Optimal Configuration of Array Elements for Hybrid Distributed PA-MIMO Radar System Based on Target Detection

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Optimal Configuration of Array Elements for Hybrid Distributed PA-MIMO Radar System Based on Target Detection

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Abstract: How to utilize limited system resources budget to maximize the effectiveness potential of the entire system through optimal allocation has always been a hot issue in radar resource management. This paper establishes a hybrid distributed phased array multiple-input and multiple-output (PA-MIMO) radar system model. It combines coherent processing gain and spatial diversity gain to synergistically improve the target detection performance of the radar system. For the hybrid distributed PA-MIMO radar system, we derive a likelihood ratio test (LRT) detector based on the Neyman-Pearson (NP) criterion. The coherent processing gain and spatial diversity gain are jointly optimized by implementing subarray-level and array element-level optimal configuration at both transceiver and transmitter ends. Moreover, a quantum particle swarm optimization-based stochastic rounding (SR-QPSO) solution algorithm is proposed for the integer planning-based configuration model. And the optimal array element configuration strategy is guaranteed to be obtained with fewer iterations and realize the joint optimization between subarray and array levels. Finally, numerical simulations are carried out using three typical optimization problems to demonstrate the effectiveness of the optimal configuration of the hybrid distributed PA-MIMO radar system.

Keywords: Radar Resource Optimization; Target Detection; Array Element Configuration; PA-MIMO Radar

1. Introduction

The diversity of modern radar targets and the complexity of the battlefield environment have exposed the inadequacies of existing radar regimes and detection techniques. In order to
cope with complex targets and environments [1] and seek breakthroughs in target detection theory and technology, regime modification and resource management for radar are being continuously and intensively carried out [2-4]. Maximizing the ability of radar sensor systems to obtain electromagnetic information [5], optimizing the utilization of existing radar resources [6, 7], and improving the target detection capability of radar systems are fundamental topics and practical and urgent tasks faced in the field of radar information processing and optimal resource management [8].

Multiple-input multiple-output (MIMO) radar has recently received extensive attention as a novel radar system [9]. Generally, the MIMO radar can be divided into two categories based on the antennas’ spatial configuration: One is the collocated MIMO radar [10], with array elements spaced at half-wavelength level, which mainly uses tuned detection signals to achieve superior waveform diversity. The other is distributed MIMO radar [11], which achieves joint signal processing through the spatially scattered configuration of array elements. And the spatial diversity gain of echo signals caused by angular extension can effectively overcome target scintillation to improve detection performance [12]. Compared to distributed MIMO radars, the T/R elements of conventional phased arrays are more closely distributed in space and have a strong correlation between channels, allowing for excellent spatial sampling capability and freedom of information processing [13].

Both coherent processing gain and spatial diversity gain can improve radar detection performance [14]. However, distributed MIMO radars transmitting orthogonal waveforms will lose spatial coherence gain while obtaining spatial diversity gain due to the different modes of radar operation. Whether the distributed MIMO radar using diversity gain or phased array radar with coherent processing gain is non-optimal with a certain number of array elements. It is far from sufficient to simply increase the total resources without considering
the cooperation between individual terminals.

The proposal of phased-array multiple-input multiple-output (PA-MIMO) radar [15] opens a new avenue for developing MIMO radar. The hybrid distributed PA-MIMO radar is a combination of traditional phased array radar technology and MIMO radar technology. It utilizes the coherent processing gain and spatial diversity gain, which are obtained simultaneously from the coherence of array elements signal within the subarray and the orthogonality of the inter-subarray signal, respectively. So that the hybrid distributed PA-MIMO radar system can maintain the advantages of MIMO radar while having the benefits of coherent processing of phased-array radar, which is a compromise and effective implementation scheme [16].

Numerous scholars have conducted in-depth studies on the array elements configuration of the radar systems. The division of the transmitting array into multiple overlapable subarrays in the [17] improves the angular resolution and target capacity. Ref.[18] studies the optimal sparse array optimization configuration problem in the presence of multiple sources of interest (SOI). Ref. [19] proposed an algorithm for the joint arrangement of transmitter and receiver in distributed MIMO radar to improve the positioning accuracy. There is also a solid research foundation on improving system detection performance through array element configuration optimization. Ref. [20] optimizes the target detection capability by deploying the array elements in space through an exhaustive method and completing the power allocation through a waterfilling-type algorithm. The ref. [16] divides the transmit array into uniformly overlapping subarrays to obtain coherent processing gain and waveform diversity gain, and the theoretical derivation and simulation experiments demonstrate the superiority of phased array MIMO radar. In [21], the optimal allocation of two gains in a MIMO-MSRS system is proposed from the receiver side through the configuration of the spatial location of
the array elements. Refs [22, 23] investigated the optimal configuration of digital array radar arrays to study the effect of array space configuration optimization on radar system performance improvement from the receiver side. However, few references simultaneously consider the allocation and optimization of coherent processing gain and spatial diversity gain in a radar system from both the transmitter and receiver sides.

Aiming at solving the issues above, we establish the radar system signal model and array space configuration model based on a hybrid distributed PA-MIMO radar. Then, the likelihood ratio test (LRT) detector are derived under fixed noise and construct the array space configuration model based on Neyman-Pearson (NP) criterion. On this basis, three typical optimization problems are discussed, i.e., maximizing the detection probability, maximizing the effective radar range, and minimizing the radar system equipment volume for a given detection index. In this regard, the respective closed-form approximate solutions are constructed and solved by the proposed quantum particle swarm optimization-based stochastic rounding (SR-QPSO) algorithm to obtain the optimal strategy for the array element configuration. Finally, the solution realizes the optimal cooperation among the array elements to improve the radar detection performance based on the total amount of existing radar resources.

