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# FPGA IMPLEMENTATION OF ADAPTIVE ZERO-TRACKING ALGORITHM FOR REAL-TIME DOA ESTIMATION USING A LINEAR ANTENNA ARRAY

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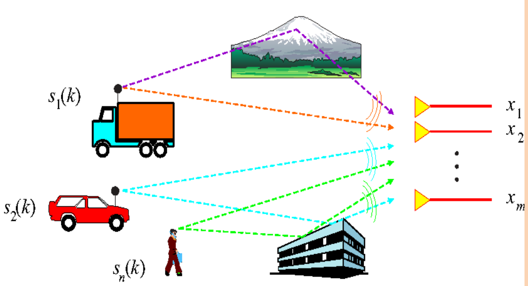
**Graphical abstract**




**Abstract**

In this paper, we employed blind separation techniques to estimate the direction of arrival (DOA) in a smart antenna system. Indeed, we have processed the antenna's output signal through the Symmetric Pre-Whitening algorithm in order to isolate each incident wave. Since we are interested by defining the DOA of strongest wave, we have characterized each separated wave using the power spectral density. The most powerful wave is then modeled by a three order autoregressive model whose complex zeros, computed and tracked adaptively, will be plotted in the unit circle. After convergence of the zero-tracking process, we assumed that the DOA corresponds to the phase of the zeros whereas the radius will give an idea on its magnitude. To assess the efficiency of the developed method in real-time, we compared the simulation results with those obtained from implementing the Symmetric Pre-Whitening and zero-tracking algorithms on the Artix-7 FPGA board. The results obtained by simulation and hardware implementation are quite similar.

*Keywords*: Blind Separation source, DOA, Smart antenna, Symmetric Pre-Whitening, Zero-tracking, Artix-7, FPGA



## 1.0 INTRODUCTION

The source separation technique has created a growing interest since its appearance. It has quickly become an attractive field of signal processing. The problem consists in extracting useful signals, also called sources, from mixtures of instantaneous or convoluted nature, called observations. Generally, observations are signals collected from a set of sensors (microphones, cameras, antennas).

Blind source separation (BSS) [1], introduced and formulated by Herault and Jutten in the mid-1980s, refers to a situation where there is a lack of a priori information regarding the sources or the mixing process (i.e., the situation of the observations). In such cases, no pre-existing knowledge is available. Since then, this topic has been the subject of much research in various application areas. Among the fields of application of BSS, we can mention for example the study of acoustic signals, telecommunications, biomedical, Earth observation or astrophysics.

In the radio and wireless communication field, observations from an antenna array can encompass the effects of mutual coupling between its elements [1]. To tackle this scenario, researchers have employed approaches utilizing Independent Component Analysis (ICA) for blind source separation. ICA necessitates the sources to be uncorrelated stationary random signals and has been effectively utilized to separate the signals received by the antennas [1], [2]. Ganage, D. et al., put forward a preprocessing technique that relies on the Dual Tree Complex Wavelet Transform (DTCWT) and Independent Component Analysis (ICA) to improves the performance of the MUSIC algorithm, which is widely used for high-resolution DOA estimation [2]. Zaho L. et al., demonstrated that the multipath signal DOA estimation problem can be translated into an l1 norm minimization one using FastICA algorithm [3]. For accurate determination of weaker coherent and non-coherent signals, Dhar, A., combined in [4], a BSS based Joint Approximation Diagonalization of Eigen matrixes (JADE) method and the MUSIC algorithm [5]. This results in a very good enhancement of the MUSIC algorithm resolution and thus the capability of the DOA of incoming signals. In [6], Ge, M. & al., addressed the problem of the suppression of main lobe jamming to obtain the DOA estimation of weak target for phased array radar. For this purpose, they have used the JADE blind source separation algorithm to estimate the steer vector and the waveform of main lobe jamming. Tachikawa, T. and al., used an underdetermined BSS method based on convex optimization which allowed simultaneous estimation of DOA and source signals under predetermined spatial dictionary and sparsity assumptions [7]. Recently, Correia Filho, L. & al., have presented a method based on ICA for locating electromagnetic sources with an optimized number of measurements. Their method can also detect the DoA of sources in special cases even when the signal sources are overlapped [8].

