

where A is an $(M \times N)$ Fourier sensing matrix, x, is an $(N \times 1)$ sparse radar signal. The solution of this equation can be obtained using $\ell 1$-norm optimization using the following relation:

$$\delta = M/N, \rho = k/M \tag{2}$$

where δ, is the under-sampling factor or reduction ratio, ρ, is the radar signal sparsity, and *k*, is the number of nonzero samples. The sparse signal, x, can be estimated according to the sensing matrix, A using the Restricted Isometry Property (RIP) condition, and it can be calculated as:

$$(1-\gamma)x_2^2 \leq A.x_2^2 \leq (1+\gamma)x_2^2 \tag{3}$$

where $\gamma \in (0, 1)$ and since RIP is practically impossible to compute for any real signals with N samples, there is a metric that is often used to design a suitable CS matrix is incoherence [15]. The coherence μ(B,C) between any two matrices $B = [b1, b2, b3, \ldots . b_N]$ and $C = [c1, c2, c3, \ldots . c_N]$ is defined as:

$$\mu(B, C) = \sqrt{N} \max_{1 \leq i,j \leq N} \left| b_i^T c_j \right| \tag{4}$$

From this equation, it is clear that the coherence is the maximum correlation between any two columns of the matrices B and C. The number of CS measurements (*M*) needed for perfect reconstruction can be calculated according to the next relation:

$$M \geq k^2 \ln N \tag{5}$$

Adaptive CAMP algorithm

CAMP is an iterative algorithm used to reconstruct the target information such as range and speed. The adaptive CAMP algorithm is used to enhance the radar detection performance because iterative algorithms are faster than ℓ1-norm minimization during processing. The iterative algorithms are the simplest among all the reconstruction algorithms, where the only operations that are needed for each iteration are the multiplication of a vector by a matrix, A^T. The adaptive recovery CAMP algorithm is performed in many research papers for pulsed and FMCW radars based on an adaptive threshold [11] as shown in Fig. 4. The main idea of the adaptive threshold depends only on independent and identically distributed observation cells controlled by an exponential distribution [16]. The probability of detection increases as the reference window, which is based on a fixed threshold. The noise level is estimated by averaging the leading and lagging of 5 range cells around the CUT, and then the threshold is chosen according to a comparator. If the greatest output of the comparator is chosen, then the adaptive threshold is called the Greatest of (GOF), and if the least amount of summation is chosen, the adaptive threshold is called the Smallest of (SOF). The high computational complexity of inner point methods to solve large convex optimization problems stimulated the development of first-order methods to solve the lasso problem [17]. The threshold has been suggested to be adaptive for LFMCW radar signals in [11] and the pseudocode has presented in Fig. 4.

The adaptive recovery algorithm depends mainly on the soft thresholding function (η) that its rule is applied to the compressed radar signal. Applying the soft thresholding rule is used to reduce the number of nonzero coefficients in the adaptive SOF. The details of the soft thresholding rule are expressed in [18]. The global threshold, τ, is given by:

$$\tau = \sigma\sqrt{2\ln n} \tag{6}$$

where σ is a Mean Square Error (MSE) of the noise signal and n is the coefficient number of the processed signal at a specific scale.

The level of the adaptive threshold can be controlled using a factor which is called a multiplication factor to control the probability of false alarm output. Three steps can be obtained using the adaptive algorithm to recover the radar signals; estimating the noisy signal $\tilde{x}$, calculating the adaptive threshold, and smoothing the noisy estimated signal to recover the radar signal,$\hat{x}$. A modification is made to this threshold of the adaptive CAMP algorithm to enhance the detection performance as discussed in the next section.

Adaptive Recovery CAMP algorithm
Input: y, A.
Initialization: $\hat{x} = 0,\ z^0 = y$.
$\tilde{x}^t = A^* z^{t-1}$.
$\epsilon = adaptive\ SOF\ (\tilde{x}^t)$.
$\hat{x}^t = \eta\left(\tilde{x}^t\ ;\ \epsilon\right)$.
Output: $\hat{x}$, MSE.