The rest of the paper is organized as follows: The hybrid distributed PA-MIMO system model along with the system configuration based on the diversity conditions are demonstrated in Section 2. Section 3 derives the LRT detector from the NP criterion based on the signal processing flow of the hybrid distributed PA-MIMO radar. In Section 4, three optimization scenarios are considered and propose a solution algorithm based on integer programming. Section 5 presents numerical results and analysis. Finally, Section 6 concludes the paper.
2. System Model

2.1 Proposed Hybrid Distributed PA-MIMO Radar System and Signal Model

Considering a hybrid distributed PA-MIMO radar observation model shown in Fig. 1, which uses \( M \) transmitting array elements and \( N \) receiving array elements in a two-dimensional plane \( x-o-y \) to simultaneously transmit orthogonal waveform signals and receive the target echo signal. Under this approach, each sub-array of the radar system is a phased array radar, and the MIMO mode is conducted between different sub-arrays. In addition, the transient transmitted power of each element is \( P_t \), the transmitting antenna gain is \( G_t \), the receiving antenna gain is \( G_r \), and the transmitting signal wavelength is \( \lambda \). Then, according to the primary radar equation and the MIMO radar signal model [14], the signal scattered by the target located at \((x_0, y_0)\) and received by the \( n \)-th receiving element can be expressed as

\[
r_{mn}(t) = \sqrt{\frac{P_t G_m G_r \lambda^2 \sigma_{mn}^x}{(4\pi)^3 R_m^2 R_n^2 L}} s_m(t - \tau_{mn}) + n_n(t)
\]  

where \( s_m(t) \) presents the narrowband signal transmitted by the \( m \)-th transmitting array.
element, which satisfies the MIMO radar quadrature signal condition
\[ \int s_m(t) s_n^*(t) \, dt = \delta_{mn}, \]
where \( \delta_{mn} \) is the Kronecker Delta function, and \( \|s_m(t)\|^2 = 1 \). The term \( L \) is the system loss, \( \varphi_{nm} \) is the phase difference caused by the spatial configuration of radar elements in multi-channel sampling, and \( \tau_{mn} = \left( R_m + R_n \right) / c \) represents the time delay caused by the sum of the distance \( R_m \) from the \( m \)-th transmitting array element to the target centroid and the distance \( R_n \) from the target to the \( n \)-th receiving array element in the \( n \)-\( m \)-th channel, wherein the constant value \( c \) is the light speed. The fluctuating value \( \sigma_{nm} \) is the radar cross-section (RCS) observed by the \( m \)-\( n \)-th channel. In addition, the distance between the target and each element of the radar system satisfies the far-field condition, while the maximum distance between the elements is much smaller, that is \( R_m = R_n = R \). Furthermore, the target scattering coefficient in \( m \)-\( n \)-th channel is defined as
\[ \alpha_{mn} = \sqrt{\frac{G_m G_n \lambda^2 \sigma_{nm}}{(4\pi)^3 R^4 L}} \]  
where \( \sigma_{nm} \) is assumed to satisfy the Swerling I model which obeys a complex Gaussian distribution with mean 0 and variance \( \sigma^2 \). And \( \alpha_{nm} \) can be regarded as a complex Gaussian-distributed variable with a variance \( \sigma_{\alpha}^2 \). Then, the signals received by \( N \) receiving array elements can be expressed as
\[ r(t) = \sqrt{P} \text{diag} (a) H \text{diag} (b) s(t - \tau) + n(t) \]  
where \[ a = \left[ 1, e^{-j\varphi_1}, \ldots, e^{-j\varphi_N} \right]^T \] denotes the receiving steering vector of the radar system, \( H \) represents the \( NM \times \) dimensional coefficient matrix of the target scattering coefficient corresponding to the independent channel of the radar system, where \( [H]_{mn} = a_{mn} \cdot \sigma_{nm} \), \[ b = \left[ 1, e^{-j\varphi_1}, \ldots, e^{-j\varphi_M} \right]^T \] is the transmitting steering vector, \( s(t) = \left[ s_1(t), s_2(t), \ldots, s_M(t) \right]^T \)
is the transmitted signal vector. \( \mathbf{n}(t) = [n_1(t), \ldots, n_N(t)]^T - \mathcal{N}(0, \sigma^2_n \mathbf{I}_N) \) represents an additive white Gaussian noise vector, where \( \mathbf{I}_N \) is a \( N \times N \) dimensional matrix.

2.2 Hybrid Distributed PA-MIMO Radar Spatial Diversity Conditions and System Configuration

The correlation between the elements of the target scattering coefficient matrix can be adjusted by changing the distance between each subarray of the radar system [12], thus changing the processing mode of the echo signal in the radar system. Without loss of generality, the correlation of the spatial signal is defined by the array element spacing \( d \) as [24]

\[
d \geq \lambda R / D
\]

where \( D \) is the tangential length of the target.

The spatial configuration of the hybrid distributed PA-MIMO radar and the allocation of the proportions of the two gains in the radar system essentially change the correlation of elements in the target scattering coefficient matrix \( \mathbf{H} \). If the array elements spacing does not satisfy the space diversity condition in (4), the subarrays are combined into a phased array radar; on the contrary, the sub-arrays follow the MIMO radar signal processing mechanism. Therefore, changing the distance between the radar elements ensures that the corresponding target scattering coefficients are perfectly correlated or uncorrelated.

Once the target scattering coefficients \( \alpha_{lk} \) and \( \alpha_{nm} \) are completely uncorrelated, the radar system possesses an angular broadening of the space target, resulting in a spatial diversity gain. Accordingly, when \( \alpha_{lk} \) and \( \alpha_{nm} \) are entirely correlated, the radar system performs coherent processing on \( r_{lk} \) and \( r_{nm} \) to improve the signal-to-noise ratio (SNR) of the target echo signals. Herein, the target scattering coefficient matrix is reorganized and divided according to the correlation of each channel, and the target scattering coefficient
matrix $\hat{H}$ will be reconstructed as (5) after the configuration.

$$\hat{H} = \begin{bmatrix}
H_{11} & \ldots & H_{1M} \\
\vdots & \ddots & \vdots \\
H_{N1} & \ldots & H_{NM}
\end{bmatrix}_{N \times M}$$

(5)

where target scattering coefficient matrix sub-block $H_{nm}$ contains $a_m \times b_n$ coherent processing channel. Fig. 2 intuitively illustrates the array element configuration of the hybrid distributed PA-MIMO radar. $M$ transmitting array elements and $N$ receiving array elements are reorganized and divided into $\hat{N}$ and $\hat{M}$ subarrays, respectively. The $\hat{N}$ transmitter subarrays and the $\hat{M}$ receiver subarrays perform coherent processing as a phased array radar. Simultaneously, each subarray also transmits and receives independent orthogonal signals as a MIMO radar for diversity processing. So that the radar system has coherent processing gain and space diversity gain at the same time.

Fig. 2 Optimal array elements configuration of hybrid distributed PA-MIMO radar

Spatial diversity processing can improve the detection performance by increasing the number of independent channels, and coherent processing improves the detection performance by increasing the detection SNR of each channel. By dividing the target scattering coefficient matrix into blocks, the proportion of space diversity gain and coherent
processing gain in the radar system is coordinated and allocated to optimize the target detection performance of the radar system.

