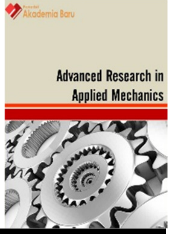
Penerbit Akademia Baru

Journal of Advanced Research in
Applied Mechanics

Journal homepage: www.akademiabaru.com/aram.html
ISSN: 2289-7895



Design and Implementation of Compressive Sensing on Pulsed Radar

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ARTICLE INFO

Article history:
Received 8 July 2017
Received in revised form 24 October 2017
Accepted 4 December 2017
Available online 24 March 2018

ABSTRACT

This paper presents the application of Compressive Sensing (CS) theory in radar signal processing. CS uses the sparsity property to reduce the number of measurements needed for digital acquisition, which causes reduction in the size, weight, power consumption, and the cost of the CS radar receiver. Complex Approximate Message Passing (CAMP) algorithm is a fast iterative thresholding algorithm which is used to reconstruct the under-sampled sparse signal and improves its Signal-to-Noise Ratio (SNR) [10]. In present work, the hardware implementation of Compressive Sensing Radar Signal Processing (CS RSP) by using the Complex Approximate Message Passing (CAMP) Algorithm is performed using FPGA processor. On the other hand, complexity and time of processing of the CAMP algorithm will be studied well for the real time implementation.

Keywords:
Compressive Sensing, CAMP, Compressive Sensing Radar signal processing

1. Introduction

In radar signal processing, in order to be able to accurately probe the target, to have a good radar resolution, and to reducing the effect of various jamming techniques, large-bandwidth and high dynamic range signal need to be launched, which requires a very high signal sampling rate and high speed A/D converter which should be compatible with sampling rate of the large-bandwidth signal. Nyquist rate (Shannon theory) restricts that the sampling frequency should equal at least twice the signal bandwidth [1].

Using very high sampling frequency according to large-bandwidth increases both errors in the A/D converter (sampling and quantization error), needs very high speed A/D converter which should be compatible with the sampling rate, and finally needs a very high speed signal processors. Currently available A/D converters and signal processors technology is a limiting factor in the design of wide bandwidth (high resolution) radar systems [1], because in many cases the required performance is either beyond what is technologically possible or too expensive.

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In 2004, Donohue and Candes proposed Compressive sensing theory, which showed that a signal having a sparse representation can be recovered exactly from a small set of linear, non-adaptive measurements [2]. CS theory combines the sampling and compression to reduce the signal sampling rate, the cost of the transmission, and the processing time. The CS theory shows that, when the signal has the characteristic of sparsity, the original radar signal can be exactly or approximately reconstructed from under-sampled measurements [3].

This paper is organized as follows; after the introduction, section 2 gives a survey on the bases of CS theory. Section 3 focuses on the feature of the CAMP algorithm (kind of the iterative thresholding algorithms). Hardware implementation of CAMP algorithm is presented in section 4. Experimental results of the implemented CAMP algorithm is presented in section 5. Finally, conclusion comes in section 6.

2. Compressive Sensing Theory

Based on the characteristic of sparsity of signal, CS theory converts the high dimensional signal to a lower dimensional signal using a sensing matrix, A, then reconstructs the original signal with high probability using a small number of measurements. Considering the problem of recovering a sparse signal, x, from an undersampled set of measurements, y [4]:

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

and,

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

where y is (M×1) measurement matrix, A is (M×N) sensing matrix, x is (N×1) sparse radar signal, n is Gaussian random noise with zero mean and unity variance, ρ is the radar signal sparsity, and δ is the under-sampling factor. The process of compression and reconstruction of signal using CS theory is organized, as shown in Figure 1 [5].

