

## Direct signal suppression in passive bistatic radar by amplitude control using PSO algorithm

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### ABSTRACT

*This paper proposes a solution to suppress the direct signal in passive bistatic radar with a circular antenna array (CAA) using a particle swarm optimization (PSO) algorithm. With the proposed solution, the null with the required depth and width in the direction of the transmitter is generated by controlling the amplitudes of the array elements. The validity and effectiveness of the proposed solution are demonstrated through simulation results of CAA beam patterns under various null generation scenarios, considering the beam pattern of each element.*

**Keywords:** Passive radar; Direct signal suppression; Null-steering; Particle swarm optimization.

### 1. INTRODUCTION

Passive radar can detect, measure, and track targets on the ground, in the air, and on the water by exploiting radiation sources from the targets themselves or radiation sources in the operating environment, such as FM radio signals, DVB-T/T2 television signals, global positioning satellites, or WIFI [1-3]. With this principle, passive radar systems have high stealth capabilities, low energy consumption, and are resistant to interference from enemy electromagnetic warfare devices. To determine the target location, passive radars are often multistatic radar systems. Based on the simple structure and high performance, bistatic passive radar systems using radio and television signals have been widely studied and deployed in both practical and theoretical applications [3-5].

The transmitting station is much stronger than the reflected signal from the target. To increase the effective dynamic range of these systems using radio and television waves, it is necessary to suppress the direct signal from the transmitting station at the surveillance channel antenna [1, 6, 7]. The suppression of direct signals in bistatic passive radars can be achieved by physical shielding, Fourier processing, adaptive beamforming, and adaptive filtering [1, 8]. With the location of the transmitting station known, the adaptive beamforming technique, which generates a null in the surveillance channel in the direction of the transmitting station, is effective and simple in suppressing direct interference in these radars.

Unlike some conventional radar antenna arrays, which are typically linear arrays, the surveillance channel antenna array in a bistatic passive radar is a circular antenna array (CAA). For a linear antenna array, it is possible to solve a system of linear equations to find the amplitude and phase distribution generating the number of nulls less than the number of elements in the array [9]. In the case of a CAA, the generation of nulls by solving the system of equations becomes more complicated as the multiplication rule applicable to linear arrays cannot be used when considering the individual beam pattern of each element.

Based on the particle swarm optimization (PSO) algorithm, this paper proposes a solution for producing a null in CAA by controlling the amplitude distribution to suppress the direct radiation

signal in the direction of the transmitting station. With the proposed solution, it is possible to generate the null with a specified depth and width in a required direction without having to solve a complex system of equations. The effectiveness of the proposed solution is demonstrated by the simulation results of the beam pattern, which considers the element beam pattern in CAA.

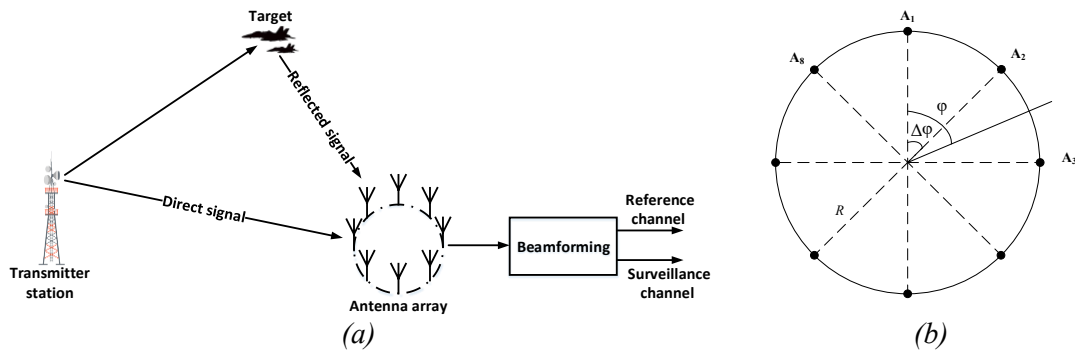
## 2. SYSTEM MODEL

Figure 1a illustrates a bistatic passive radar system consisting of a transmitter and a receiver. To process signal correlation, the receiver includes a surveillance channel and a reference channel [1]. The surveillance channel detects and measures the target's parameters, while the reference channel is used for correlation processing and interference mitigation. In surveillance, CAAs are widely employed to provide full 360° coverage [1, 4].