Fig. 4 Pseudo code of the Adaptive Recovery CAMP algorithm [11]

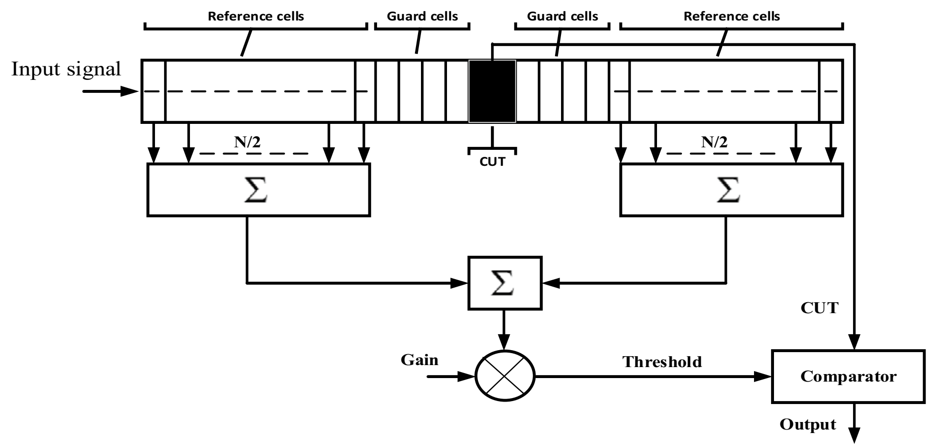

Fig. 5 The architecture of the CA-CFAR Algorithm [17]

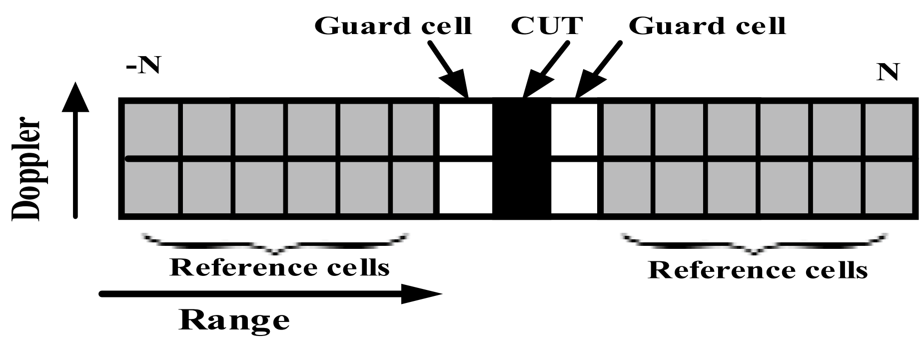

Fig. 6 Detection approach based on CACAFR

CA_CFAR modification in the adaptive camp algorithm

Radar signals have a main problem with detection due to an unknown noise background. One of the most famous detectors is the Cell Average Constant False Alarm Rate (CFAR) algorithm, which is considered to be applied to the detection of a stationary Gaussian signal against a normal noise background [19]. The threshold of the CA-CFAR is set adaptively depending on the background noise by processing a window of reference cells surrounding the cell under test (CUT) as shown in Fig. (5). In the conventional scheme of CA-CFAR, many guard cells surround the CUT rather than the reference cells. The detection of the range-Doppler radar system is mainly dependent on the number of cells in the range and Doppler directions. Therefore, *N* range cells and Z azimuth cells are assumed in both range and Doppler directions, respectively. Also, the range-Doppler cells are selected to be 2 N + 1 in range direction with an order of [− N…,− 1, 0, 1…N] as shown in Fig. (6).

The modification is presented where the guard window is chosen to be one cell around the cell under test (i.e., cell number 1 and number − 1) associated with the rest of the cells that act as reference windows.

The improvement in the CA-CFAR processing is achieved in the calculation of the threshold value, which is mainly dependent on the CUT and reference cell locations

[19, 20]. The difference from the traditional CA-CFAR algorithm is the selection of CUT cells surrounding a single spectrum. The modification is performed by taking the cells surrounding the detection window as a guard cell (two cells only compared to the traditional algorithm) and both the leading and lagging cells as reference cells, as illustrated in Fig. (6).