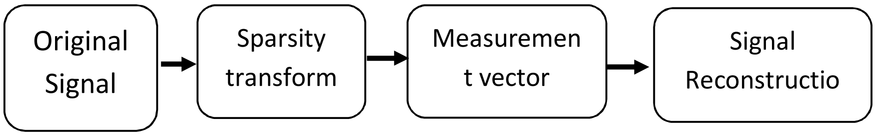


Fig. 1. General Compressive Sensing diagram

As shown in figure (1), application of CS in radar signal processing may be organized separately in three aspects: sparse representation of radar signal, designing of sensing matrix, and reconstruction of the radar signal. Firstly, Sparse representation of a signal mean that the number of unuseful values (zero elements or samples) is larger than the number of useful values (non-zero elements or values). Precondition of compressive sensing theory is that the radar signal is sparse or compressible. According to the definition of the sparsity property. The pulsed radar signal is considered as a sparse signal, as the number of targets is typically much smaller than the number of resolution cells in the illuminated area or volume [5], as shown in Figure 2.

Then, the sensing matrix, A, represents a dimensionality reduction of the radar signal. The sensing matrix maps, RN, where, N, is generally large (length of high dimensional radar signal) into RM, where, M << N, (under-sampled radar signal). It is designed using the Restricted Isometry

Property (RIP), and the Incoherence property to ensure that the sparse radar signal, x, can be reconstructed perfectly [5].

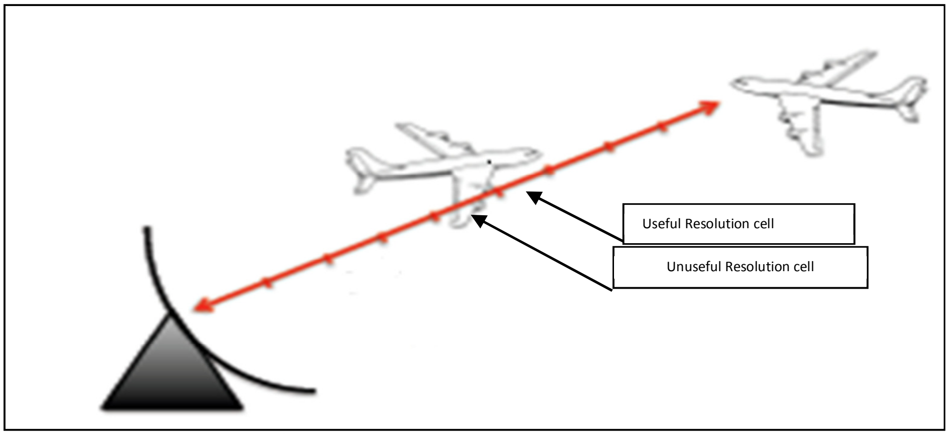


Fig. 2. Sparsity property of the radar signal

Finally, the radar signal can be reconstructed by using one of the reconstructed algorithms of CS theory. ℓ1-norm minimization algorithm requires very few measurements but is computationally more complex. On the other extreme are combinatorial algorithms, which are very fast, but require many measurements that are sometimes difficult to obtain. Iterative thresholding algorithms are in some sense a good compromise between those extremes concerning computational complexity and the required number of measurements [5].

2. Complex Approximate Message Passing (CAMP) Algorithm

CAMP algorithm is one of the most successful algorithms for the CS problem [6]. The CAMP algorithm is considered to be as the AMP algorithm for reconstructing the radar signal but in the complex domain [7]. On the other hand, CAMP algorithm is better than the AMP algorithm in the radar signal processing as the radar applications needs a complex analysis, where each non-zero element of the radar signal corresponds to the (complex) Radar Cross Section (RCS) of a target and may include propagation and other complex factors normally associated with the radar equation. On the other hand, CAMP shares some interesting features with AMP [8].

3. Hardware Implementation of CAMP Algorithm

In this section, FPGA design of CAMP algorithm is presented. The Xilinx Spartan 6 FPGA SP605 Evaluation Kit (XC6SLX45T-3C in FGG484 package), which is produced by Xilinx. All designed modules are performed by writing a VHDL code by using the Xilinx package ISE13.2, and simulated by using the ModelSim 6.3 simulator [9]. The flow chart of the implemented CAMP algorithm is shown in figure 3 [10].

The general block diagram of the implemented CAMP algorithm is shown in figure 4, the received radar signal is assumed to be a pulsed radar signal with duration of 1 us and 3 ms repetition period. The received radar signal is converted into digital form by means of ADC with a sampling rate of 1 MHz, which is chosen according to Shannon sampling theory.