3. Hybrid Distributed PA-MIMO Radar System with Optimal Configuration

3.1 Signal Processing Flow of Hybrid Distributed Phased Array MIMO Radar

For the proposed hybrid distributed PA-MIMO radar system, Fig. 3 shows the signal processing schematic. \( \hat{M} \) orthogonal transmit signals are scattered by the target to \( \hat{N} \) receiver subarrays. Subsequently, matched filter banks are used to generate \( \hat{N} \times \hat{M} \) independent channel outputs. Then, coherent accumulation and space-time compensation are performed within the subarray, and finally, signal sampling and likelihood ratio detection are performed [25].

\[
\hat{r}_{nm}(t) = a_n b_m \sqrt{P_r} \hat{a}_{nm} + n_{nm}
\]

Fig. 3 Signal processing flowchart of hybrid distributed PA-MIMO radar

Then, for the detection unit containing a target, the \( \hat{N} \times \hat{M} \) channel samplings may be approximated as
where $a_m$ represents the number of transmitter array elements contained in the reorganized subarray, and $b_n$ represents the number of transmitter array elements. $n_{m,n}$ is the white Gaussian-distributed noise samplings of the $n$-th channel with auto-correlation $b_n\sigma_n^2$. Since the subarray configuration follows the non-overlapping principle, it satisfies

$$M = \sum_{m=1}^{M} a_m,$$

$$N = \sum_{n=1}^{N} b_n.$$  

(7)

Therefore, the SNR corresponding to the sampling value of each subarray can be approximated as

$$\rho_{m,n} = \frac{(a_m b_n)^2 T_s \sigma_n^2}{b_n \sigma_n^2} = a_m^2 b_n \rho_0$$

(8)

where $T_s$ is the duration of transmitting pulse. For simplicity, we define $\rho_0 = \sigma_T^2 P T_s / M \sigma_n^2$ as the reference channel SNR, indicating the SNR provided by a single independent channel on the target at a distance $R_0$.

3.2 LRT Detector of the Hybrid Distributed PA-MIMO Radar System

The spatial configuration of different subarrays satisfying the spatial diversity condition in equation (4) makes the outputs of each subarray independent and orthogonal to each other. Assuming that the received noise level is known, then each echo signal $\hat{r} = [\hat{r}_{1,1}, \hat{r}_{1,2}, \ldots, \hat{r}_{N,M}]_{1 \times N M}$ is an independent identically distributed (IID) complex Gaussian random variable. Therefore, the square-law detection outputs of different stations of the radar system are given by

$$X = [X_{1,1}, X_{1,2}, \ldots, X_{N,M}]_{1 \times N M}$$

where $X_{m,n} = \|\hat{r}_{m,n}\|^2$, furthermore, the target detection problem can be expressed as follows
\[ \begin{cases} \mathcal{H}_0: \hat{r}(t) = n(t), \text{Target does not exist at delay } \tau \\ \mathcal{H}_1: \hat{r}(t) = \hat{H}s(t) + n(t), \text{Target exists at delay } \tau \end{cases} \] (10)

On this basis, a hypothesis test is constructed, and the probability density function can be expressed as

\[
\begin{align*}
f(X|\mathcal{H}_0) &= \prod_{n=1}^{\hat{N}} \prod_{m=1}^{M} \left[ \frac{1}{b_n \sigma_n^2} \exp \left( -\frac{X_{\hat{m}n}}{b_n \sigma_n^2} \right) \right] \\
f(X|\mathcal{H}_1) &= \prod_{n=1}^{\hat{N}} \prod_{m=1}^{M} \left[ \frac{1}{b_n \sigma_n^2 (1 + \rho_{\hat{m}n})} \exp \left( -\frac{X_{\hat{m}n}}{b_n \sigma_n^2 (1 + \rho_{\hat{m}n})} \right) \right]
\end{align*}
\] (11)

Based on the NP criterion, this paper constructs a hybrid distributed PA-MIMO radar LRT detector, which must be expressed as the following structure

\[
T_{\text{HDPM}} = \frac{f (X | \mathcal{H}_1)}{f (X | \mathcal{H}_0)} > \eta_0 \\
\frac{f (X | \mathcal{H}_0)}{f (X | \mathcal{H}_1)} < \tau_0
\] (12)

We have

\[
T_{\text{HDPM}} = \frac{f (X | \mathcal{H}_1)}{f (X | \mathcal{H}_0)} = \prod_{n=1}^{\hat{N}} \prod_{m=1}^{M} \left[ \frac{1}{1 + \rho_{\hat{m}n}} \exp \left( -\frac{\rho_{\hat{m}n} X_{\hat{m}n}}{b_n \sigma_n^2 (1 + \rho_{\hat{m}n})} \right) \right]
\] (13)

where \( f (X | \mathcal{H}_1) \) and \( f (X | \mathcal{H}_0) \) respectively represent the conditional distribution density function under the two assumptions, \( T_{\text{HPM}} \) is the test statistic constructed from \( X_{\hat{m}n} \). Further taking logarithms on both sides of (13), the log-likelihood ratio of the whole hybrid distributed phased-array MIMO radar is the sum of different field points.

\[
\ln (T_{\text{HDPM}}) = \sum_{n=1}^{\hat{N}} \sum_{m=1}^{M} \left[ \ln \left( \frac{1}{1 + \rho_{\hat{m}n}} \right) + \frac{\rho_{\hat{m}n} X_{\hat{m}n}}{b_n \sigma_n^2 (1 + \rho_{\hat{m}n})} \right]
\] (14)

where

\[
R_{\hat{m}n} = \frac{X_{\hat{m}n}}{b_n \sigma_n^2} \sim \chi^2_2 \quad \hat{m} = 1,2,\ldots,\hat{M}; \hat{n} = 1,2,\ldots,\hat{N}
\] (15)
\[ \omega_{nm} = \frac{\rho_{nm}}{1 + \rho_{nm}} \]  

(16)

where \( \chi^2 \) represents a chi-square distribution with 2 degrees of freedom (DOF). Herein, the LRT detector of the hybrid distributed PA-MIMO radar system can be expressed as

\[ T_{HDPM} = \sum_{n=1}^{\hat{N}} \sum_{m=1}^{\hat{M}} \frac{\omega_{nm} R'_{nm}}{\rho_{nm}} \geq \eta_0 \]  

(17)

where \( \eta_0 \) is a threshold preset according to the preset constant \( P_F \). Finally, the weighted sum of the ratio detector is used for LRT. Hence, the test statistic of hybrid distributed PA-MIMO radar system will be performed under the \( \mathcal{H}_0 \) and \( \mathcal{H}_1 \) assumptions, respectively.

