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Research Article

Resource Allocation Schemes for Multiple Targets Tracking in Distributed MIMO Radar Systems

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Considering the demands of different location accuracy for multiple targets tracking, performance-driven resource allocation schemes in distributed MIMO radar system are proposed. Restricted by the tracking antenna number, location estimation mean-square error (MSE), and target priorities, an optimization problem of the minimal antenna subsets selection is modeled as a knapsack problem. Then, two operational schemes, modified fair multistart local search (MFMLS) algorithm and modified fair multistart local search with one antenna to all targets (MFMLS_OAT) algorithm, are presented and evaluated. Simulation results indicate that the proposed MFMLS and MFMLS_OAT algorithm outperform the existing algorithms. Moreover, the MFMLS algorithm can distinguish targets with different priorities, while the MFMLS_OAT algorithm can perform the tracking tasks with higher accuracy.

1. Introduction

Multiple Input Multiple Output (MIMO) radar [1] can be divided into two basic regimes of architecture, centralized MIMO radar and distributed MIMO radar. The former can obtain the waveform diversity and degree of freedom to improve the parameter estimation performance with centralized antennas, which is suitable for a point target model due to the lack of angle diversity [2, 3]. The latter offers enhanced target detection and localization capabilities by widely spaced antennas where an extended target model can be achieved [4, 5]. With the development of stealth technology, the targets may be invisibility, while the target fluctuation characteristic is difficult to control. Considering that the distributed MIMO radar has an advantage on overcoming the target radar cross section (RCS) fluctuation in complex electromagnetic environments [6] and performs better anti-interception and antidestroying character than centralized radar system, in this paper we focus on the distributed MIMO radar to improve target tracking capacity with a centralized signal fusion structure where global information can be collaborated and the allocation results can be directly transformed to each antenna by internal communication network, such as satellite link and fiber optic link. In distributed MIMO radar system, the advantages of multiple channels depend on the optimal system architecture and flexible signal design. Both system architecture and transmit parameters can be considered as system resources. Therefore, reasonable resource allocation schemes are needed for better system performance in distributed MIMO radar system [7–11]. The topology of the transmitters and receivers with respect to targets needs to be available for resource allocation, so the target tracking process needs to be considered [12]. Moreover, distributed MIMO radar system has advantages on multiple targets management [13]. Resource allocation schemes play an important part in multiple tasks system. Overall, researches on resource allocation problem in distributed MIMO radar system for multiple targets tracking are especially necessary.

In terms of resource allocation on system architecture, existing researches mainly focus on the intelligence of antenna selection [14, 15]. Some antennas may have greater impacts on system performance than others [16], affected by the different propagation paths, target reflection coefficients, and topologies of system with respect to targets. Reasonable antenna selection can maximize antenna utilization and minimize computational complexity and communication cost among stations. Currently, the antenna selection problem in MIMO radar system is usually modeled as a knapsack problem (KP). The Bayesian Cramer-Rao bound (BCRB) is used as the performance metric for parameter estimation. Compared with an exhaustive search, the existing heuristic algorithm can offer considerable reduction in computational complexity. Considering the data transmission and computational complexity, a single target localization scheme based on antenna selection is proposed in [17] where two optimization models are included. The first idea achieves the minimum antenna subset out of available transmitters and receivers within a given MSE threshold. The second is to select antenna subset with a specific subset size such that the location estimation capability is maximized where a constraint on operational cost is considered. Antenna cluster method for multiple targets localization is generated in [18] where each target is just tracked by the corresponding antenna subset. Greedy multistart local search (GMLS) algorithm and fair multistart local search (FMLS) algorithm are proposed. The former offers lower computational complexity with random target sequence, while the latter offers better selection performance with a more balanced allocation of antennas. Joint schemes of antenna selection and power allocation for target detection and localization are studied in [14, 15] to improve system performance. A specific TOA-based passive localization method is presented in [19] where parametric belief propagation (BP) algorithm could be attractive under the impact of receivers' position uncertainty, due to the significantly lower computational complexity.

However, previous researches on antenna selection have failed to consider specific system tasks. Therefore, further studies are still necessary in this paper. Existing studies on antenna selection mainly focus on the static target. For the resource allocation it is necessary to predict target state in advance. Antenna selection problem for moving targets is considered in this paper. Antenna utilization is ignored in [16]. For the improvement of the antenna utilization and the demands of other tasks, a constraint on tracking antenna utilization is proposed in this paper. The same MSE threshold is set for all targets in [18]. For further close to practical application, location accuracy and priorities for different targets should be different. A modified cluster method based on [18] is presented to solve it. Antenna cluster method can reduce the data transmission to fusion center, but it is difficult for higher location accuracy. Therefore, an idea with every antenna to track all targets for different location accuracy is introduced.

In this paper, resource allocation schemes for the demands of different location accuracy are proposed in distributed MIMO radar system, which have not been studied before. The paper is organized as follows: The system model is introduced in Section 2, including the derivation of the BCRB. Resource allocation schemes are proposed in Section 3, including problem formulation and antenna selection algorithms. Simulation results in different scenarios are provided in Section 4. Finally, Section 5 concludes the paper.

2. System Model and Preliminaries

Consider a widely distributed MIMO radar system where only one antenna is configured for each station. There are M transmitters located at $\{(x_m^t, y_m^t)\}_{m=1}^M$ and N receivers located at $\{(x_n^r, y_n^r)\}_{n=1}^N$. At state k, define the time interval $k\Delta t$ where Δt is the observation interval. Q moving targets are located $\{(x_k^q, y_k^q)\}_{q=1}^Q$ and move with velocity $\{(v_{x,k}^q, v_{y,k}^q)\}_{q=1}^Q$. A set of orthogonal waveforms $\{s_m(t)\}_{m=1}^M$ are transmitted where $\int_{T_m} |s_m(t)|^2 dt = 1$, and T_m is the duration time of the transmitted signal. Define the transmit power vector $\mathbf{p}_k = [p_{1,k} \ \ p_{2,k} \ \ \cdots \ \ p_{M,k}]^T$, the effective bandwidth vector $\boldsymbol{\beta}_k = [\beta_{1,k} \ \ \beta_{2,k} \ \ \cdots \ \ \beta_{M,k}]^T$, and the effective illumination time vector $\mathbf{t}_k = [t_{1,k} \ \ t_{2,k} \ \ \cdots \ \ t_{M,k}]^T$ for transmitters.