The improved process in CA-CFAR is more sensitive to the target detection in strong noise, where the target detection can be enhanced compared with the traditional algorithm without modification. The general probability density function (PDF) of white Gaussian noise as a function of standard deviation (σ) and the mean (μ) can be obtained as:

$$f(x) = \frac{1}{\sigma} e^{-\left(\frac{x-\mu}{\sigma}\right)^2} \tag{7}$$

Assume the radar signal is immersed in Gaussian noise with zero mean and unity variance, and its PDF is given by:

$$f(x) = \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} \tag{8}$$

The cumulative distribution function (CDF) is given by:

$$F(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} e^{-t^2} dt \tag{9}$$

The total number of reference cells can be obtained by:

$$H = K.(2N - 2) \tag{10}$$

where K is the cell under test (CUT).

The average noise signals can be calculated from the sum of the reference windows as:

$$X = \sum_{i=1}^{H} x_i \tag{11}$$

The Gaussian noise in these windows is independently identically distributed, so the joint PDF of X is given by the product of the marginal PDFs [17].

$$f_H(x) = \prod_{i=1}^{H} f(x_i) = \frac{1}{\sqrt{2\pi}} \prod_{i=1}^{H} \exp\left(-x_i^2/2\right) \tag{12}$$

Then, the false alarm probability, P_{FA} can be calculated as:

$$P_{FA} = \int_{0}^{\infty} P(CUT > TX) f_H(x) dx$$

$$= \frac{1}{\sqrt{2\pi}} \int_{0}^{\infty} \exp\left(-(XT)^2/2\right) dx13$$

where T is the threshold product factor used in the CFAR algorithm to detect the user or target signal. Equation (13) can be reduced to:

$$\begin{aligned} P_{FA} &= \frac{1}{\sqrt{2\pi}} \left| \frac{\exp\left(-(XT)^2/2\right)}{-XT^2} \right|_0^{\infty} \\ &= \frac{1}{\sqrt{2\pi}} \left[0 + \frac{1}{XT^2} \right] \qquad 14 \\ &= \frac{1}{\sqrt{2\pi} XT^2} \end{aligned} \tag{13}$$

Consequently, the threshold, T, can be obtained as:

$$T = \left[\sqrt{2\pi} X P_{FA}^{-1} \right]^{-1/2} 15 \tag{14}$$

So, the threshold can be obtained from the false alarm probability in CA-CFAR, which can be used in the adaptive recovery CAMP algorithm. This modification in the threshold calculation can enhance the detection probability of LFMCW radar in 2 dimensions (range and Doppler) as discussed in the next sections.

Off-pin filter structure

Detection of targets with off-pin locations is very difficult in radar systems due to the bad reconstruction process. In [14], the authors suggest a filter to enhance off-pin radar target detection in a range direction. The proposed filter is applied to both range and Doppler directions to enhance the radar performance in 2D- dimensions as shown in Fig. (7).