This study uses a blind separation approach to estimate the Direction Of Arrival (DOA) of the main signal through a linear array antenna system. From one of our previous work [9] we have concluded that SYM-WHITE is the most efficient algorithm to separate the mixture signals of a such system and identify independent incident waves. The main goal is to evaluate the phase and magnitude of the incident wave that has the highest power spectral density (PSD). To accomplish this objective, our proposal involves modeling the selected wave using an autoregressive (AR) model with complex zeros. By calculating and adaptively tracking these complex zeros, we can gain insights into the DOA of the wave.

To assess the efficacy of the proposed method under real-time conditions, we implemented the developed process in the Artix-7 FPGA board. This hardware solution will allow an experimental validation of the simulation results, including notably the computation of the angle and magnitude of the extracted incident signal.

Previously, limited research has focused on implementing real-time DOA estimation algorithms. For instance, Liu, T., & Zhang, Y. [10] and Yu, H., & Chang, S. J. [11] have implemented the MUSIC algorithm on an FPGA platform for the DOA estimation. In 2020, Tang, J., et al. [12] developed an FPGA implementation of the ESPRIT algorithm for wideband DOA estimation.In 2021, Venkatraman, V. S., & Shanmugavel, S. [13] implemented a DOA estimation algorithm for smart antenna systems using an FPGA board.

Although these differents DOA algorithms implentations results are certainly interesting, this work that we propose is distinguished by the implementation of the Adaptive Zero-Tracking algorithm jointly with a DOA algorithm. This approach provides the opportunity to extract more details about the incident signal's angle and power.

## 2.0 MATERIALS AND METHODS

This study, which focuses on determining the direction of arrival of the useful source from a mixture of signals incident on a linear antenna array, is based mainly on the use of the BSS blind source separation technique and the zero-tracking algorithm. Figure 1 provides an illustration of the flowchart for this strategy.

### 2.1 Blind Adaptive Beamforming System

Figure 2 illustrates the structure of blind adaptive beamforming for smart antenna arrays. Each antenna element receives a signal, which is then weighted by complex weights $W_l$ (l = 1,2, ..., M). The array of antennas is positioned in the far field of D sinusoidal sources, all with the frequency $f_0$.

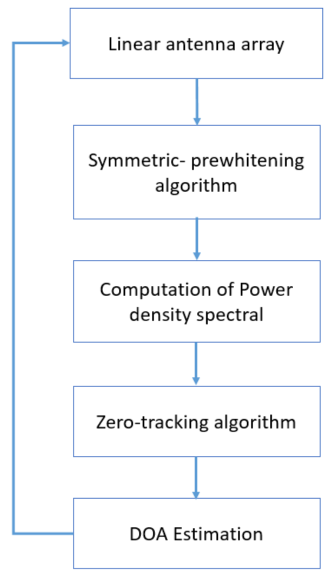



**Figure 1** Flowchart of the implemented methodology

The arrival directions of the incoming signals are denoted by $\theta_i$ (i=1, 2, ..., D). Consequently, the observed output signal $x_i(k)$ produced by each antenna element $x_l$ can be expressed using the following formula [8]:

$$x_l(k) = \sum_{i=1}^{D} m_i(k+\tau_i(\theta_i))e^{j2\pi f_0(k+\tau_i(\theta_i))} + v_i(k) \quad (1)$$

where m(θ) is a modulation function, v(k) is the noise signal received and τ(θ) is the arrival time of the wave $S_i(k)$ on the element i of the antenna:

$$\tau_l(\theta_i) = \frac{d}{c}(l-1)\sin\theta_i \quad (2)$$

Or, d= λ / 2 represents the distance between two elements of the antenna.

From the equation (1), we can express the process using matrix form as follows:

$$X(k) = A(\theta)S(k) + N(k) \approx Y(k) \quad (3)$$

The mixing matrix, denoted as A(θ), represents a [1xM] matrix. The observation vectors, X(k), encompass p vectors. The vector S(k) represents a [Dx1] vector comprising n independent components, which appear mixed at the output of the receiving antenna and need to be estimated. Additionally, there is an additive noise vector denoted as N(k).

Equation (3) represents the problem of blind source separation (BSS) in the scenario of instantaneous and linear mixtures. The vector Y(k) provides the estimated sources, while their corresponding projections for the various antennas are obtained from the estimated matrix: $M=W^{-1}$ [1].