For simplicity time synchronization has been satisfied between different receivers. The low-pass signal observed at receiver n can be written as

$$r_{n,k}(t) = \sum_{q=1}^{Q} \sum_{m=1}^{M} \sqrt{\alpha_{mqn,k} p_{m,k}} \zeta_{mqn,k} s_m \left(t - \tau_{mqn,k}\right) \cdot e^{-j w_{mqn,k} t} + w_{n,k}(t), \quad (1)$$

where mqn denotes propagation channel along the path transmitter m-target q-receiver n. $\tau_{mqn,k}$ is the time delay along path mqn, satisfying

$$\tau_{mqn,k} = \frac{R_{m,k}^q + R_{n,k}^q}{c}, \quad (2)$$

where $R_{m,k}^q = \sqrt{(x_{m,k}^t - x_k^q)^2 + (y_{m,k}^t - y_k^q)^2}$ and $R_{n,k}^q = \sqrt{(x_{n,k}^r - x_k^q)^2 + (y_{n,k}^r - y_k^q)^2}$, respectively, denote the Euclidean distances from transmitter m to target q and from target q to receiver n. c is the speed of light. $w_{mqn,k}$, the Doppler shift due to the target velocity, can be expressed as

$$w_{mqn,k} = -\frac{2\pi}{\lambda} \left[\cos\left(\phi_{m,k}^q + \varphi_{n,k}^q\right) v_{x,k}^q + \sin\left(\phi_{m,k}^q + \varphi_{n,k}^q\right) v_{y,k}^q\right], \quad (3)$$

where $\phi_{m,k}^q$ and $\varphi_{n,k}^q$ are the angle from transmitter m to target q and the angle from receiver n to target q. $\alpha_{mqn,k}$ models the path-loss in free space along the path mqn where $\alpha_{mqn,k} \propto 1/(f_c R_{m,k}^q R_{n,k}^q)^2$. f_c is the carrier frequency. $\zeta_{mqn,k}$ represents the corresponding targets reflection coefficients. For sufficiently spaced antennas each target is modeled as a collection of reflection coefficients forming the RCS model. The noise $w_{n,k}(t)$ is assumed circularly symmetric, zero-mean, complex Gaussian noise, spatially and temporally white with autocorrelation function $\sigma_w^2 \delta(\tau)$. According to [20], $\text{SNR}_{mqn,k} = p_{m,k} |\zeta_{mqn,k}|^2 / f_r (R_{m,k}^q R_{n,k}^q)^2 \delta_w^2$, where f_r is pulse repetition frequency.

Define the state vector $\mathbf{x}_k^q = (x_k^q, y_k^q, v_{x,k}^q, v_{y,k}^q)^T$ for target q. At state k, the state-transition model for target q is a linear motion model, represented as

$$\mathbf{x}_{k+1}^q = \mathbf{F}\mathbf{x}_k^q + \mathbf{v}_k^q, \quad (4)$$

where $\mathbf{F}$, the state-transition matrix for uniform motion, is of the form

$$\mathbf{F} = \begin{pmatrix} 1 & \Delta t \\ 0 & 1 \end{pmatrix} \otimes \mathbf{I}_2. \quad (5)$$

$\mathbf{v}_k^q$, plant noise modeled as Gaussian noise process with covariance matrix $\mathbf{Q}_{\mathbf{v},k}$, is of the form

$$\mathbf{Q}_{\mathbf{v},k} = q_0 \mathbf{I}_2 \otimes \begin{pmatrix} \frac{1}{3}\Delta t^3 & \frac{1}{2}\Delta t^2 \\ \frac{1}{2}\Delta t^2 & \Delta t \end{pmatrix}. \quad (6)$$

q_0 is the noise intensity.

Define measurable vector $\boldsymbol{\psi}_k^q = [(\boldsymbol{\tau}_k^q)^T (\mathbf{w}_k^q)^T]^T$, where $\boldsymbol{\tau}_k^q = [\tau_{1q1,k}\ \tau_{1q2,k}\ \cdots\ \tau_{MqN,k}]^T$, $\mathbf{w}_k^q = [w_{1q1,k}\ w_{1q2,k}\ \cdots\ w_{MqN,k}]^T$.

The observation vector $\mathbf{z}_k^q$ is a nonlinear function of the vector $\boldsymbol{\psi}_k^q$:

$$\mathbf{z}_k^q = f(\boldsymbol{\psi}_k^q) + \mathbf{n}_k^q, \quad (7)$$

where $f(\cdot)$ stands for the observation process and $\mathbf{n}_k^q$ is the observation noise.

At high signal-to-noise ratio (SNR) [21], the target location estimation MSE is close to the BCRB; the latter may be used to evaluate the location estimation performance. At state k, 4×4 BCRB matrix of target q can be expressed as

$$\mathbf{C}_k^q (\mathbf{x}_k^q)\big|_{\mathbf{z}_k^q} = \left[\mathbf{J}_B (\mathbf{x}_k^q)\big|_{\mathbf{z}_k^q}\right]^{-1}, \quad (8)$$

where $\mathbf{J}_B(\mathbf{x}_k^q)$ denotes the Bayesian Information Matrix (BIM) of target q, and the recursive BCRB is of the form

$$\mathbf{J}_B (\mathbf{x}_k^q) = \left[\mathbf{Q}_v + \mathbf{F}\mathbf{J}_B^{-1}(\mathbf{x}_{k-1}^q)\mathbf{F}^T\right]^{-1} + E\left[\mathbf{J}_D(\mathbf{x}_k^q)\right], \quad (9)$$

where $E[\cdot]$ is the expectation; $\mathbf{J}_D(\mathbf{x}_k^q)$ is the Fisher Information Matrix (FIM), which can be obtained by applying the chain rule $\mathbf{J}_D(\mathbf{x}_k^q) = \mathbf{H}_k \mathbf{J}_D(\boldsymbol{\psi}_k^q)\mathbf{H}_k^T$, where the Jacobi matrix is $\mathbf{H}_k = \partial(\boldsymbol{\psi}_k^q)/\partial(\mathbf{x}_k^q)$; $\mathbf{J}_D(\boldsymbol{\psi}_k^q)$ is the FIM of $\boldsymbol{\psi}_k^q$, which can be derived by the conditional probability distribution function $p(\mathbf{z}_k^q \mid \boldsymbol{\psi}_k^q) \propto \exp\{-(1/\sigma_w^2)\sum_{n=1}^{N}\int_T |\mathbf{r}_{n,k}^q(t) - \sum_{m=1}^{M}\sqrt{\alpha_{mqn,k}p_{m,k}}\zeta_{mqn,k}s_m(t-\tau_{mqn,k})e^{-jw_{mqn,k}t}|^2 dt\}$.