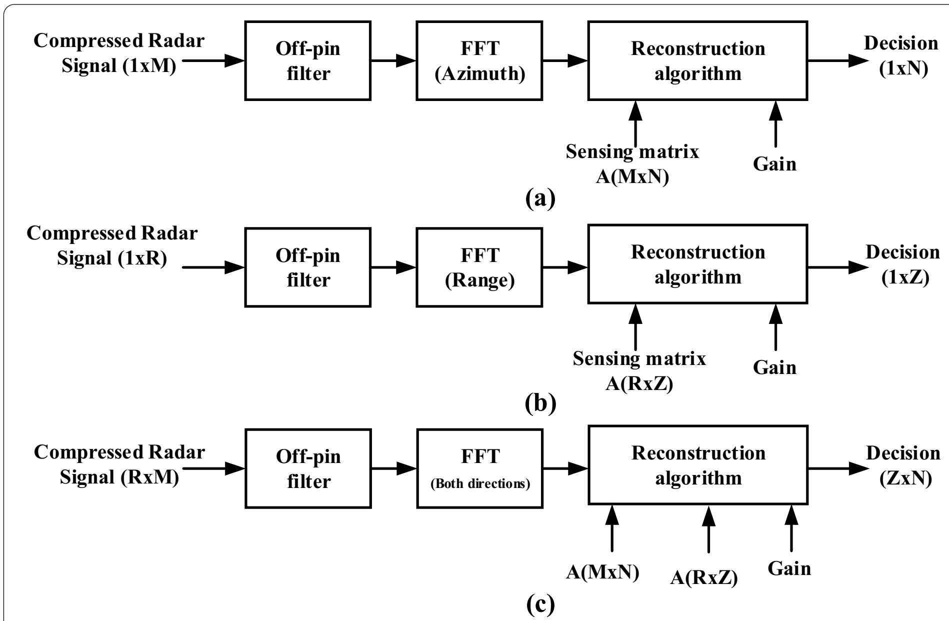

Fig. 7 Range-Doppler processor of LFMCW radar associated with off-pin filter in: **a** Range direction only. **b** Azimuth direction only. **c** Both directions

The proposed filter is chosen with certain coefficients after the first Fast Fourier Transform (FFT) processor in range to enhance the radar range detection and after the second FFT processor to enhance the target Doppler. The coefficients of this filter are chosen to be 1 and -0.5 to solve the problem of middle Doppler frequencies. The realization of this filter is illustrated in Fig. (8).

For the proposed filter, the difference equation can be written as:

$$y(n) = x(n) - 0.5x(n-1)16 \tag{15}$$

where x(n) and y(n) represent the output of the FFT processor and the output of the proposed filter, respectively. The transfer function of the proposed filter can be written as:

$$Y(Z) = X(Z)\left(1 - 0.5Z^{-1}\right)$$

Therefore,

$$H(Z) = 1 - 0.5Z^{-1}17 \tag{16}$$

To solve the problem of middle Doppler frequencies, the filter coefficients are chosen to be 1 and − 0.5 [14]. Also, to ensure high detection capability, the proposed filter is located in the head of the first FFT processor (as a window function) to ensure high detection capability before the range-Doppler processor.

Computer simulation

Two-dimensional LFMCW radar performance can be evaluated using Matlab simulation with specifications listed in the next table. The performance is compared to that of both the conventional CAMP and adaptive CAMP algorithms under the same conditions to verify a fair comparison. The linear modulation of FMCW radar is obtained to perform the target range alongside its Doppler (Table 1).

For simulation, the baseband radar signal is assumed for simulation to have 128 range samples and 16 Doppler samples in the range-Doppler processor. This radar signal is added with an additive white Gaussian noise with zero mean and unity variance in addition to the known target returns. To evaluate the simulation process; Firstly, detection performance can be achieved by calculating the signal-to-noise ratio (SNR) under the

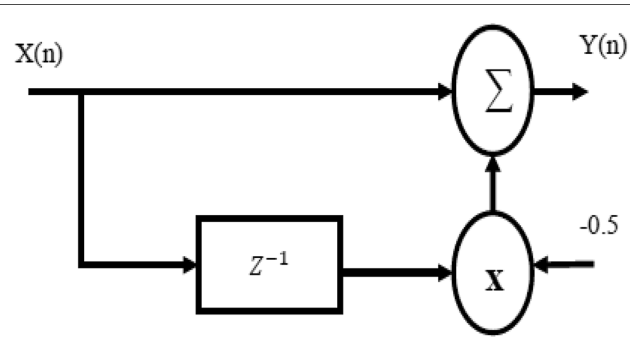

Fig. 8 Realization of the proposed filter processor

Table 1 Specification of the simulated radar parameters

Radar parameter	Specifications
Operating Frequency	5.3 GHz
Bandwidth	150 MHz
Pulse Repetition Frequency (PRF)	2 kHz
Pulse width	10 μsec
Duty Cycle	1%