Consider a receiving station using a CAA with radius  $R$  and  $N$  elements spaced at a distance  $d$  along the circle, as shown in Figure 1b. The blocking angle between two consecutive elements on the circle is  $\Delta\varphi = 2\pi / N$ . To simultaneously observe directions in the azimuth plane, the system generates beams around the circle. By selecting a circular arc and moving the position of the arc along the circle, it is possible to steer the beam to 360° without rotating the antenna [10]. This capability is crucial for enhancing observation speed in passive radar, as it enables rapid reception of signals from targets in various directions.

In a bistatic passive radar system utilizing television or radio signals, the locations of the transmitting stations are known in advance. This enables the formation of beam patterns with a null directed toward the transmitter. Additionally, nearby objects may generate strong reflections that interfere with target detection. Therefore, both direct-path signals and strong reflections near the transmitter must be suppressed.

To generate nulls in the beam pattern and steer the beam toward a desired direction, it is necessary to apply phase and amplitude weights to the array elements according to a specific relationship. If the beam is to be steered toward  $\varphi_0$  and a null is to be formed at  $\varphi_{null}$  in the azimuthal plane, the phase and amplitude distributions must be designed so that the signals are in phase at  $\varphi_0$  and destructively interfere at  $\varphi_{null}$ . With a CAA, when generating a narrow beam, the maximum effective aperture length is half a circle. Therefore, the angle covered by  $M$  active elements is often chosen to be values such as 90°, 120°, 180° [10, 11]. To maximize the utilization of the aperture, this paper selects the number of active elements covering half of a circle (180°).



where  $k = \frac{2\pi}{\lambda}$  is the wave number, and  $\lambda$  is the wavelength.

For the direct interference suppression, the radiation pattern synthesis for CAA is usually focused on the azimuth direction. By suppressing the radiation pattern in the elevation plane ( $\theta_0 = 0$ ), the array factor when steering the main beam to the direction  $\varphi_0$  is determined as:

$$AF(\theta) = \sum_{m=1}^M a_m \exp \left( jkR \cos \left( \varphi - \frac{2\pi}{N}(m-1) \right) - jkR \cos \left( \varphi_0 - \frac{2\pi}{N}(m-1) \right) \right) \quad (2)$$

where  $a_m$  is the amplitude excitation for the  $m^{\text{th}}$  element,  $j$  is the imaginary unit ( $j^2 = -1$ ).

When taking into account the beam pattern of each element, the functional form  $1 + \cos \left( \varphi - \frac{2\pi}{N}(m-1) \right)$  can be chosen for the  $m^{\text{th}}$  element [10]. With the assumption, the beam pattern of CAA in the azimuth plane is expressed as:

$$F(\varphi) = \sum_{m=1}^M a_m \exp \left( jkR \cos \left( \varphi - \frac{2\pi}{N}(m-1) \right) - jkR \cos \left( \varphi_0 - \frac{2\pi}{N}(m-1) \right) \right) \times \left( 1 + \cos \left( \varphi - \frac{2\pi}{N}(m-1) \right) \right) \quad (3)$$

The normalized beam pattern of the array is defined by:

$$F_n(\varphi) = \frac{F(\varphi)}{\max(F(\varphi))} \quad (4)$$

Based on the given phase distribution and beam pattern, generating a null at direction  $\varphi$  requires adjusting the excitation amplitudes of the array elements such that the normalized beam pattern equals 1 in the desired direction and is approximately zero in the direction of the direct signal.

### 3. DIRECT SIGNAL SUPPRESSION IN PASSIVE RADAR USING CAA

#### 3.1. Building the objective function

To steer the main beam toward the target direction and suppress the direct signal from the transmitter direction, the modulus of the beam pattern function needs to achieve a maximum value at the target direction and approximately zero at the direction of the direct signal. In optimization problems, the depth of the null of the beam pattern is usually required to be below a certain threshold. This value satisfies the criteria of the dynamic range for the surveillance channel in the passive radar. In addition, the beam pattern of the array exhibits a low side-lobe level (SLL) to reduce the reception of the signal from side lobes.