At each iteration, the extracted sources are processed to calculate their respective Power Spectral Densities. The source with the highest DSP value is then modeled by an autoregressive model whose zeros are adaptively tracked until convergence is reached. This approach allows the DOA to be efficiently calculated from the arrangement of the zeros in the unit circle of the complex plane. The adaptive block in Figure 2 combines all these steps. Its function is to optimize the weights $w_i$ so that the beamforming is oriented towards the optimum DOA.

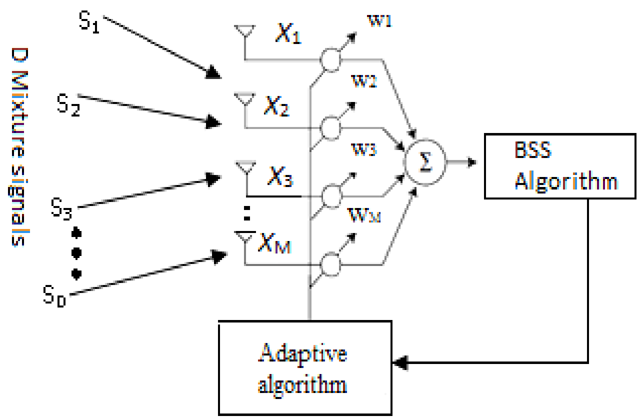



**Figure 2** The diagram describes the block structure of the blind adaptive beamforming designed for smart antenna arrays.

### 2.2 Symmetric-Prewhitenning Algorithm

A literature overview of different BSS algorithms have been established, but ICA algorithms have emerged as the most widely utilized ones in numerous signal preprocessing applications. These algorithms enable the estimation of original signals from a mixture of sources [1], [14] and have found extensive application in the telecommunications field [14], [15], [16]. As mentionned In our previous work [9], the Symmetric Pre-Whitening (Sym-White) [17], [18], is the best performing algorithm for the treatment of our BSS system. In our study, we conducted tests on a total of 15 distinct ICA algorithms. These algorithms were ranked based on their performance index and signal-to-noise ratio (SNR), which we assessed for both the estimated sources and the computed mixing matrix A [1], [9], [17].

The power of the Sym-White algorithm is demonstrated in its reliable source separation, in an efficient way, even in very difficult scenarios. It can thus adapt to situations where the mixture matrix A is symmetric and the covariance matrix of the original sources is assumed to be the identity. In practice, it achieves a unique prewhitening form, allowing the computation of a prewhitened matrix W, as indicated by [1], [17]:

$$W = inv(\sqrt{R_{xx}}) \qquad (4)$$

$R_{xx}$ represents the covariance matrix.

### 2.3 DOA estimation

To address the non-stationary nature of the acquired signals, our initial step involves determining their power spectral density. The power spectral density is defined as the Fourier transform of the autocorrelation function, representing the time-varying spectrum of the signals (Equation 5):

$$S_{xx}(\omega) = \sum_k R_{xx}(k) e^{-j\omega k} \qquad (5)$$

By using this function, we can select the most powerful independent component, which represents the incident source. To model this component, we use an autoregressive model Ar(z) with complex zeros. The model is computed and tracked adaptively using the zero-tracking algorithm, and is plotted within the unit circle algorithm [19], [20].

Let the autoregressive model Ar(z) of order N and of norm equal to 1 which is described by the coefficients $a_i$ (i = 1, ..., N) as follows:

$$Ar(Z) = \sum_{i=0}^{N-1} a_i z^{-i} \qquad (6)$$

The zero tracking algorithm searches for peaks in the spectrum by computing the roots of A(z) , which is defined as follows:

$$Ar(Z) = \prod_{k=1}^{N} (1 - z_k z^{-1}) \qquad (7)$$

The roots of the polynomial Ar(z), denoted as $z_i$ where i = 1, ..., N, are considered as the zeros in this context. These zeros are responsible for representing the signal's spectrum in the complex plane, with their location within the unit circle [15], [16].

When dealing with non-stationary signals, the model Ar(z) becomes time-varying, resulting in the adaptive computation of each zero's value. Furthermore, each zero is instantaneously represented as a singular point within the unit circle. At the convergence, the DOA is obtained according to angle of the optimal values of the model's zero.

### 2.4 Overview of the Artix-7 FPGA Family

The Artix-7 FPGA is a fully customizable development kit, perfect for embedded system designers looking for a flexible, low-power FPGA. Compared with the previous series, the Artix-7 series has reduced power consumption by half and cost by 35%.