I. Under-sampling module: is used to generate the measurement vector, y. the received radar signal is converted to samples by using the ADC. These samples are collected in the under-sampling module serially and stored in RAM with dimensions 16X1 samples. The measurement vector, y, (smaller numbers of samples than the Nyquist rate) is obtained by multiplying the sensing matrix, A, by the chosen window from the input radar signal. The sensing matrix, A, is generated randomly in the matlab-program (to satisfy the incoherence and the Restricted Isometry Properties), and is stored in a Ram (as an array) in the under-sampling module in the off-line case with dimensions 11X16. The output measurement vector, y, has a dimensions of 11 samples.

II. CAMP module: is used to reconstruct the sparse radar signal from a small number of samples smaller than the Nyquist rate. The output from the generating the measurements module is the measurement vector, y, feds a smaller number of samples than the Nyquist rate samples to the CAMP module.

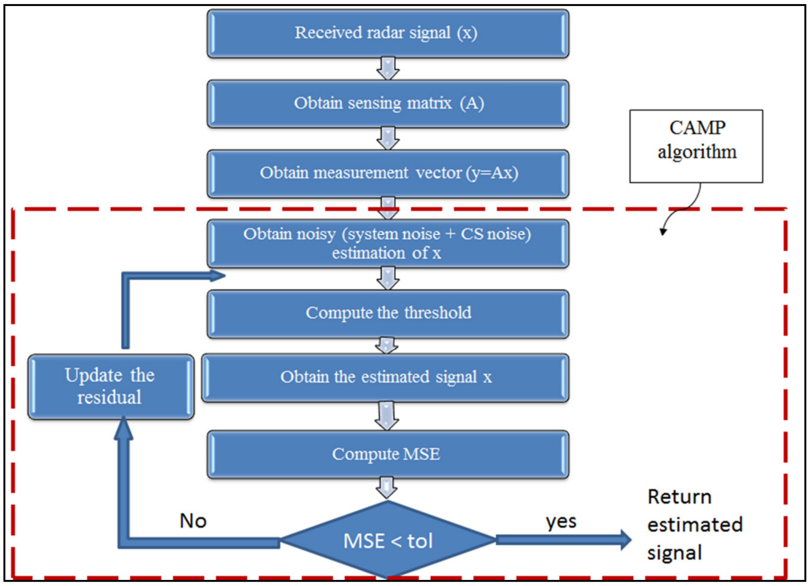


Fig. 3. Flow chart of CAMP algorithm

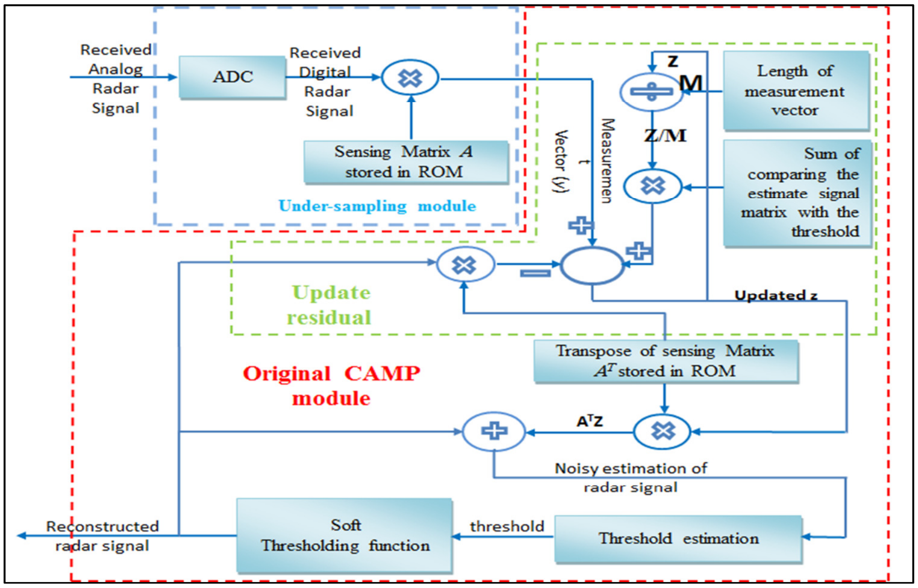


Fig. 4. Block diagram of CAMP algorithm