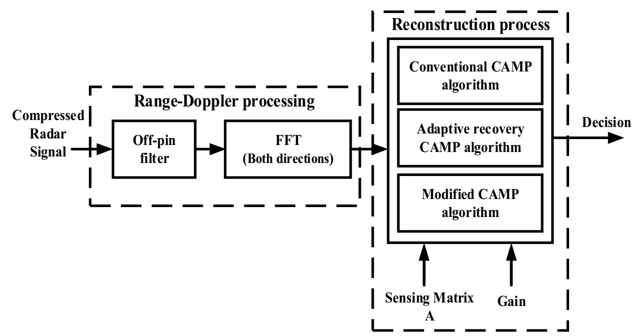

Fig. 9 Block diagram of Signal recovery using the conventional, adaptive, and modified CAMP algorithms

assumption of white Gaussian noise associated with the input radar signal. The amplitude of the radar signal varies according to the desired value of SNR, and the input signal power is divided by the power of associated noise to achieve the required SNR. Secondly, the resolution is tested for both range and azimuth directions by estimating the locations of targets and comparing them with the resulting information.

Figure (9) shows the block diagram of reconstructing the radar signals using the conventional CAMP and adaptive CAMP algorithms compared to the modified algorithm. The simulation comparison is achieved by two main aspects; detection performance in range and Doppler directions using ROC curves and the other aspect is the resolution in both directions.

Detection performance

The detection performance setup procedure is valid for the conventional CAMP, the adaptive CAMP, and the proposed algorithms based on CS using an FFT processor to extract the target information. The detection of these algorithms is performed by ROC curves using Matlab. A single target can be detected at a 50% reduction ratio ($\delta = 0.5$) for all algorithms and a probability of false alarm (P_{fa}) of 10^{-5} as shown in Fig. (10). The effect of an off-pin target can be shown in Fig. (11) with a range of off-pin number between 65,66 in the range direction and a Doppler off-pin number located between pin 5 and pin 6 in the azimuth direction.

From the ROC curves, it is found that the modified reconstruction algorithm has an improvement in detection performance for in-pin targets compared to that of the adaptive and conventional CAMP algorithms by nearly 14 dB and 70 dB, respectively. An enhancement is performed in the radar detection for off-pin targets when applying the

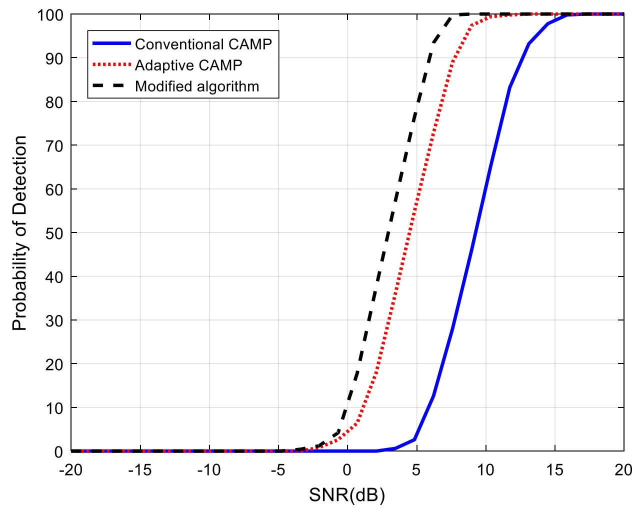

Fig. 10 ROC of the Range-Doppler processing of LFMCW radar for a single target at P_{fa} of 10^{-5} and reduction ratio of 50%.

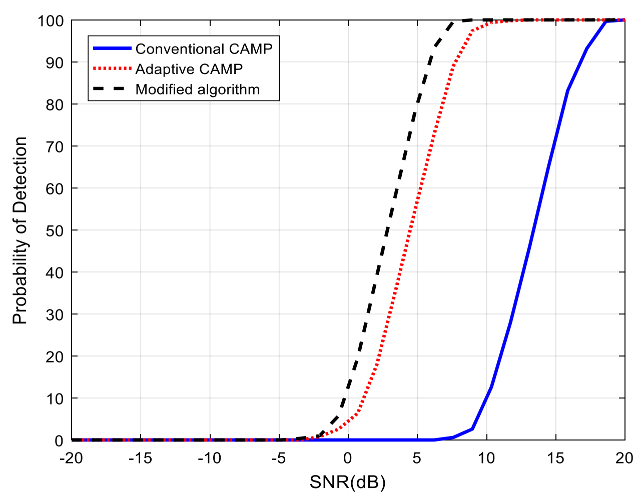

Fig. 11 ROC of the Range-Doppler processing of LFMCW radar for an off-pin target at P_{fa} of 10^{-5} and reduction ratio of 50%.

