Joint Beam Selection and Power Allocation for Multi-target Tracking in C-MIMO Radar Network

1st Hao Jiao
National Key Laboratory of Radar Signal Processing
Xidian University
Xi'an, China
jiaohao@stu.xidian.edu.cn

2nd Peng Zhang
National Key Laboratory of Radar Signal Processing
Xidian University
Xi'an, China
pzhang_3@stu.xidian.edu.cn

3rd Junkun Yan
National Key Laboratory of Radar Signal Processing
Xidian University
Xi'an, China
jkyan@xidian.edu.cn

4th Xudong Dang
National Key Laboratory of Radar Signal Processing
Xidian University
Xi'an, China
dangxudong@xidian.edu.cn

5th Bo Jiu
National Key Laboratory of Radar Signal Processing
Xidian University
Xi'an, China
bojiu@xidian.edu.cn

6th Hongwei Liu
National Key Laboratory of Radar Signal Processing
Xidian University
Xi'an, China
hwliu@xidian.edu.cn

***Abstract*—In this paper, a joint beam selection and power allocation (JBSPA) scheme for multi-target tracking is proposed in a collocated MIMO (C-MIMO) radar network. The goal of this scheme is to achieve better resource utilization efficiency with a given resource budget. Under the condition of sufficient resources, the scheme minimizes the total resource consumption of the C-MIMO radar network. When the sensor resources are insufficient, the scheme maximizes the number of tracked targets that meet the tracking requirements. To evaluate the performance of multi-target tracking, we normalize and utilize the Bayesian Cramér-Rao lower bound (BCRLB) as the performance evaluation criterion. The JBSPA scheme is formulated as a non-convex optimization problem involving integer and continuous variables that are coupled. To address this problem, we propose a fast and effective three-step solution technique. Simulation results demonstrate that the proposed JBSPA scheme can save resources, significantly increase the target capacity, and improve the resource utilization efficiency of the C-MIMO radar network.**

***Index Terms*—multi-target tracking, resource allocation, C-MIMO radar network, BCRLB**

I. Introduction

The resource allocation of radar networks will emerge as a crucial direction in the future development of radar systems. It can flexibly reconfigure sensor transmission power, beam pointing, dwell time, and other resources to improve the performance of multi-target tracking tasks [1]–[3].

In recent years, the collocated MIMO (C-MIMO) radar has been widely used because of its flexible beam. It has been proved that these systems have obvious advantages over traditional radars [4]–[6]. For example, in [4], a resource allocation strategy for single C-MIMO radar is studied, which aims at minimizing the multi-target tracking error and optimizing the power of each beam of single C-MIMO radar. In [5], the Bayesian Cramér-Rao lower bound (BCRLB) is used as the evaluation criterion of system performance, and a robust power allocation algorithm for single C-MIMO radar is proposed. In [6], considering the probability uncertainty of radar cross section (RCS) parameters of targets, the RCS fluctuation model of targets is studied by using different probability distribution forms, and a robust opportunity-constrained power allocation scheme is proposed for multi-target positioning in C-MIMO radar system. However, the above-mentioned resource allocation problem [4]–[6] mainly focuses on solving the resource optimization problem under the background of single C-MIMO radar or phased array radar network, and there is little research on the background of C-MIMO radar network [7], [8]. In [7], combined with particle filtering, a resource allocation scheme of the C-MIMO radar network with joint power and bandwidth allocation is proposed. In [8], the covariance intersection fusion calculation is used to realize the unknown information correlation between radar nodes, and the resource allocation of the C-MIMO radar network is realized by maximizing the overall tracking performance of multi-targets. However, the existing resource allocation work in C-MIMO radar networks fails to consider the limitation of the number of beams. Given the limitation of the number of beams in C-MIMO radar nodes, optimizing beam pointing becomes crucial due to the increased complexity arising from the mutual coupling mechanism between resources and target tracking performance. In addition, the above resource allocation scheme only aims at maximizing the target tracking performance or

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minimizing the radar network resource consumption, without considering the task requirements and considering the lack of resources. This will make it unable to cope with complex multi-target scenarios such as saturation attacks.