Define antenna selection vectors $\mathbf{f}_{tx} = [f_{tx_1}\ f_{tx_2}\ \cdots\ f_{tx_M}]^T$ for the transmitters and $\mathbf{f}_{rx} = [f_{rx_1}\ f_{rx_2}\ \cdots\ f_{rx_N}]^T$ for receivers. $f_{tx_m}, f_{tx_n} \in \{0,1\}$, where 0 means abandoned and 1 means selected. The diagonal elements of BCRB matrix satisfy $\mathrm{var}(\hat{x}^q) + \mathrm{var}(\hat{y}^q) \geq \mathbf{C}_k^q(\mathbf{x}_k^q)|_{\mathbf{z}_k^q(1,1)} + \mathbf{C}_k^q(\mathbf{x}_k^q)|_{\mathbf{z}_k^q(2,2)} = \mathbb{G}_k^q(\mathbf{x}_k^q)$. An expression for localizing target q with antenna selection is derived in [22]

$$\mathbb{G}_k^q(\mathbf{f}_{tx}, \mathbf{f}_{rx}) = \frac{1}{\eta} \cdot \frac{(\mathbf{f}_{rx})^T(\mathbf{A}_k^q + \mathbf{B}_k^q)\mathbf{f}_{tx}}{\left[(\mathbf{f}_{rx})^T\mathbf{A}_k^q\mathbf{f}_{tx}\right]\left[(\mathbf{f}_{rx})^T\mathbf{B}_k^q\mathbf{f}_{tx}\right] - \left[(\mathbf{f}_{rx})^T\mathbf{C}_k^q\mathbf{f}_{tx}\right]^2}, \quad (10)$$

where $\eta = 8\pi^2/\sigma_w^2$, $\mathbf{A}_k^q$, $\mathbf{B}_k^q$, and $\mathbf{C}_k^q$ are, respectively, expressed as

$$\mathbf{A}_k^q = \begin{bmatrix} a_{1,1,k}^q & a_{2,1,k}^q & \cdots & a_{M,1,k}^q \\ a_{1,2,k}^q & a_{2,2,k}^q & \cdots & a_{M,2,k}^q \\ \vdots & \ddots & & \vdots \\ a_{1,N,k}^q & a_{2,N,k}^q & \cdots & a_{M,N,k}^q \end{bmatrix},$$
$$\mathbf{B}_k^q = \begin{bmatrix} b_{1,1,k}^q & b_{2,1,k}^q & \cdots & b_{M,1,k}^q \\ b_{1,2,k}^q & b_{2,2,k}^q & \cdots & b_{M,2,k}^q \\ \vdots & \ddots & & \vdots \\ b_{1,N,k}^q & b_{2,N,k}^q & \cdots & b_{M,N,k}^q \end{bmatrix}, \quad (11)$$
$$\mathbf{C}_k^q = \begin{bmatrix} c_{1,1,k}^q & c_{2,1,k}^q & \cdots & c_{M,1,k}^q \\ c_{1,2,k}^q & c_{2,2,k}^q & \cdots & c_{M,2,k}^q \\ \vdots & \ddots & & \vdots \\ c_{1,N,k}^q & c_{2,N,k}^q & \cdots & c_{M,N,k}^q \end{bmatrix},$$

where

$$\begin{aligned} a_{mn,k}^q = p_{m,k}\Bigg\{&\Big[\frac{1}{c}\sqrt{\alpha_{mqn,k}}\zeta_{mqn,k}\beta_{m,k}\big(\cos\phi_{m,k}^q + \cos\varphi_{n,k}^q\big)\Big]^2 + \Bigg\{\frac{2\pi}{\lambda} \\ &\cdot\sqrt{\alpha_{mqn,k}}\zeta_{mqn,k}t_{m,k}\Bigg[v_{x,k}^q\left(\frac{\sin^2\phi_{m,k}^q}{R_{m,k}^q} + \frac{\sin^2\varphi_{n,k}^q}{R_{n,k}^q}\right) \\ &- v_{y,k}^q\left(\frac{\sin\phi_{m,k}^q\cos\phi_{m,k}^q}{R_{m,k}^q} + \frac{\sin\varphi_{n,k}^q\cos\varphi_{n,k}^q}{R_{n,k}^q}\right)\Bigg]\Bigg\}^2\Bigg\}, \end{aligned} \quad (12)$$

$$\begin{aligned} b_{mn,k}^q = p_{m,k}\Bigg\{&\Big[\frac{1}{c}\sqrt{\alpha_{mqn,k}}\zeta_{mqn,k}\beta_{m,k}\big(\sin\phi_{m,k}^q + \sin\varphi_{n,k}^q\big)\Big]^2 + \Bigg\{\frac{2\pi}{\lambda} \\ &\cdot\sqrt{\alpha_{mqn,k}}\zeta_{mqn,k}t_{m,k}\Bigg[v_{y,k}^q\left(\frac{\cos^2\phi_{m,k}^q}{R_{m,k}^q} + \frac{\cos^2\varphi_{n,k}^q}{R_{n,k}^q}\right) \\ &- v_{x,k}^q\left(\frac{\sin\phi_{m,k}^q\cos\phi_{m,k}^q}{R_{m,k}^q} + \frac{\sin\varphi_{n,k}^q\cos\varphi_{n,k}^q}{R_{n,k}^q}\right)\Bigg]\Bigg\}^2\Bigg\}, \end{aligned} \quad (13)$$

$$\begin{aligned} c_{mn,k}^q = p_{m,k}\Bigg\{&\frac{1}{c}\left[\sqrt{\alpha_{mqn,k}}\zeta_{mqn,k}\beta_{m,k}\right]^2\left(\cos\phi_{m,k}^q + \cos\varphi_{n,k}^q\right) \\ &\cdot\left(\sin\phi_{m,k}^q + \sin\varphi_{n,k}^q\right) + \left[\frac{2\pi}{\lambda}\sqrt{\alpha_{mqn,k}}\zeta_{mqn,k}t_{m,k}\right]^2 \end{aligned}$$

$$\cdot \left[v^q_{x,k} \left(\frac{\sin^2 \phi^q_{m,k}}{R^q_{m,k}} + \frac{\sin^2 \varphi^q_{n,k}}{R^q_{n,k}} \right) - v^q_{y,k} \left(\frac{\sin \phi^q_{m,k} \cos \phi^q_{m,k}}{R^q_{m,k}} + \frac{\sin \varphi^q_{n,k} \cos \varphi^q_{n,k}}{R^q_{n,k}} \right) \right] \cdot \left[v^q_{y,k} \left(\frac{\cos^2 \phi^q_{m,k}}{R^q_{m,k}} + \frac{\cos^2 \varphi^q_{n,k}}{R^q_{n,k}} \right) - v^q_{x,k} \left(\frac{\sin \phi^q_{m,k} \cos \phi^q_{m,k}}{R^q_{m,k}} + \frac{\sin \varphi^q_{n,k} \cos \varphi^q_{n,k}}{R^q_{n,k}} \right) \right] \Bigg\}. \tag{14}$$

3. Resource Allocation Schemes

In multiple tasks system radar systems need to deal with the problem of insufficient resources. Reasonable resource allocation schemes are important for application demands of given location MSE. Antenna selection is considered to improve resource utilization when the resources on transmit parameters are enough. The detailed allocation process can be described as follows: at one state, orthogonal signals transmitted by transmitters are reflected by the targets and observed by receivers. All the receivers directly transfer the a global signal from multiple targets to one centralized fusion center where the effective data is employed to predict target state and calculate the optimal resource allocation strategy for next state. In the end, the allocation results can be directly informed to each antenna by internal communication network for next tracking.