The CAMP module is responsible for reconstructing the chosen window of the received digital radar signal by using the measurement vector, y. The CAMP (reconstruction) module consists of the noisy estimation sub-module, the threshold estimation sub-module, the soft thresholding function sub-module, and the division sub-module. The noisy estimation vector of the reconstructed radar signal is determined by multiplying the measurement vector, y, by the transpose of the sensing matrix, AT, then the noisy estimation vector will be directed to the threshold estimation sub-module which is designed to calculate the threshold value by getting the average of the absolute value of the noisy estimation of the reconstructed radar signal. Finally, the output of the threshold estimation sub-module is compared with the noisy estimation vector to smooth the reconstructed radar signal and to reduce the noise of the estimated radar signal due to reconstruction process by using the soft thresholding function sub-module. Figure 5 shows the schematics diagram of the CAMP algorithm, which is generated by the Xilinx package ISE13.1 program.

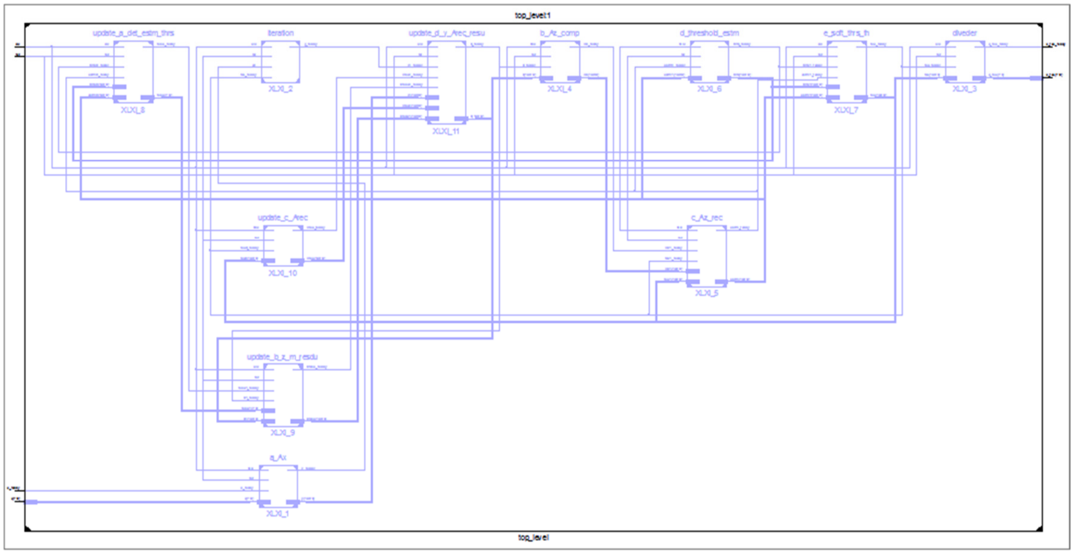
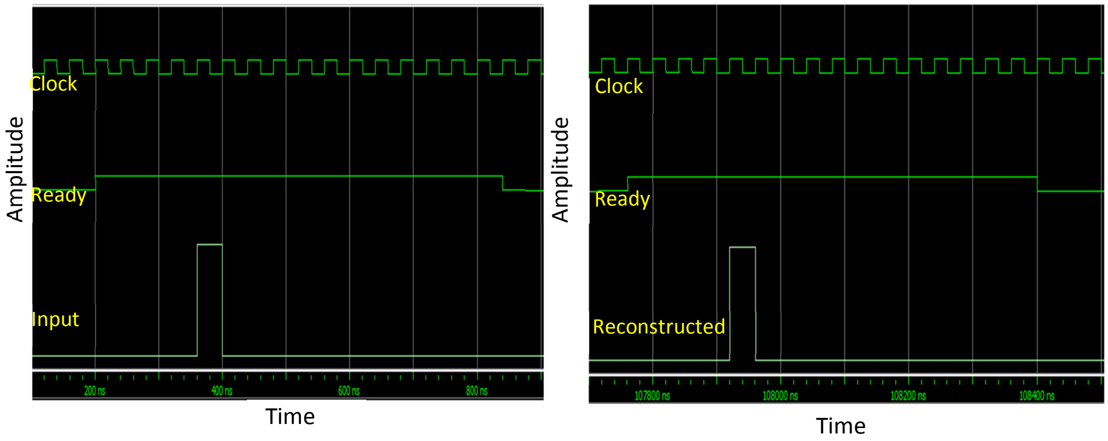