1. LRT Statistical Analysis under \( \mathcal{H}_0 \) Hypothesis

Under the hypothesis of \( \mathcal{H}_0 \), the radar detection unit has no target echo signal, let \( R'_{nm} = R_{nm} \), \( \omega'_{nm} = \rho_{nm} / (1 + \rho_{nm}) \), then the LRT detector under the \( \mathcal{H}_0 \) hypothesis can be reformulated as

\[ T_{HDPM|\mathcal{H}_0} = \sum_{n=1}^{\hat{N}} \sum_{m=1}^{\hat{M}} \omega'_{nm} R'_{nm} \geq \eta_0 \]  

(18)

with

\[ R'_{nm} \sim \chi^2_{(2)} \]  

(19)

where \( R'_{nm} \) is a 2 DOF cardinality distribution variable, i.e., a standard exponential distribution variable [26]. For the test statistic \( T_{HDPM|\mathcal{H}_0} \), the weighted sum of the IID exponential distribution approximates the Gamma distribution with exponential scale parameters [27]. We have

\[ T_{HDPM|\mathcal{H}_0} = \sum_{n=1}^{\hat{N}} \sum_{m=1}^{\hat{M}} \omega'_{nm} R'_{nm} \sim \Gamma \left( \frac{\eta_0}{2}, 2g_0 \right) \]  

(20)
where \( \Gamma(\theta, \xi) \) is the gamma function, parameters \( \theta \) and \( \xi \) represent the scale parameter and shape parameter of the gamma distribution, respectively. And \( v_0, g_0 \) respectively are

\[
v_0 = \frac{2 \left( \sum_{n=1}^{\hat{N}} \sum_{m=1}^{\hat{M}} \omega'_{nm} \right)^2}{\sum_{n=1}^{\hat{N}} \sum_{m=1}^{\hat{M}} (\omega'_{nm})^2}
\]

\[
g_0 = \frac{2 \left( \sum_{n=1}^{\hat{N}} \sum_{m=1}^{\hat{M}} \omega'_{nm} \right)^2}{\sum_{n=1}^{\hat{N}} \sum_{m=1}^{\hat{M}} \left( \frac{a_n^2 b_{n}\rho_0}{1 + a_n^2 b_{n}\rho_0} \right)^2}
\]

\[
(21) V_0 = \frac{2 \left( \sum_{n=1}^{\hat{N}} \sum_{m=1}^{\hat{M}} \omega'_{nm} \right)^2}{\sum_{n=1}^{\hat{N}} \sum_{m=1}^{\hat{M}} (\omega'_{nm})^2}
\]

\[
g_0 = \frac{2 \left( \sum_{n=1}^{\hat{N}} \sum_{m=1}^{\hat{M}} \omega'_{nm} \right)^2}{\sum_{n=1}^{\hat{N}} \sum_{m=1}^{\hat{M}} \left( \frac{a_n^2 b_{n}\rho_0}{1 + a_n^2 b_{n}\rho_0} \right)^2}
\]

\[
(22) G_0 = \frac{2 \left( \sum_{n=1}^{\hat{N}} \sum_{m=1}^{\hat{M}} \omega'_{nm} \right)^2}{\sum_{n=1}^{\hat{N}} \sum_{m=1}^{\hat{M}} \left( \frac{a_n^2 b_{n}\rho_0}{1 + a_n^2 b_{n}\rho_0} \right)^2}
\]

(2) LRT Statistical Analysis under \( H_1 \) Hypothesis

Under the hypothesis \( H_1 \), the radar detection unit contains the target signal. With \( R'_{nm} = R_{nm} / (1 + \rho_{nm}) \), \( \omega'_{nm} = (1 + \rho_{nm}) \omega_{nm} = \rho_{nm} \), the LRT detector of the system in hypothesis \( H_1 \) can be re-expressed as

\[
T_{\text{HDPM}|H_1} = \sum_{n=1}^{\hat{N}} \sum_{m=1}^{\hat{M}} \omega'_{nm} R'_{nm} > \eta_0 \]

\[
(23) T_{\text{HDPM}|H_1} = \sum_{n=1}^{\hat{N}} \sum_{m=1}^{\hat{M}} \omega'_{nm} R'_{nm} > \eta_0
\]

where

\[
R'_{nm} - \chi^2(2)
\]

\[
(24) R'_{nm} - \chi^2(2)
\]

Then, we have

\[
T_{\text{HDPM}|H_0} = \sum_{n=1}^{\hat{N}} \sum_{m=1}^{\hat{M}} \omega'_{nm} R'_{nm} - \Gamma \left( \frac{\nu_1}{2}, 2, g_1 \right)
\]

\[
(25) T_{\text{HDPM}|H_0} = \sum_{n=1}^{\hat{N}} \sum_{m=1}^{\hat{M}} \omega'_{nm} R'_{nm} - \Gamma \left( \frac{\nu_1}{2}, 2, g_1 \right)
\]

where

\[
\nu_1 = \frac{2 \left( \sum_{n=1}^{\hat{N}} \sum_{m=1}^{\hat{M}} \omega'_{nm} \right)^2}{\sum_{n=1}^{\hat{N}} \sum_{m=1}^{\hat{M}} (\omega'_{nm})^2}
\]

\[
\nu_1 = \frac{2 \left( \sum_{n=1}^{\hat{N}} \sum_{m=1}^{\hat{M}} \omega'_{nm} \right)^2}{\sum_{n=1}^{\hat{N}} \sum_{m=1}^{\hat{M}} (\omega'_{nm})^2}
\]

\[
(26) \nu_1 = \frac{2 \left( \sum_{n=1}^{\hat{N}} \sum_{m=1}^{\hat{M}} \omega'_{nm} \right)^2}{\sum_{n=1}^{\hat{N}} \sum_{m=1}^{\hat{M}} (\omega'_{nm})^2}
\]
Therefore, considering equations (17), (20) and (25) together, the LRT detector of the hybrid distributed PA-MIMO radar system is obtained as follows.