In this paper, targets are assumed to be moving in low attitude. All the targets are not treated equally, which are divided into general targets, suspicious targets, and hot targets. And the corresponding tracking location estimation MSE are successively reduced with MSE ranges $20^2 \sim 30^2\ \mathrm{m}^2$, $10^2 \sim 20^2\ \mathrm{m}^2$, and $0 \sim 10^2\ \mathrm{m}^2$. The lower the MSE threshold is, the higher the priority will be.

3.1. Problem Formulation. In multiple targets tracking system, the key targets need to be preferred for the system demands. Meanwhile, the location accuracy for others needs to be improved. Under the constraint of tracking antenna number and location estimation MSE, a uniform problem formulation for antenna selection may be expressed as

$$\begin{aligned} \min_{\mathbf{f}_{tx},\mathbf{f}_{rx}} \quad & \mathbb{N}_k(\mathbf{f}_{tx}, \mathbf{f}_{rx}) \\ \text{s.t.} \quad & \mathbb{G}^q_k(\mathbf{f}_{tx}, \mathbf{f}_{rx}) \le \mathrm{MSE}^q \\ & q \in \left\{1^0, \ldots, Q^0\right\} \cup \{1, \ldots, Q\} \\ & \mathbb{N}_k(\mathbf{f}_{tx}, \mathbf{f}_{rx}) \le (M+N)\eta, \end{aligned} \tag{15}$$

where $\mathbb{N}_k(\mathbf{f}_{tx}, \mathbf{f}_{rx})$ denotes the selected active antenna number. MSE^q is given location MSE threshold for target q. $\{1^0, \ldots, Q^0\}$ are the targets with high priorities, which will be ensured beforehand. $\{1, \ldots, Q\}$ are the targets with low priorities, which will be ensured after. η is the antenna utilization for targets tracking.

3.2. Antenna Selection Algorithms. Different resource allocation schemes are considered to process different tracking accuracy requirements. Two resource allocation schemes, modified fair multistart local search (MFMLS) algorithm for high location MSE and modified fair multistart local search with one antenna to all targets (MFMLS_OAT) algorithm for low location MSE, are, respectively, proposed.

3.2.1. MFMLS Algorithm for High Location Estimation MSE. Studies on antenna selection in [18] indicate that the minimal antenna subset with a given high MSE threshold could be obtained with antenna cluster method, where GMLS and FMLS algorithm are proposed. The optimized target is random by GMLS algorithm, though it may realize a prior tracking requirement for some target. A more balanced allocation is generated by FMLS algorithm, but it ignores the different targets priorities processing. In this case, MFMLS algorithm inspired by GMLS and FMLS algorithm is proposed where the targets in the same and different priorities are considered.

Assume that there are general targets $\{1, \ldots, Q\}$ and suspicious targets $\{1^0, \ldots, Q^0\}$ in multiple targets tracking system with high MSE thresholds; the latter are considered as the key targets in this section. Under the constraint of tracking antenna number, the radar system needs to ensure the demand for suspicious targets where an antenna cluster method is employed. At one measurement, every antenna can be selected one time at most for just tracking one target. Therefore, antenna selection vectors, $\mathbf{f}^q_{tx} = \left[f^q_{tx_1}\ f^q_{tx_2}\ \cdots\ f^q_{tx_M}\right]^T$ and $\mathbf{f}^q_{rx} = \left[f^q_{rx_1}\ f^q_{rx_2}\ \cdots\ f^q_{rx_N}\right]^T$ just effective for target q, are introduced in this section. And problem (15) can be rewritten as

$$\begin{aligned} \min_{\mathbf{f}^q_{tx},\mathbf{f}^q_{rx}} \quad & \sum_{q\in\{1^0,\ldots,Q^0\}\cup\{1,\ldots,Q\}} \left(\sum_{m=1}^{M} f^q_{tx_m} + \sum_{n=1}^{N} f^q_{rx_n} \right) \\ \text{s.t.} \quad & \mathbb{G}_k(\mathbf{f}^q_{tx}, \mathbf{f}^q_{rx}) \le \mathrm{MSE}^q \\ & q \in \left\{1^0, \ldots, Q^0\right\} \cup \{1, \ldots, Q\} \\ & \sum_{q\in\{1^0,\ldots,Q^0\}\cup\{1,\ldots,Q\}} \left(\sum_{m=1}^{M} f^q_{tx_m} + \sum_{n=1}^{N} f^q_{rx_n} \right) \\ & \le (M+N)\eta \\ & \sum_{m=1}^{M} f^q_{tx_m} \ge 1, \quad f^q_{tx_m} \in \{0, 1\} \\ & \sum_{n=1}^{N} f^q_{rx_n} \ge 1, \quad f^q_{rx_n} \in \{0, 1\}, \end{aligned} \tag{16}$$

where $\mathbb{N}_k(\mathbf{f}_{tx}, \mathbf{f}_{rx}) = \sum_{q\in\{1^0,\ldots,Q^0\}\cup\{1,\ldots,Q\}} (\sum_{m=1}^{M} f^q_{tx_m} + \sum_{n=1}^{N} f^q_{rx_n})$ denotes the optimal total antenna number.

In Algorithm 1, the specific MFMLS algorithm is proposed. A radar subset is initially generated by selecting one transmitter and one receiver $\{f^q_{tx_m}, f^q_{rx_n}\}$ for every target. Meanwhile, they are discarded from the original antenna sets