In this paper, we present a JBSPA strategy for multi-target tracking in the C-MIMO network. The primary objective of this strategy is to enhance the resource utilization efficiency of the radar network. Under conditions where the system has sufficient resources, the JBSPA strategy minimizes the total resource consumption of the radar network. On the other hand, when the system resources are limited, the strategy maximizes the number of tracked targets that meet the tracking requirements. To formulate the resource allocation strategy, we express it as a mathematical optimization problem. This problem is non-convex and involves a mix of integer and continuous variables. To tackle this challenge, we propose a fast and effective three-step solution technique that combines greedy search and gradient descent. This technique enables us to solve the optimization problem efficiently and obtain the steady-state solution.

II. Problem Formulation

A. Problem Scenario

Consider a scenario in which a radar network consisting of N C-MIMO radars tracks Q targets. In this scene, the position of C-MIMO radar n in the Cartesian coordinate system is expressed as (x_n, y_n), and the radars of each node are in synchronous working mode. Several realistic assumptions are made as follows: (a) The multiple beams of each radar are orthogonal to each other, so that there is no interference between the echo signals of each beam. (b) Each radar node works in different frequency bands, and each radar can only receive its own transmitted signal. (c) The total transmitting resources of each radar is fixed, which makes the radar beams of radar have resource competition. (d) The target source measurement is correctly associated with its source.

B. Target Motion and Measurement Model

Let $\mathbf{x}_k^q = [x_k^q, \dot{x}_k^q, y_k^q, \dot{y}_k^q]^T$ and $\mathbf{z}_{k,n}^q = [r_{k,n}^q, \dot{r}_{k,n}^q, \theta_{k,n}^q]^T$ represent the state vector and measurement vector of target q at kth sampling time, respectively. $r_{k,n}^q$, $\dot{r}_{k,n}^q$ and $\theta_{k,n}^q$ represent the radial distance, velocity and azimuth of the target q relative to radar n, respectively. The dynamic model and the measurement model of target q can be written as [9]

$$\begin{cases} \mathbf{x}_k^q = f(\mathbf{x}_{k-1}^q) + \mathbf{v}_k^q \\ \mathbf{z}_{k,n}^q = h_n(\mathbf{x}_k^q) + \mathbf{w}_{k,n}^q \end{cases}, \tag{1}$$

where $f(\mathbf{.})$ and $h_n(\mathbf{.})$ are the state transition function and the measurement function of the nth radar, respectively. Consider the linear motion model [10], $f(\mathbf{.})$ is a linear function, under the model of constant velocity (CV), the transition function can be simplified as

$$f(\mathbf{x}_{k-1}^q) = \mathbf{F} \cdot \mathbf{x}_{k-1}^q = \left(\mathbf{I}_2 \otimes \begin{bmatrix} 1 & T_0 \\ 0 & 1 \end{bmatrix}\right) \cdot \mathbf{x}_{k-1}^q, \tag{2}$$

where $\mathbf{F}$ is the state transition matrix, T_0 is time interval. $\otimes$ denotes the Kronecker operator, and $\mathbf{I}_m$ denotes an identity matrix of order m.

In (1), $\mathbf{v}_k^q$ and $\mathbf{w}_k^q$ are independent process noise vector and measurement error vector, with $\mathbf{v}_k^q \sim \mathcal{N}(0, \mathbf{Q}_k^q)$and $\mathbf{w}_{k,n}^q \sim \mathcal{N}\left(0, \Sigma_{k,n}^q\right)$. $\sum_{k,n}^q$ can be expressed as [11]

$$\Sigma_{k,n}^q = blkdiag\left(\sigma^2_{r_{k,n}^q}, \sigma^2_{\dot{r}_{k,n}^q}, \sigma^2_{\theta_{k,n}^q}\right), \tag{3}$$

with

$$\begin{cases} \sigma^2_{r_{k,n}^q} \propto (\alpha_{k,n}^q p_{k,n}^q |h_{k,n}^q|^2 \beta_n^2)^{-1} \\ \sigma^2_{\dot{r}_{k,n}^q} \propto (\alpha_{k,n}^q p_{k,n}^q |h_{k,n}^q|^2 T_{c,n}^2)^{-1} \\ \sigma^2_{\theta_{k,n}^q} \propto (\alpha_{k,n}^q p_{k,n}^q |h_{k,n}^q|^2 / B_{3dB,n}^2)^{-1} \end{cases}, \tag{4}$$