\[
g_1 = \frac{\sum_{\tilde{n}=1}^{\tilde{N}} \sum_{\tilde{m}=1}^{\tilde{M}} (\alpha_{\tilde{n}\tilde{m}}')^2}{\sum_{\tilde{n}=1}^{\tilde{N}} \sum_{\tilde{m}=1}^{\tilde{M}} \alpha_{\tilde{n}\tilde{m}}'^2} = \frac{\sum_{n=1}^{N} \sum_{m=1}^{M} (a_m^2 b_n \rho_0)^2}{\sum_{n=1}^{N} \sum_{m=1}^{M} a_m^2 b_m \rho_0}
\]

(27)

4. Optimization Model Establishment and Solution

4.1 Overview of the Optimization Problem for Hybrid Distributed PA-MIMO Radar Systems

Optimizing the array element configuration of the hybrid distributed PA-MIMO radar system aims to improve detection performance. Generally speaking, the evaluation criteria for target detection performance are as follows: detection probability \( P_D \) [28], detection range \( R_{E_{max}} \) [21], resolution and SNR [29], etc. However, different optimal configuration strategies may be used for different optimization purposes. \( P_D \) is usually the most intuitive performance index used to describe the detection capability of the radar system; In addition, for a certain detection probability \( P_D \) and false alarm probability \( P_{FA} \), the maximum operating distance \( R_{E_{max}} \) of the radar system is pursued; Thirdly, it is also of great practical significance to reduce the amount of equipment of the radar system with the given false alarm probability \( P_{FA} \) and detection probability \( P_D \). Therefore, according to system design purposes, the optimal configuration of the hybrid distributed PA-MIMO radar can be divided into the following three optimization problems:

**Optimization problem 1:** With a given \( M \times N \) hybrid distributed PA-MIMO radar system,
constant $P_F$ and $\rho_0$, obtain the maximum target detection probability value, i.e., $P_D$, by optimizing the diversity vector $\beta = (\hat{M}, a_1, \ldots, a_M)$ and $\gamma = (\hat{N}, b_1, \ldots, b_N)$ based on the LRT detector of the radar system.

**Optimization problem 2:** With a given $M \times N$ hybrid distributed PA-MIMO radar system, constant $P_F$, $P_D$ and $\rho_0$, obtain the maximum operating distance $R_{max}$ by optimizing the diversity vector $\beta = (\hat{M}, a_1, \ldots, a_M)$ and $\gamma = (\hat{N}, b_1, \ldots, b_N)$ based on the LRT detector of the radar system.

**Optimization problem 3:** With a given constant $P_F$, $P_D$ and $\rho_0$, minimize the equipment quantity of a hybrid distributed PA-MIMO radar by optimizing the diversity vector $\beta = (\hat{M}, a_1, \ldots, a_M)$ and $\gamma = (\hat{N}, b_1, \ldots, b_N)$ based on the LRT detector of the radar system.

4.2 Detection Performance Analysis of Typical Hybrid Distributed PA-MIMO Radar System

In fact, the above three optimization problems consider improving the target detection capability from different perspectives, but the core problem is to optimize the vector $\beta$ and $\gamma$. However, there is also a parameter coupling problem in the process of optimizing high-dimensional integer programming problems, which makes the analytical solution complex and impossible. To reduce the search time and solution complexity, array elements are divided into a certain number of non-overlapping subarrays, i.e.

$$
\begin{align*}
\hat{a}_m &= \frac{M}{\hat{M}} \\
\hat{b}_n &= \frac{N}{\hat{N}}
\end{align*}
$$

(29)

According to the array element configuration scheme, the hybrid distributed PA-MIMO radar system can be decomposed into four typical structures:

(1) **Distributed MIMO radar** with full diversity processing;
(2) **Phased array radar** with full coherent processing;

(3) **MISO radar** with full diversity processing at the transmitter side and full coherent processing at the receiver side;

(4) **SIMO radar** with full diversity processing at the receiver side and coherent processing at the transmitter side.

Similarly, the distribution of test statistics of these typical radars is obtained as

\[
T_{\text{MIMO}} = \begin{cases} 
\Gamma\left(MN, \frac{2\rho_0}{1+\rho_0}\right), & \mathcal{H}_0 \\
\Gamma\left(MN, 2\rho_0\right), & \mathcal{H}_1 
\end{cases} \quad (30)
\]

\[
T_{\text{PHASE}} = \begin{cases} 
\Gamma\left(1, \frac{2M^2N\rho_0}{1+M^2N\rho_0}\right), & \mathcal{H}_0 \\
\Gamma\left(1,2M^2N\rho_0\right), & \mathcal{H}_1 
\end{cases} \quad (31)
\]

\[
T_{\text{MISO}} = \begin{cases} 
\Gamma\left(M, \frac{2N\rho_0}{1+N\rho_0}\right), & \mathcal{H}_0 \\
\Gamma\left(M, 2N\rho_0\right), & \mathcal{H}_1 
\end{cases} \quad (32)
\]

\[
T_{\text{SIMO}} = \begin{cases} 
\Gamma\left(N, \frac{2M^2\rho_0}{1+M^2\rho_0}\right), & \mathcal{H}_0 \\
\Gamma\left(N, 2M^2\rho_0\right), & \mathcal{H}_1 
\end{cases} \quad (33)
\]

Thus, the \(P_D\) corresponding to each typical radar system with a certain \(P_{\text{FA}}\) can be given by

\[
P_{D-\text{MIMO}}(P_{\text{FA}}) = 1 - Q_{X_{\text{MIMO}}}^{-1}\left(1 - P_{\text{FA}}\right) \frac{Q_{X_{\text{MIMO}}}^{-1}}{1+\rho_0} 
\]

\[
P_{D-\text{PHASE}}(P_{\text{FA}}) = 1 - Q_{X_{\text{PHASE}}}^{-1}\left(1 - P_{\text{FA}}\right) \frac{Q_{X_{\text{PHASE}}}^{-1}}{1+M^2N\rho_0} 
\]

\[
P_{D-\text{MISO}}(P_{\text{FA}}) = 1 - Q_{X_{\text{MISO}}}^{-1}\left(1 - P_{\text{FA}}\right) \frac{Q_{X_{\text{MISO}}}^{-1}}{1+\rho_0} 
\]

\[
P_{D-\text{SIMO}}(P_{\text{FA}}) = 1 - Q_{X_{\text{SIMO}}}^{-1}\left(1 - P_{\text{FA}}\right) \frac{Q_{X_{\text{SIMO}}}^{-1}}{1+M^2\rho_0} 
\]
where \( Q_{\chi_{(2n)}} \) and \( Q_{\chi_{(2n)}}^{-1} \) represent the complementary cumulative distribution functions of chi-square with a 2MN-DOF and its inverse function, respectively. Clearly, array configuration can significantly affect the detection performance of the system. In addition, when \( M=N \), the MISO radar and SIMO radar test statistics have the same DOF, i.e., the same number of independent channels, yet the SIMO radar obtains a SNR gain that is \( M \) times that of the former. And further analysis shows the optimal configuration of the system is \( \hat{M} \times \hat{N} \) independent channels, where the SNR gain can be expressed as

\[
\mathcal{K} = \frac{M^2 N}{M^2 N} = \frac{M^2 N}{D} \cdot \frac{1}{M}
\]

A more general implication of the equation (38) is that configuring the subarray should utilize as many receive array elements as possible to achieve the diversity number so that the transmitter can improve the coherent processing gain with a minimum division strategy [30].