Based on the above objectives, the objective function to steer the beam to the direction  $\varphi_0$ , generate a null at  $\varphi_{null}$  with a level less than or equal to  $L_{null}$ , and reduce SLL is described as follows:

$$\begin{aligned} & \text{if } |F_n(\varphi_0)| < 1 \\ & \quad F_{ob} = -20 \times \log_{10} |F_n(\varphi_0)| \\ & \text{else} \\ & \quad \text{if } 20 \times \log_{10} |F_n(\varphi_{null})| > L_{null} \\ & \quad \quad F_{ob} = 20 \times \log_{10} |F_n(\varphi_{null})| \\ & \quad \text{else} \\ & \quad \quad F_{ob} = L_{null} + SLL_{\max} \\ & \quad \text{end} \\ & \text{end} \end{aligned} \quad (5)$$

where  $SLL_{\max}$  is determined by the expression [11]:

$$SLL_{\max} = \max(20 \times \log_{10} F_n(\varphi)) \quad \text{with } \theta \in [0, \varphi_{nu1}] \cup [\varphi_{nu2}, 360^\circ] \quad (6)$$

where  $\varphi_{nu1}$  and  $\varphi_{nu2}$  are the first nulls to the left and right of the main lobe, respectively.

With the amplitude distribution producing nulls near the main lobe, the first two nulls can be approximately determined by:

$$\varphi_0 - \varphi_{nu1} \approx \varphi_{nu2} - \varphi_0 \approx 0.8 \times HPBW \quad (7)$$

where  $HPBW$  denotes the half-power beamwidth. When the number of active elements is selected corresponding to half of a circle,  $HPBW$  is calculated as in [10]:

$$HPBW \approx 82.2 \frac{\lambda}{2R} \quad (8)$$

The optimization according to (5) consists of three steps performed in sequence. The first step is to steer the beam toward the target. This objective is easily achieved by using the phase distribution from (1). It is introduced to ensure that changes in the amplitude distribution do not affect the beam control in the target direction. The second objective in (5) ensures that the null at the transmitter direction is below a required threshold. By shifting the main beam position according to the order of the active elements on the selected arc, the null position shifts relative to the main beam in the surveillance channel. The third objective is to reduce the side lobes in the beam pattern to avoid multiple azimuth measurements. The optimization according to (5) is considered successful when the objective function reaches its minimum value.

In practice, direct signals can be received by the surveillance channel antenna over a wide angle range due to reflections from objects surrounding the transmitter. Therefore, the direct signal suppression may need to be performed within a wide azimuth range. To steer the beam to the direction  $\varphi_0$ , produce a null within the range from  $\varphi_{nu-desired1}$  to  $\varphi_{nu-desired2}$  at a level below  $L_{null-wide}$ , and reduce SLL, the objective function can be formulated as follows:

$$\begin{aligned} & \text{if } |F_n(\varphi_0)| < 1 \\ & \quad F_{ob} = -20 \times \log_{10} |F_n(\varphi_0)| \\ & \text{else} \\ & \quad \text{if } 20 \times \log_{10} |F_n(\varphi_{nu-desired1} : \varphi_{nu-desired2})| > L_{null-wide} \\ & \quad \quad F_{ob} = \max(20 \times \log_{10} |F_n(\varphi_{nu-desired1} : \varphi_{nu-desired2})|) \\ & \quad \text{else} \\ & \quad \quad F_{ob} = L_{null-wide} + SLL_{\max} \\ & \quad \text{end} \\ & \text{end} \end{aligned} \quad (9)$$

In (9), the main lobe width and SLL are determined by formulas (6), (7), and (8).

The objective functions constructed based on formulas (5) and (9) can be used for amplitude distribution optimization, phase distribution optimization, or complex weight optimization (including both amplitude and phase distributions). This study uses the amplitude method as it is simpler than complex weight optimization.

### 3.2. Direct signal suppression using an amplitude-controlled PSO

To apply the PSO algorithm, this study uses an  $M$ -dimensional hyperspace corresponding to the  $M$  amplitude distribution coefficients to generate a beam pattern with the main lobe steered toward the target direction, produce a null at the transmitter direction, and reduce SLL. Suppose the swarm

consists of  $K$  particles. At each iteration, each particle moves to its best position ( $p_{best}^t$ ) and the global best position ( $g_{best}^t$ ) in the swarm. The optimal solution obtained corresponds to the position of the particle when the objective function  $F_{ob}$  reaches its minimum value. From there, the velocity vectors  $v$  and position  $x$  of the  $i^{th}$  particle ( $1 \leq i \leq K$ ) in the  $M$ -dimensional hyperspace at the  $(t+1)^{th}$  iteration are determined according to the following expressions [12]:

$$v_i^{t+1} = \omega v_i^t + c_1 r_1 (p_{best}^t - x_i^t) + c_2 r_2 (g_{best}^t - x_i^t) \quad (10)$$

$$x_i^{t+1} = x_i^t + v_i^{t+1} \quad (11)$$

where  $\omega$  is the inertia weight,  $r_1$  and  $r_2$  are random vectors uniformly distributed in the interval  $[0, 1]^M$ , and  $c_1$  and  $c_2$  are acceleration coefficients. The coefficients in equations (10) and (11) are determined as follows:  $c_1 = c_2 = 2$ , and the inertia weight is linearly decreased from 0.9 to 0.4 throughout the iterations, from the first to the last [11].

#### 4. RESULTS AND DISCUSSION

To illustrate the effectiveness of the proposed solution, this study considers a typical CAA consisting of 12 elements ( $N = 12$ ) [1, 13] with  $d = \lambda/2$ . A dipole antenna array is a suitable antenna model. Since the most efficient aperture for steering a narrow beam is half a circle [10], this study selects the first 7 elements to generate the beam pattern ( $M = 7$ ). With an array of 12 elements, there are 12 combinations of 7 consecutive elements to shift the main beam over  $360^\circ$ . The arcs containing these successive elements are rotations around the circle, so the selection of a single circular arc containing active elements does not reduce the generality. With different circular arc positions, the direction of the transmitter relative to the main beam will change. The simulation scenarios for two cases of a single null and a wide null are shown in the following subsections.

##### 4.1. Generation of a single null toward the direction of the transmitter

Consider that it needs to steer the main lobe in the direction of  $90^\circ$  and generate a single null to suppress the direct signal from the transmitter to a level of less than or equal to -50 dB. This value is chosen according to some popular direct signal suppression algorithms, such as normalized least mean squares, fast block least mean squares [8]. By changing the starting position of the active element and using the phase distribution expression (1), the main beam can be steered through  $360^\circ$  in the azimuthal plane. With a fixed transmitter position, the positional relationship between the null and the main beam will change when moving the main beam in the azimuthal plane. To illustrate the two cases in which the null needs to be generated either near or far from the main beam, this section considers the two cases where the null position is at  $30^\circ$  and  $190^\circ$ .

**Table 1.** Amplitude distribution generating a single null.

| Index                           | 1      | 2       | 3       | 4       | 5       | 6       | 7      |
|---------------------------------|--------|---------|---------|---------|---------|---------|--------|
| Phase distribution ( $^\circ$ ) | 0      | -171.89 | -297.72 | -343.78 | -297.72 | -171.89 | 0      |
| Null at $30^\circ$              | 0.0938 | 1.0000  | 0.9173  | 0.6984  | 0.3988  | 0.8962  | 0.4324 |
| Null at $190^\circ$             | 0.0938 | 1.0000  | 0.9173  | 0.6984  | 0.3988  | 0.8962  | 0.4324 |

Using the objective function defined in expression (5), the PSO algorithm is applied with 100 particles and 5000 iterations. The program to determine the amplitude distribution is executed five times using MATLAB 2015A, and the run with the smallest objective function value is selected. The corresponding amplitude distribution coefficients based on (5) are presented in Table 1. The table also provides the phase distribution for the elevation angle  $\theta_0 = 0$ . The amplitude and phase distributions shown above can be generated using digital beamforming synthesizers.

With these coefficients, the array beam patterns in the two cases of nulls at  $30^\circ$  and  $190^\circ$  are shown in Figure 2. In addition to the beam pattern generated by the amplitude distribution coefficients from the proposed PSO, Figure 2 also presents the beam patterns with nulls at  $30^\circ$  and

190° using two other amplitude distributions: the Chebyshev distribution and the raised cosine-squared distribution (or the cosine-squared on a pedestal distribution). These two distributions are chosen for comparison in this study because the Chebyshev distribution is commonly used to optimize beam patterns for linear arrays, while the raised cosine-squared distribution is applied to optimize the beam pattern for some CAAs [14]. To generate a null at 30°, it is necessary to use the Chebyshev distribution with side lobe attenuation (SLA) of -22 dB and use the raised cosine-squared distribution with the pedestal level  $\Delta = 0.41$ . To generate the null at 190°, a Chebyshev distribution with  $SLA = -20.6$  dB and a raised cosine-squared distribution with the pedestal level  $\Delta = 0.45$  are applied. The detailed parameters of the beam patterns are provided in Table 2.