where $p_{k,n}^q$ is the signal transmission power of radar n to target q. $h_{k,n}^q$ represents the targets complex gains coefficient. In (4), the attenuation coefficient $\alpha_{k,n}^q$ is inversely proportional to the fourth power of the distance. β_n and $T_{c,n}$ denote the signal effective bandwidth and the effective time width of nth radar, respectively. $B_{3dB,n}$ represents the 3dB receive beam width of radar n. Understanding this relationship is essential for the rational optimization of resources.

III. Propsed JBSPA Strategy

Traditional radar network systems rely on fixed transmission modes, which seriously limit the performance of radar networks. To solve this problem, in this section, we first analyze the performance evaluation criteria of multi-target tracking. Then, a novel resource allocation strategy is proposed by beam selection and power optimization of the C-MIMO radar network. Finally, the resource allocation strategy is expressed as a mathematical optimization problem, and a fast algorithm is designed based on its unique structure.

A. Performance Metric

The BCRLB offers a lower bound for any unbiased estimator and is independent of the utilized estimation algorithm [12]. Therefore, we use it to measure the tracking performance of each target. When the state equation is linear and the measurement equation is nonlinear, the Bayesian information matrix of target q is computed as [13]

$$J_k^q = \left(\mathbf{F}(J_{k-1}^q)^{-1}\mathbf{F}^T + \mathbf{Q}_k^q\right)^{-1} + \sum_{n=1}^{N} (\mathbf{H}_{k,n}^q)^T (\Sigma_{k,n}^q)^{-1} \mathbf{H}_{k,n}^q, \tag{5}$$

where $(J_{k-1}^q)^{-1}$ is the BCRLB matrix at time $k-1$. $\mathbf{H}_{k,n}^q$ is Jacobian of $h(\cdot)$ w.r.t. $\mathbf{z}_{k,n}^q$.

Equation (5) shows the recurrence relation of the BCRLB matrix. The target tracking performance of target q depends not only on the prior information of prediction, but also on the measurement variance $\Sigma_{k,n}^q$, $n \in \{1, \cdots, Q\}$. The beam selection and transmission power of each radar node in the C-MIMO radar network will affect the tracking performance of the target q. Hence, we define an beam selection matrix $\mathbf{S}_k \in \mathbb{R}^{N \times Q}$ to describe the selection relationship between the transmitting beams of each node and the target at time k. Each element of $\mathbf{S}_k$ is defined as

$$\begin{cases} s_{k,n}^q = 1, Target\ q\ is\ irradiated\ by\ node\ n. \\ s_{k,n}^q = 0, Target\ q\ is\ \text{not}\ irradiated\ by\ node\ n. \end{cases} \quad (6)$$

A power matrix $\mathbf{P}_k \in \mathbb{R}^{N\times Q}$ is defined to describe the transmitting power of each node's transmitting beam to the target at time k. The element $p_{k,n}^q$ represents the transmission power of node n to target q.

The diagonal elements of $(J_k^q)^{-1}$ are at different scales, and thus, we normalize them and define the following equation to characterize the q-th target's tracking performance, i.e.,

$$\mathbb{C}_q(\mathbf{S}_k, \mathbf{P}_k) = \mathbf{Tr}(\Lambda \cdot (J_k^q)^{-1} \cdot \Lambda^T), \quad (7)$$

where $\Lambda = \mathbf{I}_2 \otimes diag(1,0)$ is the normalization matrix. $\mathbf{Tr}(\cdot)$ represents trace operator.