Fig. 5. Schematic diagram of CAMP algorithm

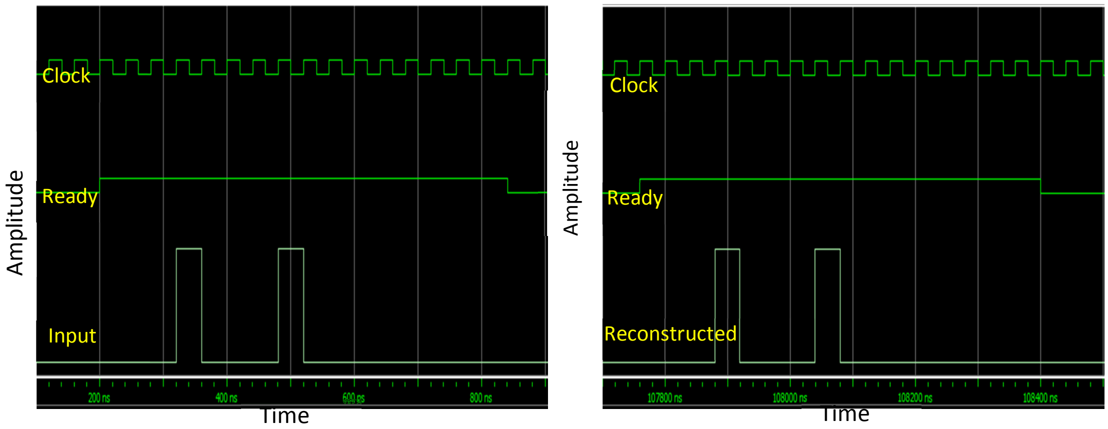
The Model-Sim simulation results are clarified in Figures 6, 7, 8, and 9. Model-Sim is a tool that integrates with Xilinx ISE to provide simulation and testing. Simulation is used to make sure that the logic of a design is correct and make sure that the design will behave as expected when it is downloaded onto the FPGA. The simulation results for reconstructing the received radar signal by using the CAMP algorithm. The input is considered to be the received radar signal (vector, x,) which contains 16 samples with 8 bits length for every sample. After designing the CAMP algorithm using the FPGA, the function and timing simulation for the design shall be performed in order to insure that it is doing its function correctly.

As shown in figure 6, 7, 8 and 9, the received radar signal is considered to have one and two targets, so the number of non-zero coefficients is k = 1 or k = 2 (sample at the pulse width), and the signal sparsity ρ = K / M = 0.053 and under-sampling factor δ = M / N = 0.18. The reconstructed radar signal by the CAMP algorithm is completely like the original radar signal.



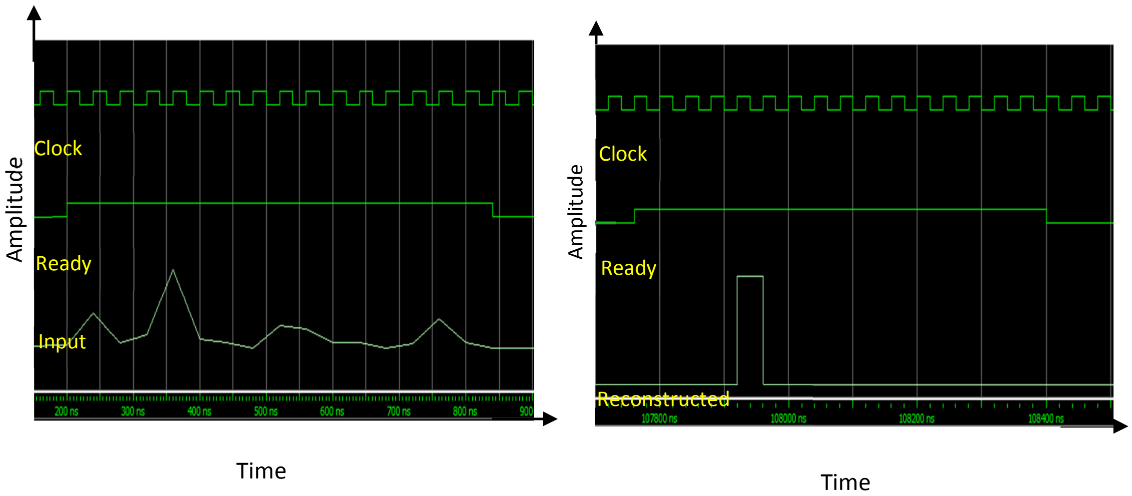
(a) (b)