modified algorithm compared with both the traditional and adaptive CAMP, as illustrated in Fig. (11). This is due to the modification in the threshold calculation of the CA-CFAR processor of the reconstruction algorithm.

Resolution performance

Resolution performance means that the smallest distance between two targets appears on the radar display, as two targets, not one target. The resolution of the proposed algorithm is compared with that of the adaptive CAMP algorithm in two directions. To measure the algorithm resolution, two successive targets are located at range cell numbers (100) and (101), respectively. Figure (12) Shows the simulation results for

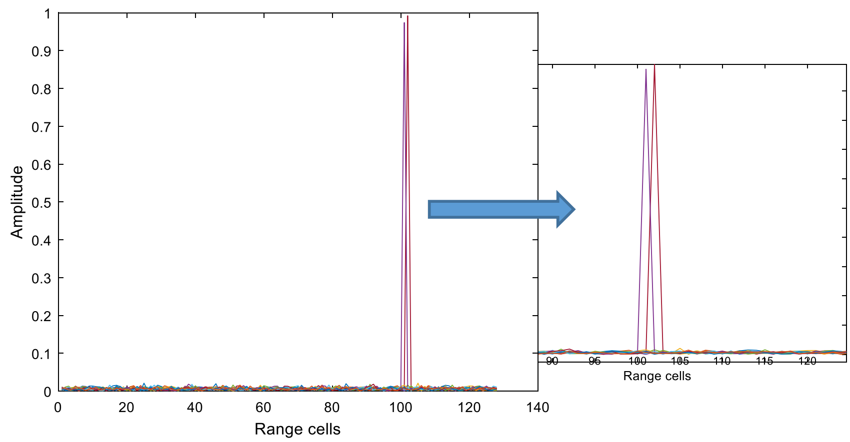

Fig. 12 Range resolution of LFMCW radar at SNR of 10 dB and 50% reduction ratio

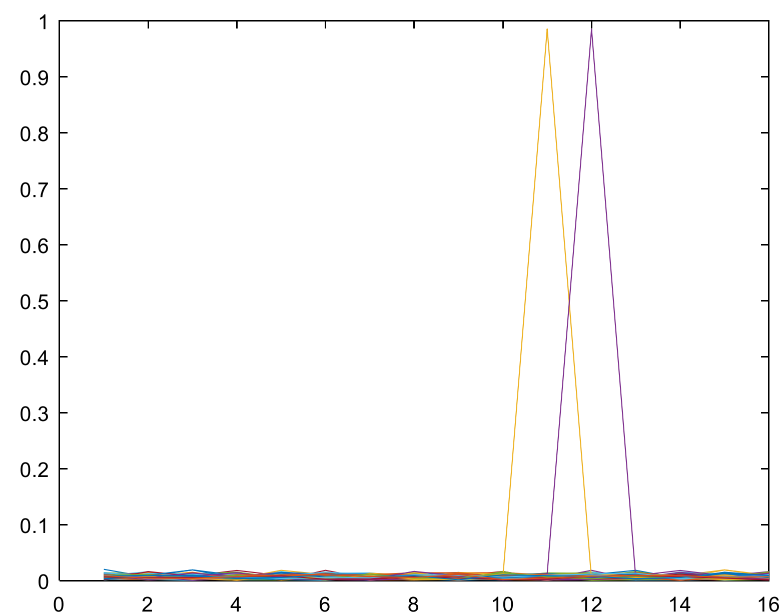

Fig. 13 Azimuth resolution of LFMCW radar at SNR of 10 dB and 50% reduction ratio

reconstructing the successive targets in range direction for both the proposed and adaptive CAMP algorithms at SNR = 5 dB, reduction ratio of 50%, and $P_{fa} = 10^{-5}$. From this figure, it is found that, the two targets appear separately which means that the range resolution in both the conventional and proposed algorithms is the same.