4.3 Optimal Uniform Configuration for Hybrid Distributed PA-MIMO Radar System

Both the transmitter and the receiver sides are configured in a uniform non-overlapping manner, and in combination with (18) and (28) are

\[
\begin{align*}
\Gamma\left(\frac{v_0}{2}, 2g_0\right) = & \Gamma\left(\frac{2NM^2 \rho_0}{NM^2 + NM^2 \rho_0}\right) = \frac{NM^2 \rho_0}{NM^2 + NM^2 \rho_0} \chi_{(2\hat{N}M)}^2, & \mathcal{H}_0 \\
\Gamma\left(\frac{v_1}{2}, 2g_1\right) = & \Gamma\left(\frac{2NM^2 \rho_0}{NM^2 \rho_0}\right) = \frac{NM^2 \rho_0}{NM^2} \chi_{(2\hat{N}M)}^2, & \mathcal{H}_1
\end{align*}
\]

For a given radar system size \( M \times N \), \( P_{FA} \) and \( \rho_0 \), we have
The target detection probability will be improved by optimizing the configuration of the array elements, which can be expressed as

\[
P_{\text{D-HPM}}(P_{\text{FA}}) = 1 - Q_{\chi_{(\text{sim})}^{-1}}\left(\frac{Q_{\chi_{(\text{sim})}^{-1}}(1 - P_{\text{FA}})\hat{NM}^2}{\hat{NM}^2 + NM^2\rho_0}\right)
\]  

(40)

(1) Model of **optimization problem 1**

The target detection probability will be improved by optimizing the configuration of the array elements, which can be expressed as

\[
P: \quad \left[\hat{M}, \hat{N}\right] = \arg \max_{M,N} \left[1 - Q_{\chi_{(\text{sim})}^{-1}}\left(\frac{Q_{\chi_{(\text{sim})}^{-1}}(1 - P_{\text{FA}})\hat{NM}^2}{\hat{NM}^2 + NM^2\rho_0}\right)\right]
\]

\[
s.t. \quad C_1: \quad \hat{M} \leq \hat{N}
\]
\[
C_2: \quad 1 \leq \hat{M} \leq M; \quad \hat{M} \in \mathbb{Z}
\]
\[
C_3: \quad 1 \leq \hat{N} \leq N; \quad \hat{N} \in \mathbb{Z}
\]

(41)

(2) Model of **optimization problem 2**

Combining equation (40) and substituting \(R_{E_{\text{max}}} = \sqrt[3]{\frac{\rho_0}{\rho_{\text{min}}}}\) into the objective function, the configuration strategy for **optimization problem 2** can be transformed into

\[
P: \quad \left[R_{E_{\text{max}}}\right] = \arg \max_{M,N} \left[NM^2\rho_0Q_{\chi_{(\text{sim})}^{-1}}(1 - P_{\text{FA}})\hat{NM}^2\right]^{\frac{1}{3}}
\]

\[
s.t. \quad C_1: \quad \hat{M} \leq \hat{N}
\]
\[
C_2: \quad 1 \leq \hat{M} \leq M; \quad \hat{M} \in \mathbb{Z}
\]
\[
C_3: \quad 1 \leq \hat{N} \leq N; \quad \hat{N} \in \mathbb{Z}
\]

(42)

(3) Model of **optimization problem 3**

While satisfying the intended target detection performance of the radar system, the volume of the required equipment is minimized through the optimal array elements configuration. Clearly, the most intuitive and logical way to reduce the amount of system equipment is to increase system integration by sharing antenna transceivers in a time-sharing manner. Accordingly, the total volume of radar system equipment is
\[
\mathcal{P}: \quad [M, N] = \arg \max_{M, N} \left[ \frac{\hat{M}^3 \left( Q^{-1}_{\chi_{[x:]}^M} (1 - P_{FA}) - Q^{-1}_{\chi_{[x:]}^M} (1 - P_D) \right)^4}{\rho_0 Q^{-1}_{\chi_{[x:]}^M} (1 - P_D)} \right]^{1/4}
\]

s.t. \quad \begin{align*}
\mathcal{C}_1: & \quad M = N \\
\mathcal{C}_2: & \quad \hat{M} = \hat{N} \\
\mathcal{C}_3: & \quad 1 \leq \hat{M} \leq M; \quad \hat{M} \in \mathbb{Z} \\
\mathcal{C}_4: & \quad 1 \leq \hat{N} \leq N; \quad \hat{N} \in \mathbb{Z}
\end{align*}

4.4 QPSO-Based Stochastic Rounding Optimization Solution Algorithm

Considering that the optimization problem is integer programming and the objective function is complex and challenging to solve, although the optimal solution can be obtained by exhaustive search, the problem size is large and the computational effort is considerable. Therefore, we propose a stochastic optimization rounding algorithm incorporating quantum-behaved particle swarm optimization (SR-QPSO) [31]. The particle swarm optimization algorithm with quantum behavior improves the algorithm to cover the whole search space during iteration by simulating the substantial uncertainty of state superposition in quantum systems. So it improves the global search weakness at the tail end of the classical PSO algorithm search and enhances the global optimization capability of the algorithm [32].