(1) initial: $\mathbf{f}_{tx} = 0, \mathbf{f}_{rx} = 0, \mathbf{A}_{\min} = \mathbf{B}_{\min} = \mathbf{C}_{\min} = \varnothing$, $set\_A = set\_B = set\_C = 0$
(2) select initial subsets: $\{f^q_{tx_m}, f^q_{rx_n}\}, q \in \{1^0, \ldots, Q^0\} \cup \{1, \ldots, Q\}$
$S_{tx} = S^0_{tx} \setminus f^q_{tx_m}, S_{rx} = S^0_{rx} \setminus f^q_{rx_n}, f^q_{tx_m} = 1, f^q_{rx_n} = 1$
(3) For all possible initial subsets: $\{\mathbf{f}^q_{tx}, \mathbf{f}^q_{rx}\}, q \in \{1^0, \ldots, Q^0\} \cup \{1, \ldots, Q\}$
(3.1) while $\exists q \in \{1^0, \ldots, Q^0\}$, s.t $\mathbb{G}_k(\mathbf{f}^q_{tx}, \mathbf{f}^q_{rx}) > \text{MSE}^q$ and $S_{tx} + S_{rx} > (M+N)(1-\eta)$
select $q^* = \arg\max_{q^* \in \{1^0,\ldots,Q^0\}} \|\mathbb{G}_k(\mathbf{f}^{q^*}_{tx}, \mathbf{f}^{q^*}_{rx}) - \text{MSE}^{q^*}\|$
select $f^{q^*} = \arg\min_{f^{q^*} \in \{S_{tx}, S_{rx}\}} \|\mathbb{G}_k(\mathbf{f}^{q^*}_{tx}, \mathbf{f}^{q^*}_{rx}, f^{q^*}) - \text{MSE}^{q^*}\|$
$\{S_{tx}, S_{rx}\} \setminus f^{q^*}, f^{q^*} = 1$
end
(3.2) while $\exists q \in \{1, \ldots, Q\}$, s.t $\mathbb{G}_k(\mathbf{f}^q_{tx}, \mathbf{f}^q_{rx}) > \text{MSE}^q$ and $S_{tx} + S_{rx} > (M+N)(1-\eta)$
select $q^* = \arg\max_{q^* \in \{1,\ldots,Q\}} \|\mathbb{G}_k(\mathbf{f}^q_{tx}, \mathbf{f}^q_{rx}) - \text{MSE}^{q^*}\|$
select $f^{q^*} = \arg\min_{f^{q^*} \in \{S_{tx}, S_{rx}\}} \|\mathbb{G}_k(\mathbf{f}^{q^*}_{tx}, \mathbf{f}^{q^*}_{rx}, f^{q^*}) - \text{MSE}^{q^*}\|$
$\{S_{tx}, S_{rx}\} \setminus f^{q^*}, f^{q^*} = 1$
end
(3.3) $(\mathbf{f}_{tx}, \mathbf{f}_{rx}) = \{(\mathbf{f}^q_{tx}, \mathbf{f}^q_{rx})\}, q \in \{1^0, \ldots, Q^0\} \cup \{1, \ldots, Q\}$
(3.4) $\mathbf{A}_{\min} = \mathbf{A}_{\min} \cup (\mathbf{f}_{tx}, \mathbf{f}_{rx})$, $set\_A = set\_A + 1$, $\mathbf{f}_{tx} = 0, \mathbf{f}_{rx} = 0$
(4) for $ka = 1$: set_A
select vectors $(\mathbf{f}'_{tx}, \mathbf{f}'_{rx}) \in \mathbf{A}_{\min}$
s.t $\min_{(\mathbf{f}'_{tx}, \mathbf{f}'_{rx})} \sum_{q \in \{1^0,\ldots,Q^0\} \cup \{1,\ldots,Q\}} \left(\sum_{m=1}^{M} f^q_{tx_m} + \sum_{n=1}^{N} f^q_{rx_n}\right)$
$\mathbf{B}_{\min} = \mathbf{B}_{\min} \cup (\mathbf{f}'_{tx}, \mathbf{f}'_{rx})$, $set\_B = set\_B + 1$
end
(5) for $kb = 1$: set_B
select vectors $(\mathbf{f}''_{tx}, \mathbf{f}''_{rx}) \in \mathbf{B}_{\min}$
s.t $\max_{(\mathbf{f}''_{tx}, \mathbf{f}''_{rx}), \{1^*,\ldots,q^*\}} \text{number}_{q \in \{1^0,\ldots,Q^0\} \cup \{1,\ldots,Q\}} \{\mathbb{G}_k(\mathbf{f}^q_{tx}, \mathbf{f}^q_{rx}) \le \text{MSE}^q\}$
$\mathbf{C}_{\min} = \mathbf{C}_{\min} \cup (\mathbf{f}''_{tx}, \mathbf{f}''_{rx})$, $set\_C = set\_C + 1$
end
(6) for $kc = 1$: set_C
select vector $(\mathbf{f}^*_{tx}, \mathbf{f}^*_{rx}) \in \mathbf{C}_{\min}$
s.t $\min_{(\mathbf{f}^*_{tx}, \mathbf{f}^*_{rx})} \max_{q \in \{1^0,\ldots,Q^0\} \cup \{1,\ldots,Q\} \setminus \{1^*,\ldots,q^*\}} \mathbb{G}_k(\mathbf{f}^q_{tx}, \mathbf{f}^q_{rx})$
end

Algorithm 1: MFMLS subset selection algorithm.

$S_{tx} = S^0_{tx} \setminus f^q_{tx_m}, S_{rx} = S^0_{rx} \setminus f^q_{rx_n}$. At each iteration, either one transmitter or receiver f^{q^*} from the remaining antennas $\{S_{tx}, S_{rx}\}$ is added to the active subset such that the trace of BCRB matrix is closer to the given MSE, until the location MSE is met $\mathbb{G}_k(\mathbf{f}^q_{tx}, \mathbf{f}^q_{rx}) \le \text{MSE}^q$, or tracking antennas use up $S_{tx} + S_{rx} \le (M+N)(1-\eta)$. According to the target priorities, an idea of target classification processing is inspired by GMLS algorithm. And problem (16) can be separated into two steps of optimization. Firstly, allow the radar system to select enough antennas to ensure tracking tasks of suspicious targets $\{1^0, \ldots, Q^0\}$. Then, select from the remaining ones to improve the tracking accuracy for general targets $\{1, \ldots, Q\}$. An idea of a balanced allocation for targets with the same priority is inspired by FMLS algorithm. An accuracy distance is defined as $d_q = \|\mathbb{G}_k(\mathbf{f}^q_{tx}, \mathbf{f}^q_{rx}) - \text{MSE}^q\|$. At each iteration, the target with large accuracy distance is preferred. Restricted by tracking antenna number and other factors, the radar systems may fail to achieve all of the tracking tasks. When the tracking tasks of suspicious targets are done, MFMLS algorithm continues to select the minimal antenna subsets for other tracking tasks. When the active antenna subset is more than one, more targets number and higher location accuracy are considered in turn.

3.2.2. MFMLS_OAT Algorithm for Low Location Estimation MSE. The lower the location estimation MSE, the more the antennas that the system will need. Though MFMLS algorithm can meet the demands of different target priorities, it may fail to reach the lower MSE thresholds. MFMLS_OAT algorithm based on MFMLS algorithm considering the target priority is proposed to improve the antenna utilization and ensure the tracking accuracy for the key targets. Instead of antenna cluster method, MFMLS_OAT algorithm employs every antenna to track all the targets where all the receivers' data are integrated to a fusion center for centralization processing.