The Artix-7 FPGA board is a complete system, packing all the functions and interfaces needed for an embedded processor system into a small package. Achieve higher transmit/receive ratio and signal processing capabilities for high-bandwidth applications, This FPGA series works best when combined with the MicroBlaze(TM) software processor.

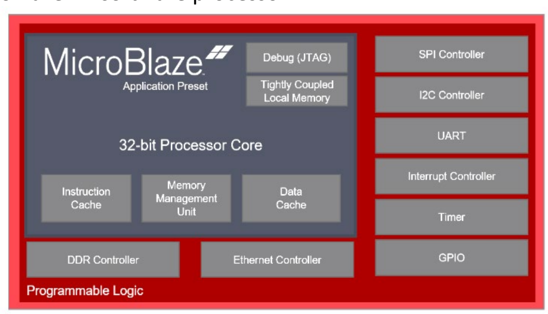



**Figure 3** Architecture of Artix-7 FPGA Family

The MicroBlaze core serves as a tightly integrated processor system designed for control applications. It houses the local memory, where both data and programs are stored. For debugging purposes, the MicroBlaze Debug Module (MDM) is available. In addition, a comprehensive suite of peripherals is incorporated, ensuring essential functionalities like the interrupt controller, UART, timers, and general-purpose inputs and outputs (Figure 3).

### 2.5 Xilinx System Generator

The Xilinx System Generator (XSG) functions as an FPGA integrator design environment (IDE), utilizing Simulink as its development platform. It is presented in the form of a collection of blocks, facilitating the design process. It has an integrated design flow (Figure 4) which allows you to jump directly to the configuration file (*.bit), needed to program the FPGA. Furthermore, this tool enables hardware co-simulations, enabling users to conduct simultaneous testing of their custom-designed cores on the target hardware alongside the model within the Simulink environment [21].

## 3.0 RESULTS AND DISCUSSION

### 3.1 Simulation Results

This section focuses on presenting the simulation results obtained through the utilization of a linear antenna array consisting of 10 rectangular elements (M=10). For that, we used 8 incident signals (D=8) that we generated mathematically by Matlab according to Equation (1) quoted previously. By analyzing the power spectral densities of all independent sources obtained, we observe distinct curves.

Figure 5 depicts the power spectral densities, indicating that the first source obtained exhibits the highest value. This observation implies that the independent source corresponds to the target incident signal.