B. Problem Formulation

Once the scalar performance evaluation metric is established, the allocation strategy can be constructed by solving the optimization problem of minimizing the C-MIMO radar network resources consumption under limited. The optimization problem can be written as

$$\begin{aligned} &\min_{\mathbf{S}_k,\mathbf{P}_k} \mathbb{F}(\mathbf{S}_k,\mathbf{P}_k) \\ s.t.\ &C1: \mathbb{C}_q(\mathbf{S}_k,\mathbf{P}_k) \le T_q, \forall q \\ &C2: \sum_{q=1}^{Q} p_{k,n}^q \le P_{total,n}, \forall n \\ &C3: \sum_{q=1}^{Q} s_{k,n}^q \le S_{max,n}, \forall n \\ &C4: \begin{cases} P_{\min,n} \le p_{k,n}^q \le P_{\max,n}, & s_{k,n}^q = 1 \\ p_{k,n}^q = 0, & s_{k,n}^q = 0 \end{cases}, \forall n, q \end{aligned} , \quad (8)$$

where $\mathbb{F}(\mathbf{S}_k, \mathbf{P}_k)$ is a system performance evaluation function related to optimizing resources. T_q is the tracking performance requirement of target q. $P_{total,n}$ is the total transmission power of radar n, which indicates that the transmission power resources of each radar node are limited. $S_{\max,n}$ is the maximum number of beams that the C-MIMO radar n can generate simultaneously. $P_{\min,n}$ and $P_{\max,n}$ are the lower and upper limit power of the beam that radar n can generate.

Physically speaking, the optimization problem (8) is to maximize the efficiency of the network system resource under the given multi-target tracking performance requirements. When the number of targets is small or the tracking performance requirements are low, the system resources are sufficient, and the resource consumption of the radar network can be minimized by solving the problem (8). $\mathbb{F}(\mathbf{S}_k, \mathbf{P}_k)$ can be written as

$$\mathbb{F}(\mathbf{S}_k, \mathbf{P}_k) = \sum_{n}^{N} \sum_{q}^{Q} p_{k,n}^q. \quad (9)$$

When resources are insufficient, optimization can achieve the goal of maximizing the number of targets to meet performance requirements. $\mathbb{F}(\mathbf{S}_k, \mathbf{P}_k)$ can be written as

$$\mathbb{F}(\mathbf{S}_k, \mathbf{P}_k) = -\sum_{q=1}^{Q} Sig(\gamma, \Delta_{k,q}), \quad (10)$$

where $Sig(\gamma, m) = 1/(1+\exp(-\gamma m))$ is the Sigmoid function. γ is a control parameters. $\Delta_{k,q} = T_q - \mathbb{C}_q(\mathbf{S}_k, \mathbf{P}_k)$ is the performance requirement difference.

The problem of (8) is mixed-boolean and non-convex, which can be classified as NP-hard. To obtain the steady-state solution of this problem, we designed a three-step solution technique.

Step 1: Determine whether resources are sufficient.

$$\begin{aligned} &\min_{\mathbf{S}_k,\mathbf{P}_k} \gamma \\ s.t. C5: &\mathbb{C}_q(\mathbf{S}_k,\mathbf{P}_k) \le \gamma T_q, \forall q, \\ &C2 - C4 \end{aligned} \quad (11)$$

where γ is a scaling factor of performance requirement. When $\gamma \le 1$, it indicates that resources are sufficient.

To find the solution of (11), we relax the constraint, i.e. set $\mathbf{S}_{k,l}$ as a definite relation matrix. According to Karush–Kuhn–Tucker conditions [14], when $\mathbf{P}_{k,opt}$ is optimal solution, $\gamma = \mathbb{C}_q(\mathbf{S}_{k,l}, \mathbf{P}_k)/T_q, \forall q$. The (11) can be relaxed as

$$\begin{aligned} &\min_{\mathbf{P}_k} \sum_{q=1}^{Q} \mathbb{C}_q(\mathbf{S}_{k,l}, \mathbf{P}_k)/T_q. \\ &s.t. C2, C4 \end{aligned} \quad (12)$$

The problem (12) is a convex problem, which can be solved by gradient descent algorithm [15]. Whether the resources are sufficient can be judged by the following iterative search.