Fig. 6. Model-Sim simulation results for CAMP algorithm for reconstructing the ideal radar signal with single target (a) original radar signal, (b) reconstructed radar signal



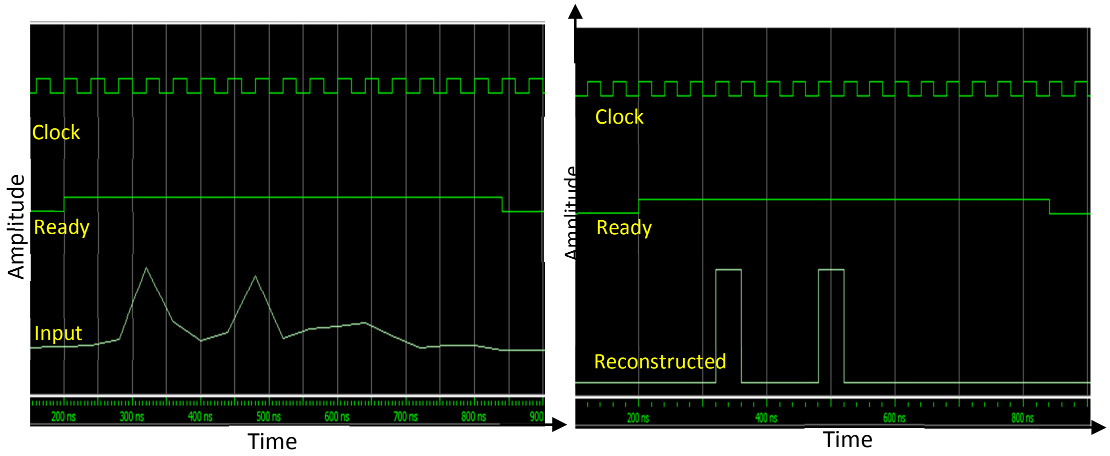
(a) (b)

Fig. 7. Model-Sim simulation results for CAMP algorithm for reconstructing the ideal radar signal with single target (a) original radar signal, (b) reconstructed radar signal



(a) (b)

Fig. 8. Model-Sim simulation results for CAMP algorithm for reconstructing the ideal radar signal with single target (a) original radar signal, (b) reconstructed radar signal



(a)

(b)

Fig. 9. Model-Sim simulation results for CAMP algorithm for reconstructing the ideal radar signal with single target (a) original radar signal,(b) reconstructed radar signal

4. Experimental results

The CAMP algorithm is implemented on a Xilinx Spartan 6 (XC6SLX45T-3C in FGG484 package) FPGA (speed grade -1) with the same throughput target for problems with a matrix A of size 11X16. CAMP is configured to perform a fixed number of iterations (T = 5) as the MSE between the reconstructed radar signal and the received radar signal gets fixed after only 5 iteration for the selected sensing matrix, as shown in figure 10.