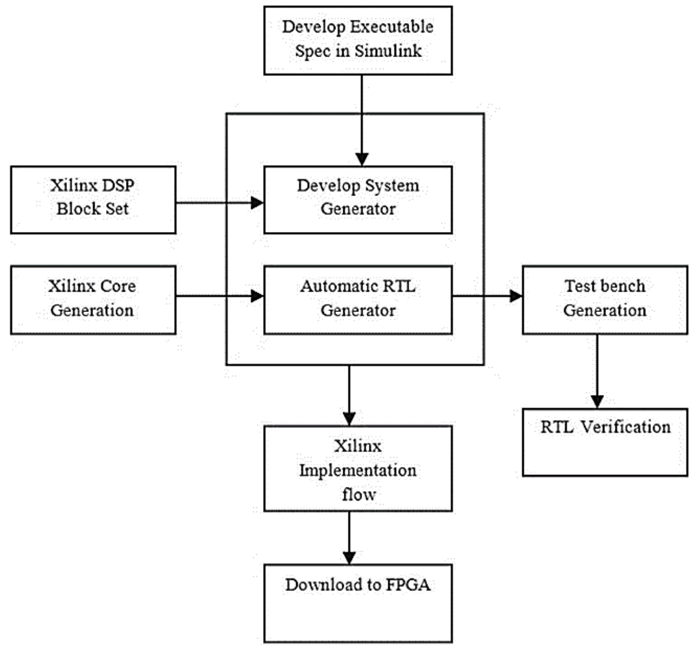



**Figure 4** The design process for Xilinx System Generator

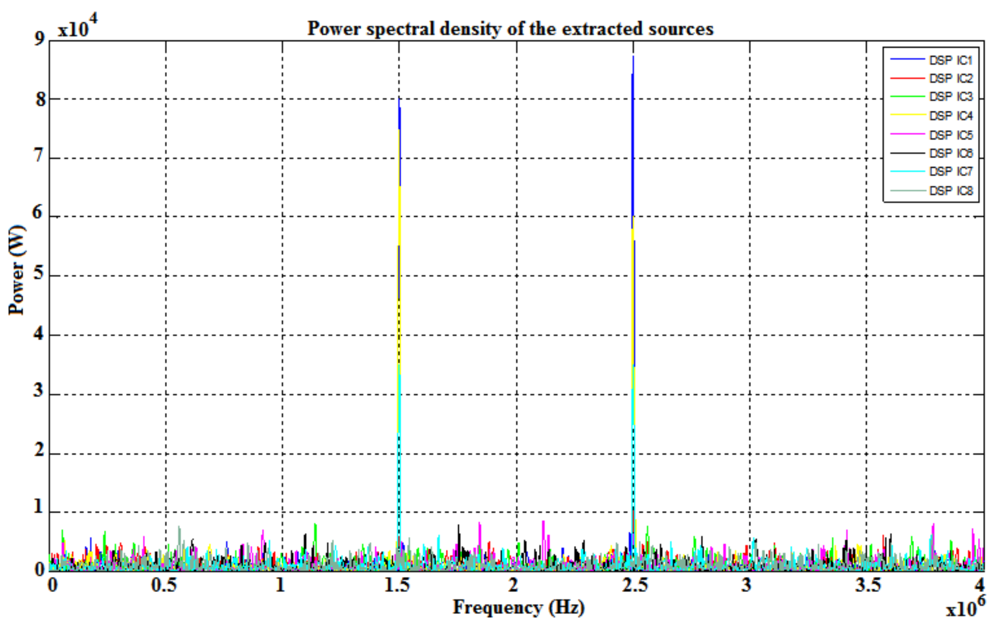



**Figure 5** Plot of the 3 tracked zeros of the AR model corresponding to the 1st extracted source.

In order to calculate its corresponding direction of arrival (DOA), we used an AR model of order N=3. This will result in 3 roots (2 complex conjugate zeros and 1 real zero) of the corresponding polynomial function Ar(Z). The results of tracking these 3 zeros, using the adaptive zero-tracking algorithm, is illustrated in the Figure 6 below.

By analyzing this figure, we can ascertain the angle of arrival for our signal. As a result, we obtain the following information:

$$\begin{cases} Cos(DOA) = 0.74 \\ Sin(DOA) = 0.64 \end{cases} \tag{8}$$

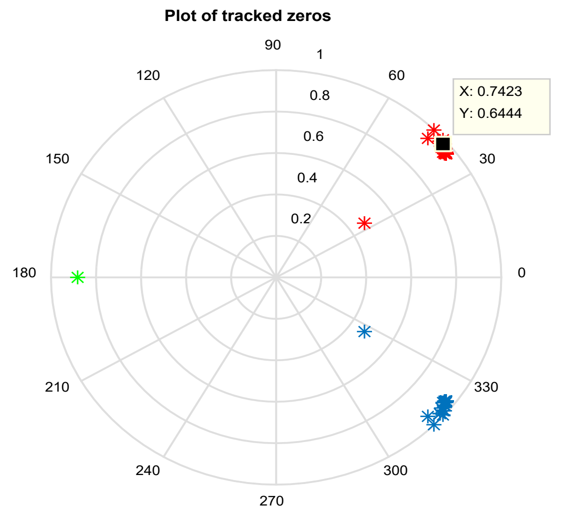



**Figure 6** Plot of the 3 tracked zeros of the AR model corresponding to the 1st extracted source.

This results in $\theta \approx 42°$, which is an estimate of the phase of the incident wave. The magnitude of this wave can be calculated as follows:

$$V = Cos(DOA)^2 + Sin(DOA)^2 \approx 0{,}96 \qquad (9)$$

### 3.2 Implementation and Experimental Results

In this experimental section, the model of the zero-tracking algorithm, created in MATLAB/Simulink with the Xilinx System Generator blocs (Figure 7), was converted into VHDL using HDL Coder, and then implemented in a Basys 3 Artix-7 board.