In this paper, a random rounding method is adopted in which the fractional part of the particle position parameter is used as the probability value for upward rounding the parameter decimal part. Although the rounded problem is no longer equivalent to the original problem, the solution set of the original problem is included in the feasible solutions of the rounded optimization problem, i.e., the maximum value of the latter is not smaller than the maximum value of the original optimization problem. The entire algorithm flow is shown in Algorithm 1.

\begin{algorithm}
\caption{SR-QPSO}
1 Initialization, set search dimensions $D$, population size $W$, and max iterations $Q$;
\end{algorithm}
2 Disperse uniform random particles in \([-X_{\text{max}}, X_{\text{max}}]\), record \(X_i^t\);
3 Normalize the positional parameters of particles, probability rounded to decimals;
4 Calculate \(p_{\text{best}} X_i^t\) and \(g_{\text{best}} G_i^t\);
5 Set the upper and lower bounds of the shrinkage factor \(\alpha_0\) and \(\alpha_1\);
6 Computes attractors for quantum-behaving particles \(P_i^t\);
7 WHILE Not met iteration termination condition DO
8 FOR \(t = 1\) TO \(Q\) DO
9 Update contraction expansion factor;
10 Calculate the average best individual position for iteration at \(t\);
11 FOR \(i = 1\) TO \(W\) DO
12 Calculate and update particle positions \(X_i^t\);
13 IF \(X_i^t \notin \left[-X_{\text{max}}, X_{\text{max}}\right]\), set \(X_i^{t+1}\) as boundary value;
14 END FOR
15 END FOR
16 END WHILE

5. Experiments and Analysis

5.1 Parameter Settings

In order to verify the effectiveness of the hybrid distributed PA-MIMO radar array configuration on target detection capability enhancement, some numerical simulations based on (41)-(43) are presented in this section. In the following, the defaulted radar system configuration parameters are \(M=N=100\), \(P_{\text{FA}} = 10^{-6}\), \(\rho_0 = 6.0913 \times 10^7\) and the target RCS is \(1\) \(\text{m}^2\). In addition, the parameters of the SR-QPSO algorithm, where the initial populations size \(W = 100\), the particle dimension \(D = 2\), the max iterations \(Q = 100\), and the particle positions are upper bounded by 100 and lower bounded by 1.
5.2 Result and Discussions

(1) Case 1: Maximize Detection Probability

Fig. 4 SR-QPSO convergence curve

Fig. 4 shows the SR-QPSO convergence curve for *Optimization problem 1*, with the population optimum as the optimal individual for each iteration. The fitness function converges as the number of iterations increases and the detection probability of the hybrid distributed PA-MIMO radar system converges to the optimal value, at which point the optimal strategy for the array element configuration is $\hat{M} = (1, 13)$, and the $P_D$ reaches 0.98.

In the following, numerical simulations are carried out according to (41), with different transmitter diversity DOF $\hat{M}$, receiver diversity DOF $\hat{N}$ and $P_{FA}$. Then, the effect of the optimal configuration on the detection probability has been investigated and analyzed based on visualization.

Fig. 5 Optimal $P_D$ versus receiver side diversity DOF
In Fig. 5, with the fixed $P_{FA} = 10^{-6}$, the $P_D$ first increases with the diversity DOF $\hat{M}$, but once $\hat{M}$ exceeds the optimum DOF the $P_D$ decreases as $\hat{M}$ increases. As can be observed, the number of receiver side diversity $\hat{N}$ has a prominent influence on the detection probability. The radar system with transmitter side diversity DOF greater than 1 has a much lower detection capability than transmitter side fully coherent radars. And the corresponding optimal transmitter side diversity DOF decreases as the number increases, confirming the conclusion of section 4.3 on transmitter diversity. Thus, subsequent experiments will not consider the case of $\hat{M} \geq 2$.

![Fig. 6 Optimal $P_D$ versus transmitter side diversity DOF](image)

Similarly, the diversity DOF $\hat{N}$ at the receiver side is varied to investigate its effect on the detection probability $P_D$. As shown in Fig. 6, increasing the diversity DOF $\hat{M}$ at transmitter side of the hybrid distributed PA-MIMO radar significantly attenuates $P_D$. Essentially, this is because the diversity at the transmitter side reduces the coherent processing gain, while the contribution of the spatial diversity gain is much smaller than the coherent processing gain. Combined with Fig. 5, it can be seen that increasing the diversity at the receiver side can improve the detection performance only if the gain at the transmitter side meets a certain level.
In Fig. 7, with the transmitter side optimally configured, the optimal transmitter-side diversity DOF $\hat{M}$ positively correlated with $P_{FA}$. At the same time, the $P_D$ obeys the general rule that it increases with the $P_{FA}$.

(2) Case2: Maximize Effective Radar Range

Assuming $P_D = 0.8$, $P_{FA} = 10^{-6}$ for the hybrid distributed PA-MIMO radar system, the SR-QPSO optimization is applied to solve optimization problem 2 based on formula (42). The convergence of the fitness function is shown in Fig. 8. With no more than 10 iterations, the effective range of the radar system $R_{E\text{max}}$ converges to the optimum value of 1166.3km. At this point, the optimal strategy for the array element configuration is $\text{Opt}(\hat{M}, \hat{N})=(1.5)$. Then,
four simulations are carried out to identify the effects of the transmitter side diversity DOF \( \hat{M} \), the receiver side diversity DOF \( \hat{N} \), \( P_D \) and \( P_{FA} \) on the effective range \( R_{Emax} \).

Fig. 9  Optimal \( R_{Emax} \) versus receiver side diversity DOF

In Fig. 9, we change the transmitter side diversity DOF \( \hat{M} = 1, 2, 3, 4, 5 \). It is clear that increasing the number of transmitter diversity DOF does not improve the range of the radar system compared to the optimal solution, but rather reduces the effective range. Moreover, the corresponding optimal transmit array division DOF for the transmit array division scheme decreases as the number of transmitter sites increases. This is still essentially a decrease in channel SNR due to transmitter side diversity. Therefore, the subsequent analysis will be based on the \( \hat{M} = 1 \).

Fig. 10  Optimal \( R_{Emax} \) versus transmitter side diversity DOF
In Fig. 10 with fixed $\hat{N}=3,4,5,6,7$, three curves of $R_{E_{\text{max}}}$ versus $\hat{N}$ are plotted according to (42), respectively. Varying $\hat{M}$, it was found that transmitter diversity also caused an attenuation of the effective range of the radar system. It can be observed that the optimal configuration strategy at the transmitter side for condition $\hat{M}=1$ is $\hat{N}=5$, and for $\hat{M}=2$ is $\hat{N}=3$. Therefore, $\hat{M}=1$ is not always the optimal transmitter-side diversity DOF for a certain $\hat{N}$. And the maximum benefit can only be achieved in coordination with the receiver-side array division.