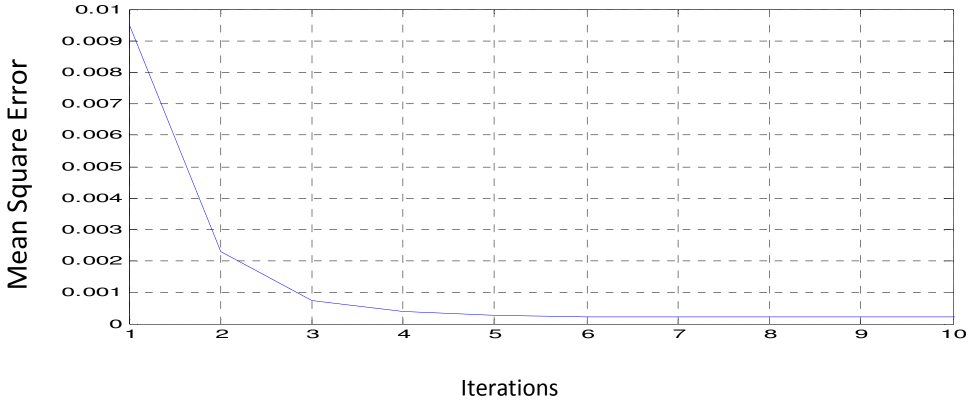
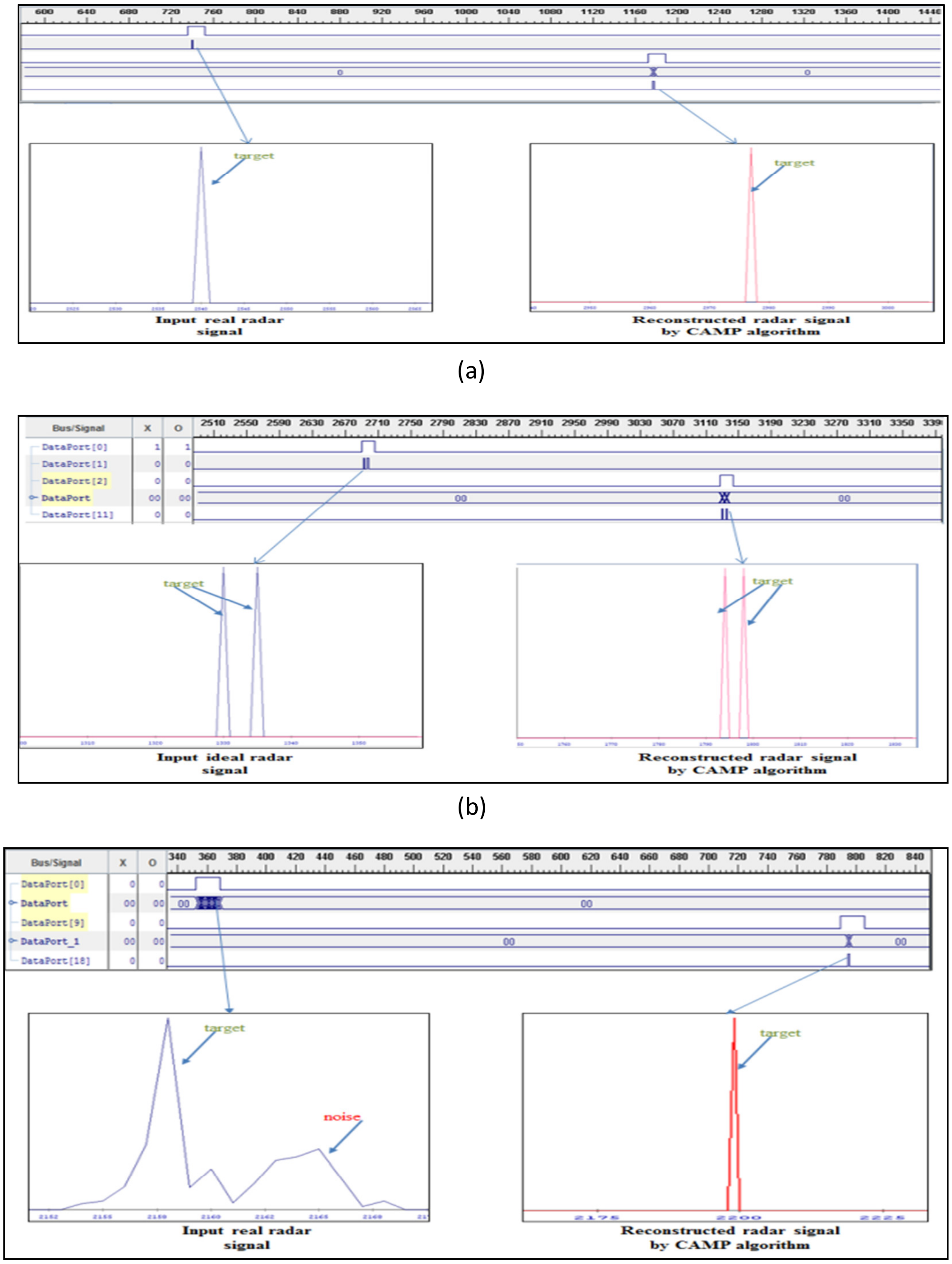