Algorithm 1: The Greedy Search Algorithm

Step (a) Initialize search parameters, i.e., $l = 0$, $s_{k,n}^q = 1, \forall q, n$;
Step (b) Repeat:
(b.1) Solving problem (12) by gradient descent algorithm;
(b.2) If $C3$, $\gamma = \mathbb{C}_q(\mathbf{S}_{k,l}, \mathbf{P}_k)/T_q, \forall q$, and $\gamma \le 1$, the resources are sufficient, $\mathbf{S}_{k,opt} = \mathbf{S}_{k,l}$, return;
(b.3) if $\gamma > 1$, the resources are insufficient $\mathbf{P}_{k,opt} = \mathbf{P}_{k,l}$, return;
(b.4) Let $l = l+1$ and $\mathbf{S}_{k,l} = \mathbf{S}_{k,l-1}$. Find all radars that do not meet $C3$, and set the $\mathbf{S}_{k,l}$ corresponding to the lowest power in $s_{k,n}^q$ to $s_{k,n}^q = 0$.
Step (c) Return judgment result, $\mathbf{S}_{k,opt}$ and $\mathbf{P}_{k,opt}$.

Step 2: Problem solving under the condition of sufficient resources

When resources are sufficient, the optimization problem is written as

$$\min_{\mathbf{P}_k} \sum_{n}^{N} \sum_{q}^{Q} p_{k,n}^{q}$$
$$s.t. \mathbb{C}_q(\mathbf{S}_{k,opt}, \mathbf{P}_k) \leq T_q, \forall q, \tag{13}$$
$$\sum_{q=1}^{Q} p_{k,n}^{q} \leq p_{total,n}, \forall n$$

where $\mathbf{S}_{k,opt}$ is the output result of Step 1. The problem (13) is a convex problem which can be solved by interior point algorithm [16].

Step 3: Problem solving under the condition of insufficient resources

When the resources are insufficient, we remove the targets with high resource consumption by discrete search, so as to maximize the number of targets that the system can track accurately. The search process following as:

a) We construct the resource occupation vector $P_{T,k} = [p_{1,k}, \cdots, p_{Q,k}]$ of each target according to $\mathbf{P}_{k,opt}$.

$$p_{q,k} = \sum_{n=1}^{N} p_{k,n}^{q}. \tag{14}$$

b) Find the target corresponding to the largest element in $P_{T,k}$ and delete it.

c) Use Algorithm 1 to judge whether the resources are satisfied. If not, repeat a) - c) until it is satisfied.

IV. Simulattion Results

We consider a multi-target tracking scenario in a C-MIMO radar network. In this scenario, the number of C-MIMO radar is $N = 3$, and it need to track $Q = 4$ targets. For simplicity, the each C-MIMO radar total transmit power and signal bandwidth are set to $p_{total} = 1kW$ and $\beta = 10MHz$. It is assumed that each radar is capable of generating two beams, with a beam width of B_{3dB} = 3°. The tracking interval between two successive frames is $T_0 = 2s$, the total number of frames is set to $N_{frame} = 30$, and the number of Monte Carlo experiments is 200. In this scenario, there are two situations: sufficient resources and insufficient resources. The scenario is shown in Fig. 1.

Fig. 2 illustrates the resource occupation of each radar, while Fig. 3 depicts the illumination relationship between the targets and each radar. As observed in Fig. 2, radar 1 concentrates its limited beam resources on irradiating targets 2 and 3. This preference is due to the close proximity of targets 2 and 3 to radar 1. On the other hand, Fig. 3 reveals that radars 2 and 3 can generate a single tracking beam during the interval $10 \leq k \leq 30$. This is because as the target tracking performance converges, the transmission power required for tracking decreases. The JBSPA scheme can then determine beam selection and power allocation based on the performance requirements of each target. Consequently, when radar 1 can accurately track targets 2 and 3, radars 2 and 3 only need to generate one beam to ensure the performance of targets 1 and 4.

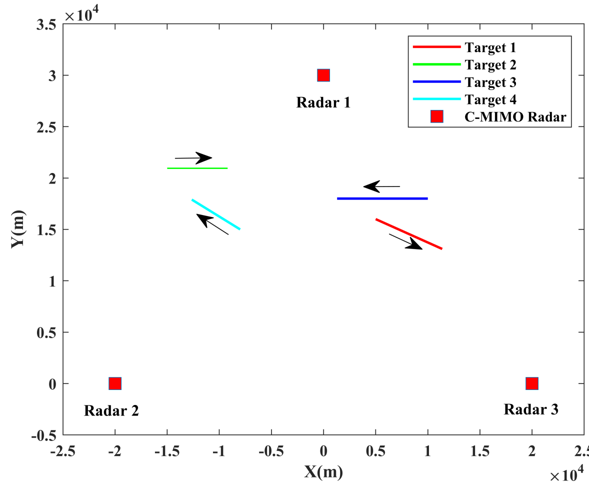

Fig. 1. Deployment of target w.r.t. the scenario.