In Fig. 10 with the fixed $P_{D_{\text{F}}} = 10^{-6}$, the maximum effective range of radar detection curves $\hat{N}$ are calculated for the hybrid distributed PA-MIMO radar system with respect to $P_{D} = 0.6, 0.7, 0.8, 0.9, 0.99$. It can be obtained that as the detection probability increases, the effective action distance decreases accordingly. Secondly, the optimal receiver diversity DOF increases with the increase of the detection probability.

Fig. 11 Impact of $P_{D}$ on optimal configuration

In Fig. 11 with the fixed $P_{D_{\text{F}}} = 10^{-6}$, the maximum effective range of radar detection curves $\hat{N}$ are calculated for the hybrid distributed PA-MIMO radar system with respect to $P_{D} = 0.6, 0.7, 0.8, 0.9, 0.99$. It can be obtained that as the detection probability increases, the effective action distance decreases accordingly. Secondly, the optimal receiver diversity DOF increases with the increase of the detection probability.
In Fig. 12 the maximum effective range $R_{E_{max}}$ versus $P_{FA} = 10^{-6}, 10^{-6}, 10^{-6}, 10^{-6}$ are calculated for the hybrid distributed PA-MIMO radar system. Without loss of generality, the lower the false alarm probability $P_{FA}$, the shorter the effective range. In contrast with Fig. 11 and Fig. 12, $P_{FA}$ has less impact on the diversity DOF at the receiver side compared to $P_{D}$, but the optimal strategies $\hat{N}$ all increase as the detection accuracy rises.

(3) Case3: Minimize System Equipment Volume

Based on the analysis in subsection 5, we have $\hat{M} = \hat{N}$, namely (43) is a univariate objective function. Then the following two experiments are conducted to investigate the configuration optimization scheme based on the minimum amount of radar system equipment with preset intended $P_{FA}$ and $P_{D}$, respectively,
In Fig. 13, the volume equipment of the radar system $M$ curves versus system diversity $\hat{M}$. The optimal radar system design is given according to (43). Also, the result with respect to $P_D = 0.6, 0.7, 0.8, 0.9, 0.99$ are all provided. Obviously, the higher the detection probability, the larger the amount of radar system equipment required. When the $P_D$ exceeds 0.8, the number of required T/R array elements first decreases and then increases with the number of division sites. Herein, the optimal division sites number is 2. Conversely, when $P_D$ is less than 0.8, the optimal array element configuration scheme is $\hat{M} = 1$. That is, the PA-MIMO is configured as a phased-array radar without diversity.

In Fig. 14, the volume equipment of the radar system $M$ curves versus system diversity $\hat{M}$. The result with respect to $P_{FA} = 10^{-3}, 10^{-4}, 10^{-5}, 10^{-6}, 10^{-7}$ are all provided. Obviously, the higher the false alarm probability, the larger the amount of radar system equipment required. When the $P_{FA}$ exceeds $10^{-5}$, the number of required T/R array elements first decreases and then increases with the number of division sites. Herein, the optimal division sites number is 2. Conversely, when $P_{FA}$ is less than $10^{-5}$, the optimal array element configuration scheme is $\hat{M} = 1$. That is, the PA-MIMO is configured as a phased-array radar without diversity.
In Fig. 14, the total volume of the radar system $M$ curves versus system diversity $\hat{M}$. The optimal radar system design is given according to (43). Also the result with respect to $P_{\text{FA}} = 10^{-4}, 10^{-6}, 10^{-8}, 10^{-10}, 10^{-12}$ are all provided. Obviously, the lower the false alarms probability, the greater the amount of radar system equipment required. Furthermore, the scheme $\hat{M} = 2$ makes the system equipment volume the smallest when $P_{\text{FA}}$ is less than $10^{-10}$. And the optimal array configuration $\hat{M} = 1, 2$ minimized the $M$ when $P_{\text{FA}} = 10^{-10}$. However, when the $P_{\text{FA}}$ is greater than 10, the optimal array configuration scheme is phased array radar.

(4) General Discussion for the hybrid distributed PA-MIMO System Optimal Configuration

From the above results in Figs. 4-14, the following general conclusions can be drawn for the hybrid distributed PA-MIMO radar system.

A. With the increase of diversity DOF for both the transmitter and receiver side, the radar detection performance will deteriorate when they exceed the optimal values. Normally, different optimization objectives have different optimal configuration schemes. And the radar detection probability and false alarm probability also affect the value of optimal diversity DOF $\hat{M}$ and $\hat{N}$.

B. The essence of the hybrid distributed PA-MIMO radar possessing superior quality detection performance lies in its coherent processing improving the local SRN within each subarray, based on which the spatial diversity gain generated between each independent subarrays will further improve the target detection capability. In particular, for all optimization problems, only a small transmitter side diversity DOF is required, because the gain generated by transmitter-side diversity does not compensate for the lost coherent processing gain.
6. Conclusions

This paper investigates the optimal array elements configuration scheme for hybrid distributed PA-MIMO radar based on target detection. Its essence is to change the coherence between the array signals through the array elements configuration, coordinate the proportion of the coherence gain and the spatial diversity gain in the radar system, and ultimately improve the target detection performance of the radar system without increasing resources. And a SR-QPSO method is proposed to solve the optimal array element configuration scheme. From the analysis in the paper, it is clear that neither distributed MIMO radar nor phased-array radar merely using diversity gain or coherent processing gain is optimal. Therefore, the system SNR is improved by coherent processing at the transmitter side, and the target detection performance will be further optimized by diversity gain at the receiver side based on a certain SNR ratio level. Finally, the theoretical derivation and numerical results confirm the effectiveness of the hybrid distributed PA-MIMO array element configuration in improving the target detection capability of the radar system, and the obtained conclusions are of reference value for the system configuration and practical application of PA-MIMO radar.

Abbreviations

MIMO: multiple-input and multiple-output; PA-MIMO: phase array multiple-input and multiple-output; LRT: likelihood ratio test; NP: Neyman-Pearson; SR-QPSO: quantum particle swarm optimization-based stochastic rounding; SOI: sources of interest; RCS: Radar cross-section; SNR: Signal-noise ratio; PSO: Particle swarm optimization; DOF: degrees of freedom; IID: independent identically distributed;

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Authors' contributions

H. Z., J. X. and C. Q. conceived and designed the experiments; C. Q. performed the experiments; C. Q., Z. D. and Z. L. analyzed the data; C. Q. wrote the paper; J. X. administrated the project. All authors read and approved the final manuscript.

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Availability of data and materials

Unfortunately, the data is not available online. Kindly, for data requests, please contact the corresponding author.

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