Resolution in Doppler is measured by assuming two successive targets at azimuth cell numbers (11) and (12) respectively, as shown in Fig. (13). The simulation results for reconstructing the successive targets in the Doppler direction for both the proposed and adaptive CAMP algorithms are presented at SNR = 5 dB, reduction ratio of 50%, and $P_{fa} = 10^{-5}$.

From these figures, it is clear that the resolution in both the range and Doppler directions of the received LFMCW radar signals does not change for the conventional and the proposed algorithms. The implementation of the adaptive recovery CAMP algorithm is performed in [19] and the modification process can be designed in the hardware without lacking in complexity. So, the overall complexity of the modification process in the adaptive CAMP reconstruction algorithm is suitable for radar applications and can be designed in real-time.

From this figure, it is clear that the resolution in the Doppler direction of the received LFMCW radar signals does not change for both algorithms.

The implementation of the adaptive recovery CAMP algorithm is performed in [12] and the modification process can be designed in the hardware without lacking in complexity. So, the overall complexity of the modification process in the adaptive CAMP reconstruction algorithm is suitable for radar applications and can be designed in real-time.

Conclusion

This paper modified the adaptive threshold of the CAMP algorithm for LFMCW radar. This modification is performed in the calculation of the threshold of the CA_CFAR processor, which is mainly dependent on one guard cell around the cell under test (CUT) in the range of samples direction, which is different from the traditional calculation, which uses many guard cells. Applying this modification in the adaptive reconstruction algorithm for two-dimensional LFMCW radar, it found that an enhancement in the radar detection in both range and Doppler by nearly 14 dB compared to the adaptive CAMP algorithm for in-pin target and around 70 dB when compared to the conventional CAMP. An enhancement of off-pin target detection for LFMCW radar is achieved when applying the modified algorithm in the reconstruction process compared to the conventional and adaptive CAMP algorithms. The detection is performed for these algorithms at a 50% reduction factor and with a false alarm probability (P_{fa}) of 10^{-5}. Another aspect for comparison is the resolution in both range and azimuth directions, and it is found that there is no change in the resolution in both directions as in the other algorithms. Hardware implementation of the proposed scheme is the main task in the future, in addition to enhancing the system complexity using real-time programmable language.

Abbreviations

CS: Comporessive sensing; LFMCW: Linear frequency modulation continuous wave.; CAMP: Complex approximate message passing.; ROC: Receiver operating characteristic.; IF: Intermediate frequency.; FFT: Fast Fourier transform.; OMP: Orthogonal matching Pursuit.; CFAR: Constant false alarm rate.; CA-CFAR: Cell average constant false alarm rate.; GOF: Gratest Of.; SOF: Smallest Of.; CUT: Cell under test.; PDF: Probability density function.; RIP: Restricted isometry property.

Acknowledgements

Not applicable.

Author's Contributions

This paper introduces a modification in adaptive threshold calculation of a reconstruction algorithm for LFMCW radar signals depending on the cell under test (CUT) in the structure of the CA-CFAR processor. The radar detection performance is enhanced compared with that of the conventional and adaptive reconstruction algorithms under the same conditions which get a better performance than the other algorithms. In this work, two contributions can be obtained. Firstly, the enhancement of the detection performance of 2D-LFMCW radar using an improvement detector based on CA-CFAR in the adaptive CAMP algorithm. The second one is the enhancement of off-pin target detection using a proposed filter in both range and Doppler direction. All the authors read and approved the final manuscript.

Competing interests
The implementation in real-time is the main task in the future using FPGA and an enhancement can be achieved by controlling the decision time using some IP cores of FPGA and assistant tools.

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