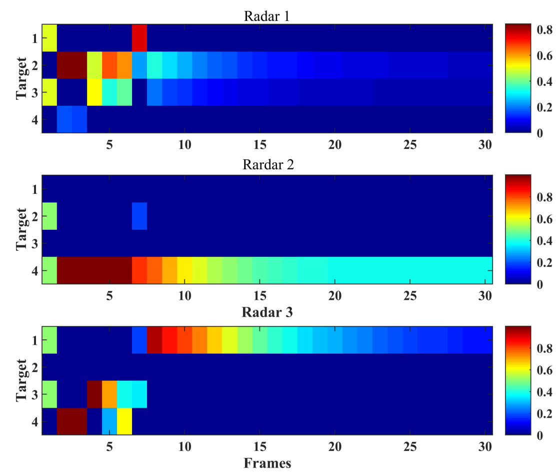

Fig. 2. Resource allocation results of the C-MIMO radar.

Fig. 4 shows the total resource consumption rate of the C-MIMO system by resource allocation. It can be seen from Fig. 4 that at $k \leq 6$, due to the influence of the spatial position of the target and the initial filtering state, the system can't track all the targets with guaranteed accuracy under the condition of limited radar network resources. Therefore, the JBSPA scheme selection consumes all resources, and the number of effectively tracked targets is improved by optimizing the beam selection and transmission power.

Fig. 5 shows the comparison of the number of effective tracking targets between the proposed JBSPA scheme and the traditional uniform allocation scheme. In the simulation, the uniform allocation scheme is to assign each beam of the radar to track several targets closest to the radar, and the transmission power of each beam is uniform allocated. As can be seen from Fig. 5, at $k \leq 16$, the uniform allocation method fails to effectively track the targets. However, as $17 \leq k$, the tracking performance of each target converges, and the

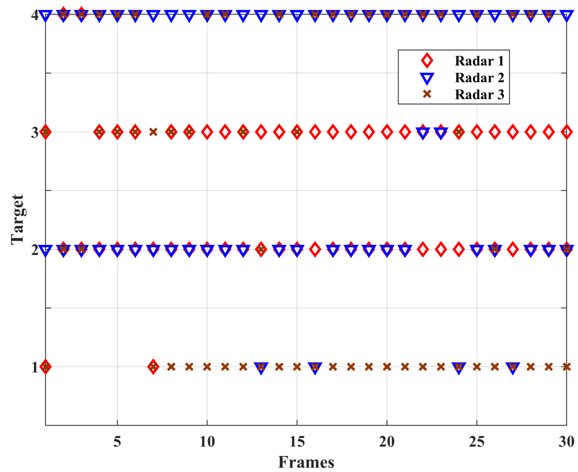

Fig. 3. Relationship between radar and target illumination.

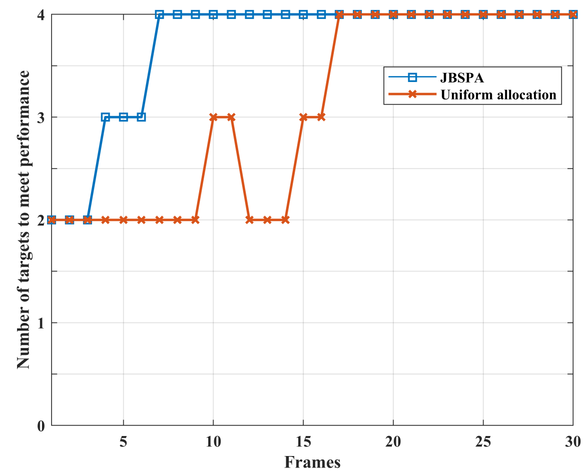

Fig. 5. The number of targets tracked effectively.