(1) initial: $\mathbf{f}_{tx} = 0, \mathbf{f}_{rx} = 0, \mathbf{A}_{\min} = \mathbf{B}_{\min} = \mathbf{C}_{\min} = \varnothing, set\_A = set\_B = set\_C = 0$
(2) for $m = 1, \ldots, M$ and $n = 1, \ldots, N$
(2.1) select initial subset: $\{f_{tx_m}, f_{rx_n}\}$
$S_{tx} = S_{tx}^0 \setminus f_{tx_m}, S_{rx} = S_{rx}^0 \setminus f_{rx_n}$
$f_{tx_m} = 1, f_{rx_n} = 1$
(2.2) while $\exists q \in \{1^0, \ldots, Q^0\}$, s.t $\mathbb{G}_k^q(\mathbf{f}_{tx}, \mathbf{f}_{rx}) > \text{MSE}^q$ and $S_{tx} + S_{rx} > (M+N)(1-\eta)$
select $q^* = \arg \max_{q^* \in \{1,\ldots,Q^0\}} \|\mathbb{G}_k^{q^*}(\mathbf{f}_{tx}, \mathbf{f}_{rx}) - \text{MSE}^{q^*}\|$
select $f_0 = \arg \min_{f_0 \in \{S_{tx}, S_{rx}\}} \|\mathbb{G}_k^{q^*}(\mathbf{f}_{tx}, \mathbf{f}_{rx}, f_0) - \text{MSE}^{q^*}\|$
$\{S_{tx}, S_{rx}\} \setminus f_0, f_0 = 1$
end
(2.3) while $\exists q \in \{1, \ldots, Q\}$, s.t $\mathbb{G}_k^q(\mathbf{f}_{tx}, \mathbf{f}_{rx}) > \text{MSE}^q$ and $S_{tx} + S_{rx} > (M+N)(1-\eta)$
select $q^* = \arg \max_{q^* \in \{1,\ldots,Q\}} \|\mathbb{G}_k^{q^*}(\mathbf{f}_{tx}, \mathbf{f}_{rx}) - \text{MSE}^{q^*}\|$
select $f_0 = \arg \min_{f_0 \in \{S_{tx}, S_{rx}\}} \|\mathbb{G}_k^{q^*}(\mathbf{f}_{tx}, \mathbf{f}_{rx}, f_0) - \text{MSE}^{q^*}\|$
$\{S_{tx}, S_{rx}\} \setminus f_0, f_0 = 1$
end
$\mathbf{A}_{\min} = \mathbf{A}_{\min} \cup (\mathbf{f}_{tx}, \mathbf{f}_{rx}), set\_A = set\_A + 1, \mathbf{f}_{tx} = 0, \mathbf{f}_{rx} = 0$
end
(3) for $ka = 1$: set_A
select vectors $(\mathbf{f}'_{tx}, \mathbf{f}'_{rx}) \in \mathbf{A}_{\min}$
s.t $\min_{(\mathbf{f}'_{tx}, \mathbf{f}'_{rx})} \sum_{m=1}^{M} f_{tx_m} + \sum_{n=1}^{N} f_{rx_n}$
$\mathbf{B}_{\min} = \mathbf{B}_{\min} \cup (\mathbf{f}'_{tx}, \mathbf{f}'_{rx}), set\_B = set\_B + 1$
end
(4) for $kb = 1$: set_B
select vectors $(\mathbf{f}''_{tx}, \mathbf{f}''_{rx}) \in \mathbf{B}_{\min}$
s.t $\max_{(\mathbf{f}''_{tx}, \mathbf{f}''_{rx}), \{1^*, \ldots, q^*\}} \text{number}_{q \in \{1^0, \ldots, Q^0\} \cup \{1, \ldots, Q\}} \{\mathbb{G}_k^q(\mathbf{f}_{tx}, \mathbf{f}_{rx}) \le \text{MSE}^q\}$
$\mathbf{C}_{\min} = \mathbf{C}_{\min} \cup (\mathbf{f}''_{tx}, \mathbf{f}''_{rx}), set\_C = set\_C + 1$
end
(5) for $kc = 1$: set_C
select vector $(\mathbf{f}^*_{tx}, \mathbf{f}^*_{rx}) \in \mathbf{C}_{\min}$
s.t $\min_{(\mathbf{f}^*_{tx}, \mathbf{f}^*_{rx})} \max_{q \in \{1^0, \ldots, Q^0\} \cup \{1, \ldots, Q\} \setminus \{1^*, \ldots, q^*\}} \mathbb{G}_k^q(\mathbf{f}_{tx}, \mathbf{f}_{rx})$
end

Algorithm 2: MFMLS_OAT subset selection algorithm.

Assume there are suspicious targets $\{1, \ldots, Q\}$ and hot targets $\{1^0, \ldots, Q^0\}$ with low MSE thresholds, and the latter are considered as the key targets in this section where one antenna can be utilized multiple times to track multiple targets. Antenna selection vectors $\mathbf{f}_{tx} = [f_{tx_1} \ f_{tx_2} \ \cdots \ f_{tx_M}]^T$ and $\mathbf{f}_{rx} = [f_{rx_1} \ f_{rx_2} \ \cdots \ f_{rx_N}]^T$ are introduced in this section. And problem (15) can be rewritten as

$$\begin{aligned}
\min_{\mathbf{f}_{tx}, \mathbf{f}_{rx}} \quad & \sum_{m=1}^{M} f_{tx_m} + \sum_{n=1}^{N} f_{rx_n} \\
\text{s. t.} \quad & \mathbb{G}_k^q(\mathbf{f}_{tx}, \mathbf{f}_{rx}) \le \text{MSE}^q \\
& q \in \left\{1^0, \ldots, Q^0\right\} \cup \{1, \ldots, Q\} \\
& \sum_{m=1}^{M} f_{tx_m} + \sum_{n=1}^{N} f_{rx_n} \le (M+N)\eta \\
& \sum_{m=1}^{M} f_{tx_m} \ge 1, \quad f_{tx_m} \in \{0,1\} \\
& \sum_{n=1}^{N} f_{rx_n} \ge 1, \quad f_{rx_n} \in \{0,1\},
\end{aligned} \tag{17}$$

where $\mathbb{N}_k(\mathbf{f}_{tx}, \mathbf{f}_{rx}) = \sum_{m=1}^{M} f_{tx_m} + \sum_{n=1}^{N} f_{rx_n}$ denotes the optimal antenna subset size.

In Algorithm 2, the proposed MFMLS_OAT algorithm is presented to improve the resource utilization for problem (17). Similar to MFMLS algorithm, the MFMLS_OAT algorithm allows the radar system to ensure the demands of hot targets firstly and then improve the tracking accuracy for suspicious targets with the remaining resources. For the targets with same priority, they are equally treated. At each iteration, one antenna is selected to improve the location accuracy for the target with large accuracy distance. Eventually, an optimal

Table 1: Comparison of computational complexity of different algorithms.

Algorithm	Computational complexity
GMLS	$O(QMN(M+N)L)$
FMLS	$O\left(Q(MN)^Q(M+N)L\right)$
MFMLS	$O\left(Q(MN)^Q(M+N)L\right)$
MFMLS_OAT	$O(QMN(M+N)L)$

antenna subset with the minimal antenna number and the highest location accuracy, $\{\mathbf{f}_{tx}^*, \mathbf{f}_{rx}^*\}$ is obtained.