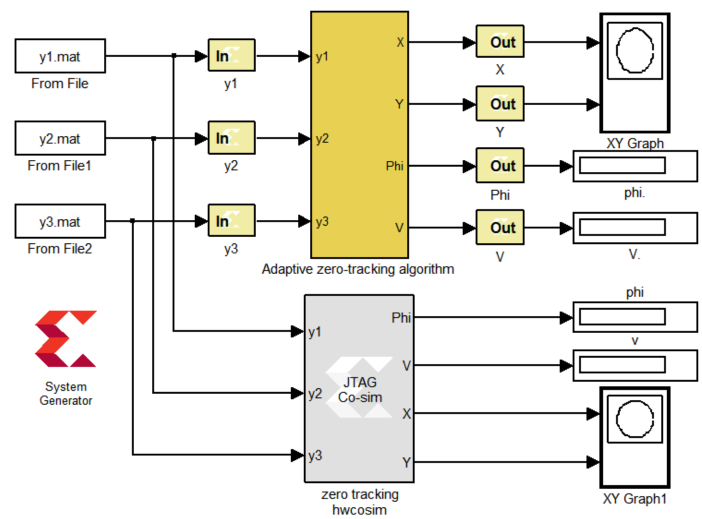



**Figure 7** Real-time estimation model for direction of arrival estimation

To estimate the angle of arrival of the signals in our dataset, we generated a hardware co-simulation block, following the steps mentioned in Figure 4, and which provided us real-time results.

Figure 8 showcases the real-time outcomes of implementing the zero-tracking algorithm on the Basys 3 Artix-7 board. The graph illustrates the angle and amplitude of the strongest arrived signal.

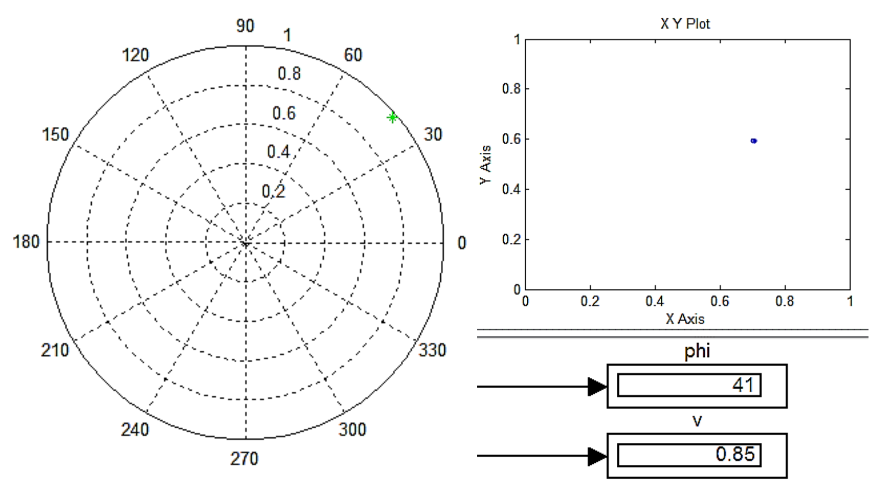



**Figure 8** Real time implementation result of the zero tracking algorithm

Based on the graph, the signal with significant spectral power, which eventually represents the source of information, exhibits an arrival angle of 41 degrees and an amplitude of 0.85 volts.

## 4.0 CONCLUSION

In order to estimate the phase and the magnitude of incident wave, we applied the Symmetric Pre-Whitening algorithm (SYM-WHITE) to smart antenna output signals. Indeed, we consider the adaptive beamforming for smart antenna arrays and we achieve the blind source separation task. We classify the estimated independent components based on their power spectral densities, arranging them in ascending order.

First, the most powerful source is then modeled via an autoregressive model of order 3. Two of its zeros are complex conjugate whereas the third is a real zero. In addition, we used a zero-tracking algorithm to adaptively track these zeros within the unit circle. This form of representation permits to estimate the phase of the source which corresponds to the angle of the optimal value of the complex zero. The radius of this last gives us an estimation of the magnitude of incident wave. For the used simulation signals, we found that the phase and the amplitude of the incoming wave were 42 degrees and 0.96 volts respectively. In a second step, we implement all of the algorithms used in this study under the Artix-7 basys 3 FPGA board. The results demonstrate that the Xilinx System Generator tool offers a straightforward and efficient approach for implementing the zero tracking algorithm, enabling validation of the findings obtained through simulations. The similarity rate between simulation and hardware implementation is 97.6%, confirming the performance of our method based on real-time DOA processing using FPGA boards.

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