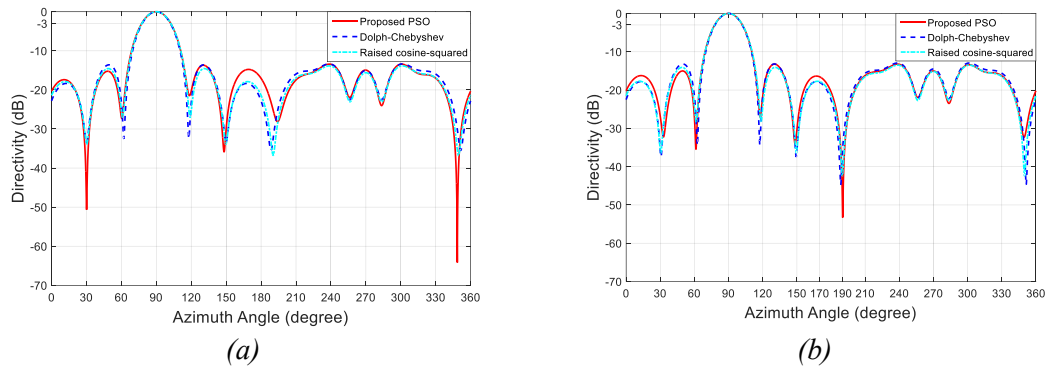


**Figure 2.** Beam patterns for direct signal suppression: a) Null at 30°; b) Null at 190°.

**Table 2.** Parameters of the beam patterns for direct signal suppression.

|                                           | Null Level (dB) | SLL (dB) | HPBW (°) |
|-------------------------------------------|-----------------|----------|----------|
| Null at 30°                               |                 |          |          |
| Proposed                                  | -50.1           | -13.41   | 24.92    |
| Chebyshev with $SLA = -46.6$ dB           | -33.47          | -13.35   | 24.21    |
| Raised cosine-squared ( $\Delta = 0.41$ ) | -33.79          | -13.86   | 24.83    |
| Null at 190°                              |                 |          |          |
| Proposed                                  | -50             | -13.23   | 24.32    |
| Chebyshev with $SLA = -20.6$ dB           | -36.35          | -12.95   | 23.95    |
| Raised cosine-squared ( $\Delta = 0.45$ ) | -42.42          | -13.49   | 24.56    |

Table 2 shows that the two conventional distributions cannot produce null depths lower than -50 dB at 30° and 190°, whereas the proposed solution achieves null levels of -50.1 dB and -50 dB, respectively. For the case of generating a null at 30°, the SLL obtained by the proposed solution is slightly lower than that of the Chebyshev distribution with  $SLA = -46.6$  dB, and slightly higher than that of the raised cosine-squared distribution ( $\Delta = 0.41$ ). In this case, the HPBW obtained from the proposed solution is slightly larger than those obtained from the other two amplitude distributions. The slight increase in SLL and HPBW of the proposed solution compared to the two traditional solutions is a trade-off for the reduction in null depth. By generating a deeper null, the proposed solution suppresses the direct interference at 30° more effectively than the Chebyshev and raised cosine-squared distributions, while producing SLL and HPBW values comparable to those of the two conventional methods.

In the case of generating the null at 190°, the proposed solution achieves a null depth of -50 dB at 190° and a minimum null depth of -53.07 dB at 190.2°. The SLL obtained from the proposed solution is slightly smaller than that obtained from the Chebyshev distribution with  $SLA = -20.6$  dB and slightly larger than that obtained from the raised cosine-squared distribution ( $\Delta = 0.45$ ). The HPBW obtained from the proposed solution is slightly larger than that obtained from the

Chebyshev distribution and somewhat smaller than that obtained from the raised cosine-squared distribution. Similar to the case with the null at  $30^\circ$ , the proposed solution suppresses direct interference much better than using the Chebyshev and raised cosine-squared distributions, while generating SLL and HPBW values equivalent to those of the two distributions.