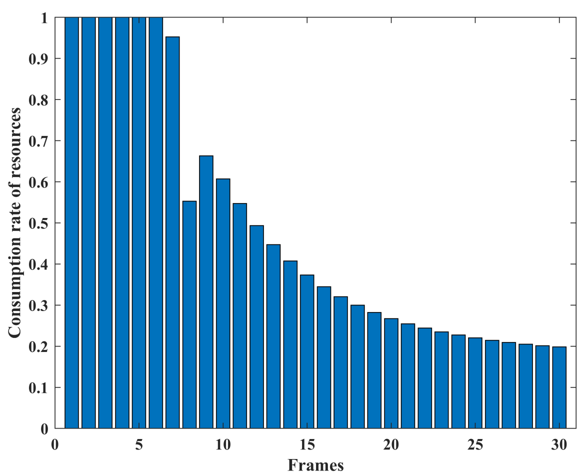

Fig. 4. The total resource consumption rate of C-MIMO network system.

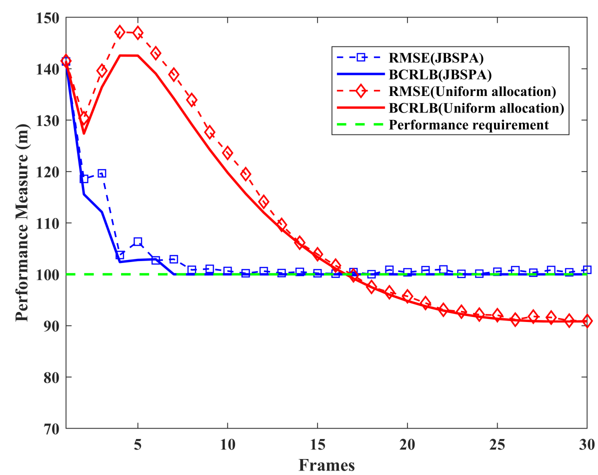

Fig. 6. The worst target tracking performance.

amount of prediction information becomes sufficient, enabling both methods to effectively track all targets. At $k \leq 6$, when combined with Fig. 4, it is evident that the proposed JBSPA scheme can significantly increase the number of effective tracking targets under resource-limited conditions. At $7 \leq k \leq 16$, the JBSPA not only conserves system resources but also maximizes the number of effective tracking targets through beam selection and transmission power allocation.

Fig. 6 displays the tracking performance of the worst target throughout the tracking process. As observed in Fig. 6, the JBSPA scheme effectively utilizes system resources and enhances the tracking root mean square error (RMSE) of the worst target under resource-limited conditions. At $7 \leq k \leq 16$, even though the JBSPA scheme ensures sufficient system resources, the uniform allocation scheme still suffers from resource insufficiency. Consequently, the worst target tracking RMSE remains unsatisfactory under the uniform allocation scheme, failing to meet system requirements. Moreover, Fig. 6 indicates that under resource-sufficient conditions, the JBSPA scheme aligns the target tracking RMSE closely with the performance requirements, thus validating the effectiveness of the proposed three-step solution technique in achieving the steady-state solution of the JBSPA scheme. Based on these observations, the proposed JBSPA scheme enhances the overall tracking performance of the system under insufficient resources, saves system resources when resources are sufficient, and improves the utilization efficiency of resources.

V. Conclusions

In this article, a JBSPA scheme is developed for multi-target tracking in C-MIMO radar network. The JBSPA scheme is to improve the maximum resource utilization efficiency of the radar network system by beam selection and power allocation. It can be divided into two situations: sufficient and insufficient. In the first case, this scheme can minimize the total resource consumption of the radar network. When the sensor resources are insufficient, this scheme can maximize the number of targets that meet the requirements of tracking. By combining greedy search and gradient descent, a fast and effective three-step solution technique is proposed to solve the non-convex problem of this mixed integer. The simulation results demonstrate that the proposed JBSPA scheme can save resources, greatly increase the target capacity, and improve the resource utilization efficiency of the C-MIMO radar network. In the future, we will consider the situation of complex targets and further study other resource allocation models in multi-target tracking.

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