3.3. Computational Complexity Analysis. To further evaluate the algorithm performance, computational complexity needs to be considered. Assume that each target needs the equal antenna number for the corresponding MSE threshold. Computational complexity of GMLS algorithm is $O(QMN(M+N)L)$, where L is the average antenna number for one target tracking. FMLS algorithm can offer a more balanced antenna allocation where the initial antenna subset is $(MN)^Q$ possibly whose complexity is added to $O(Q(MN)^Q(M+N)L)$. The balanced allocation is also employed to MFMLS algorithm whose complexity is $O(Q(MN)^Q(M+N)L)$, approximately same as FMLS. MFMLS_OAT algorithm is proposed with complexity scale $O(QMN(M+N)L)$ where the total antenna QL is assumed to simplify representation. The computational complexity of different algorithms is summarized in Table 1.

4. Simulation Results

Consider a MIMO radar system with $M = 8$ and $N = 8$. All the antenna are widely distributed as a circle formation in a 20 km × 20 km area, as depicted in Figure 1. Wire communication is employed for more stable data transmission and less time delay between the center and the receivers. Assume that the period of communication is acceptable for practical application. There are three targets moving at a speed of 100 m/s. Radar systems transmit orthogonal signals. The carrier frequency is set to 300 MHz. The pulse repetition frequency is set to 5300 Hz. The radar systems are working with maximum transmitted power 1 kw and effective illumination time 10 μs. To avoid the impact of target scattering coefficients on performance analysis, assume that all the targets are uniform complete reflectivity. The RCS models are modeled as uniform reflectivity $[1,\ldots,1;\ldots;\ 1,\ldots,1]$ for each target. The noisy variance is $1e^{-23}$. In this paper, the lowest SNR is about 25 dB where the target location estimation MSE is tightly close to the BCRB. Allowed antenna utilization for targets tracking is $\eta = 0.75$, which means there are mostly 12 antennas utilized at one measurement. Total 16-frame data is used in the simulation; the observation interval is $\Delta t = 5$ s. Performance is evaluated from the average of 500 values. Two different tracking scenarios are set for the simulation.

4.1. Resource Allocation for High Location Estimation MSE. To validate the effectiveness of the proposed MFMLS algorithm, comparisons with GMLS and FMLS algorithm are performed. The target location accuracy is assumed in Table 2

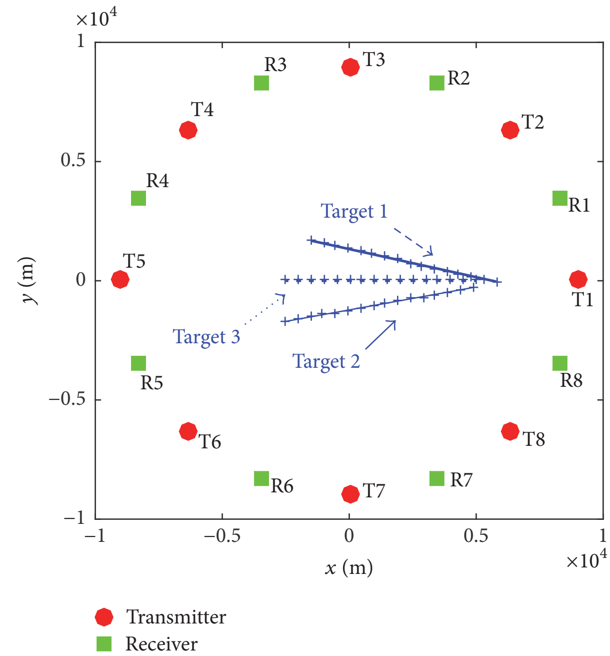


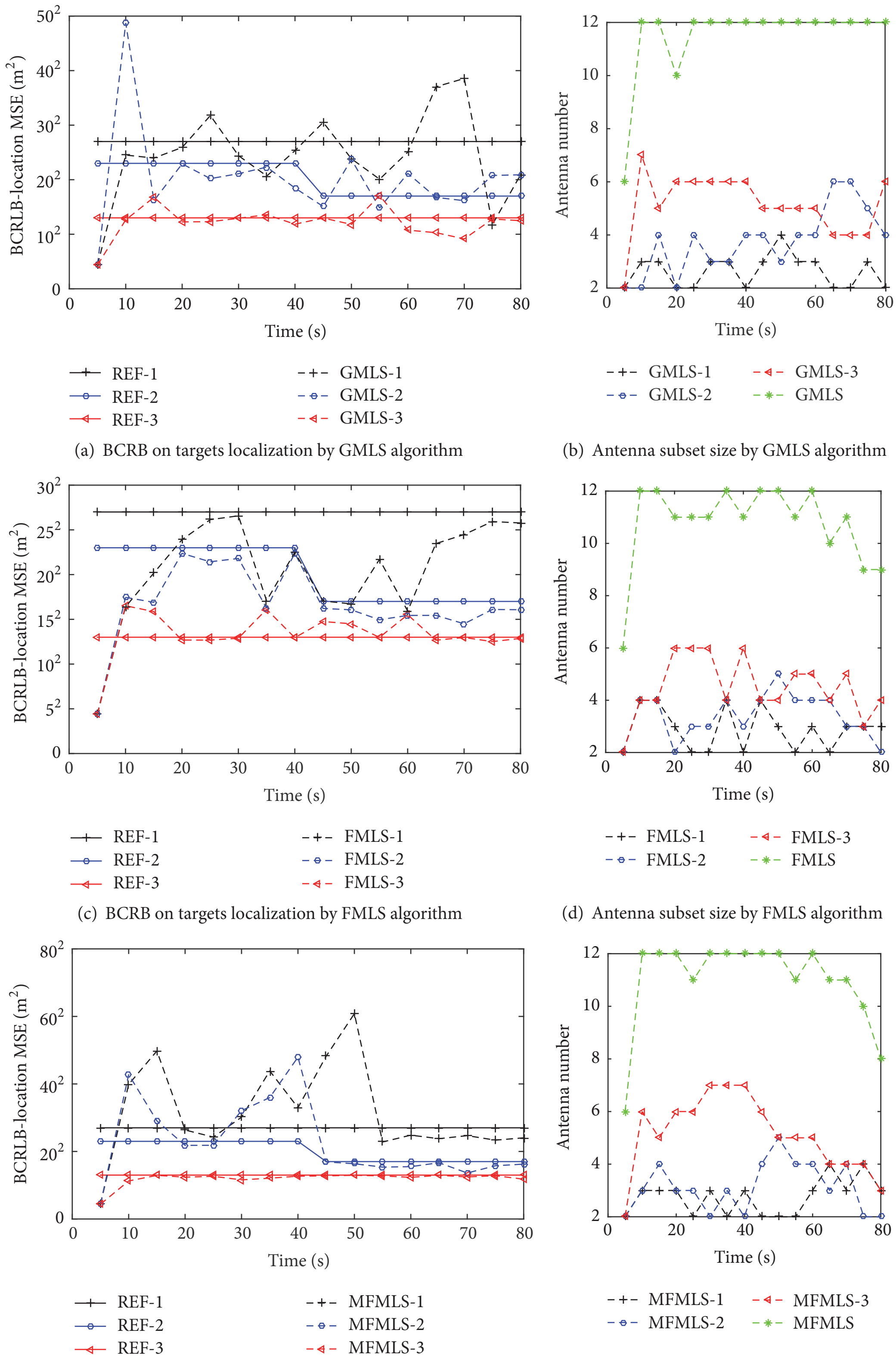
Figure 1: MIMO radar layout with moving targets.