Fig. 10. MSE for reconstructing the received radar signal by using CAMP algorithm

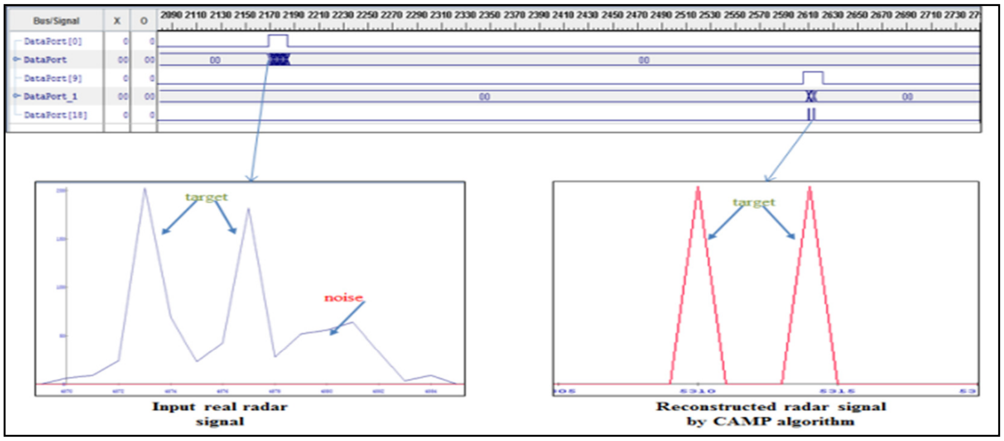
The following results are obtained by using ChipScope tool (related to Xilinx), which reserve memory blocks in the implemented FPGA chip to store the selected signals for specified period of time. Then, the selected signals can be viewed in different forms on the computer display. This method is very simple and effective in evaluating the implemented hardware. Figures (10) shows, the experimental results for the reconstructed received radar signal using the CAMP algorithm by using ChipScope software.


target
target
Input real radar signal
Reconstructed radar signal by CAMP algorithm
Bus/Signal
X
O
DataPort[0]
DataPort[1]
DataPort[2]
DataPort
DataPort[11]
target
target
Input ideal radar signal
Reconstructed radar signal by CAMP algorithm
DataPort[0]
DataPort
DataPort[9]
DataPort_1
DataPort[18]
target
noise
target
Input real radar signal
Reconstructed radar signal by CAMP algorithm

(a)

(b)

(c)



(d)

Fig. 11. Experimental results for CAMP algorithm for reconstructing the radar signal using ChipScope (a) ideal radar signal with single target, (b) ideal radar signal with two targets, (c) real radar signal with single target, (d) real radar signal with two targets

The implemented CAMP algorithm using Spartan 6 FPGA produced by Xilinx occupied 49 % of the slices of registers (26999 of 54576), and 61 % of slices LUTs (16785 of 27288), and 39 % of DSP slices (23 of 58).

4. Conclusion

The CAMP algorithm succeeded to reconstruct the received pulsed radar signal (under-sampling 75%) with a very high detection performance than the Digital Matched Filter, it gives a better detection performance (ROC 15 dB higher in SNR). On the other hand the CAMP algorithm is more complex than the Digital matched filter, as it consumes 49 % of the hardware resources of the used FPGA chip, and it takes a very high processing time (2689 clock cycle).

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