#### 4.2. Generation of a wide null toward the direction of the transmitter

Similar to 4.1, this section also uses the first 7 active elements of the CAA. Suppose that the beam needs to be steered to  $90^\circ$  and a wide null is needed to suppress the direct signal according to the transmitter location at a level less than or equal to  $-40$  dB in the angular bands  $[160^\circ, 170^\circ]$ . The suppression of the direct signal in a band means eliminating strong reflections near the transmitter. To determine the optimal distribution to steer the beam to the required direction, suppress direct interference, and reduce SLL, the PSO algorithm is used with the number of particles of 100 and the number of iterations of 5000. The programs to determine this amplitude distribution using MATLAB 2015A software are also run 5 times, and the run with the smallest objective function value is selected. The amplitude distribution coefficients determined by the PSO algorithm according to the objective function (5) are shown in Table 3. With the main beam positioned at  $90^\circ$ , the phase distribution is also presented in Table 1.

**Table 3.** Amplitude distribution generating a wide null.

| Index                  | 1      | 2      | 3      | 4      | 5      | 6      | 7      |
|------------------------|--------|--------|--------|--------|--------|--------|--------|
| Amplitude distribution | 0.0938 | 1.0000 | 0.9173 | 0.6984 | 0.3988 | 0.8962 | 0.4324 |

Figure 3 shows that the proposed solution can generate a null level less than or equal to  $-40$  dB in the angle range  $[160^\circ, 175^\circ]$ . With a received bandwidth of  $15^\circ$ , the null band from the proposed solution is  $5^\circ$  wider than the required bandwidth. Meanwhile, some conventional amplitude distributions, such as the uniform, the Chebyshev distribution, the Taylor distribution, or the raised cosine-squared distribution, cannot achieve a null depth of  $-40$  dB over a range wider than  $10^\circ$ . However, the generation of a wide range of nulls also results in a relatively high SLL of  $-7.491$  dB and an HPBW of  $22.55^\circ$ . The angular accuracy can be improved by accounting for the delay difference between the direct signal from the transmitter and the target echo [15]. To reduce the SLL and HPBW, the number of elements in the circular array can be increased. The effect of increasing the number of elements on SLL reduction during null synthesis has been demonstrated in [4]. Given the current bistatic passive radar architecture, increasing the number of elements is beyond the scope of this study. Further investigation into this issue will be conducted in future studies.

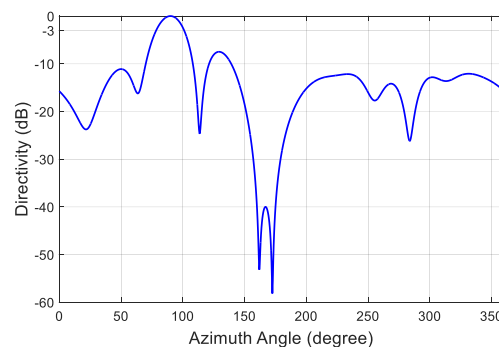


**Figure 3.** Beam pattern for direct signal suppression in  $[160^\circ, 170^\circ]$ .

## 5. CONCLUSIONS

The paper proposed a solution for direct signal suppression in a bistatic passive radar using a CAA based on the PSO algorithm to find the amplitude distribution. When steering the main beam toward the direction of interest, the proposed solution was able to generate a single null with a

level less than or equal to -50 dB and a wide null with a level below -40 dB in the direction of the transmitter. In addition, the proposed solution effectively controlled the null position and width, while also reducing SLL. The simulation results demonstrated the effectiveness of the proposed solution with improvements in parameters compared to some conventional amplitude distributions.

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## TÓM TẮT

### Triệt tín hiệu trực xạ trong ra đa thụ động hai vị trí bằng điều khiển biên độ sử dụng thuật toán tối ưu bầy đàn hạt

Bài báo này đề xuất một giải pháp triệt nhiễu trực xạ trong ra đa thụ động hai vị trí sử dụng mạng anten tròn bằng thuật toán tối ưu bầy đàn hạt. Với giải pháp đề xuất, có thể tạo điểm không trong giản đồ hướng của mạng anten ở hướng trạm phát với độ sâu nhỏ hơn một giá trị yêu cầu và độ rộng xác định, bằng cách điều khiển biên độ cho các phần tử trong mạng. Tính xác thực và hiệu quả của giải pháp đề xuất được minh chứng bằng các kết quả mô phỏng giản đồ hướng của mạng anten hình tròn trong ra đa thụ động với các tính hướng tạo điểm không khác nhau khi tính đến giản đồ hướng của mỗi phần tử trong mạng.

**Từ khóa:** Ra đa thụ động; Triệt tín hiệu trực xạ; Điều khiển điểm không; Tối ưu bầy đàn hạt.