Table 2: High MSE thresholds for multiple targets localization.

Target	MSE requirement 1 s~40 s (m^2)	MSE requirement 41 s~80 s (m^2)
Target 1	27^2	27^2
Target 2	23^2	17^2
Target 3	13^2	13^2

where targets can be divided into two types: general and suspicious targets. A lower MSE threshold is required for suspicious targets. The effective bandwidth of transmitters is assumed to be 0.8 MHz.

The location accuracy and antenna number performed by GMLS, FMLS, and MFMLS algorithm for multiple targets tracking are, respectively, presented in Figure 2. In Figures 2(a) and 2(b), the simulation with one time is analyzed for the randomness of target sequence where there is no well tracked target. In Figures 2(a) and 2(c), results show that existing GMLS and FMLS algorithm can fail to consider the demands for suspicious targets. In Figure 2(e), the performance of MFMLS algorithm is shown: the suspicious target is preferred; and targets with the same priority have the approximate location accuracy, which is low for target 1 and target 2 in the first 40 s and high for target 2 and target 3 in the second 40 s. Therefore, the proposed MFMLS algorithm can achieve the demands of different priorities better than existing GMLS and FMLS algorithm proposed in [18], though no algorithm can completely meet the accuracy demands for all targets. In Figures 2(b), 2(d), and 2(f), from the comparison of antenna number for different targets, it can be seen that target 3 with lowest MSE threshold is allocated the most antennas. On the whole, FMLS and MFMLS algorithm use



(a) BCRB on targets localization by GMLS algorithm

(b) Antenna subset size by GMLS algorithm

(c) BCRB on targets localization by FMLS algorithm

(d) Antenna subset size by FMLS algorithm

(e) BCRB on targets localization by MFMLS algorithm

(f) Antenna subset size by MFMLS algorithm

Figure 2: BCRB on targets localization and antenna subsets by different algorithms with high MSE thresholds.

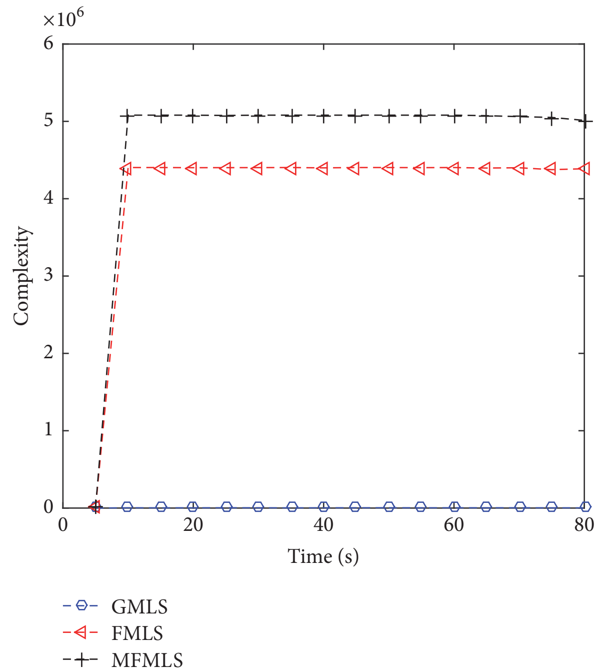


Figure 3: Computational complexity by different algorithms with high MSE thresholds.

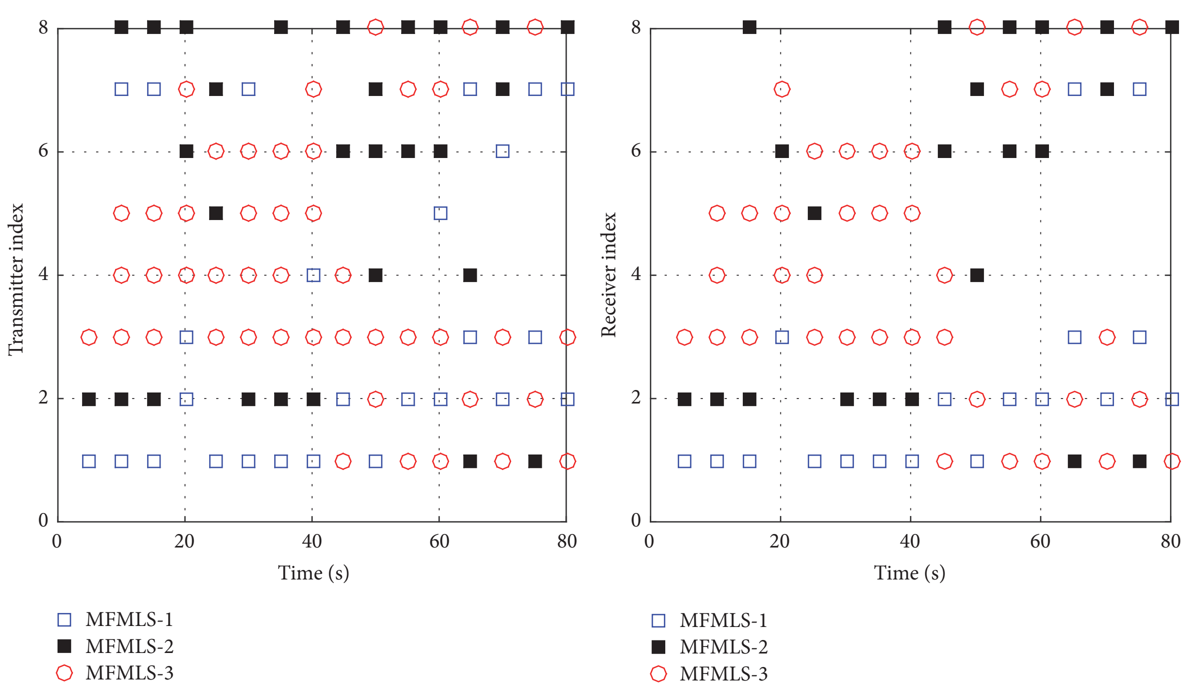
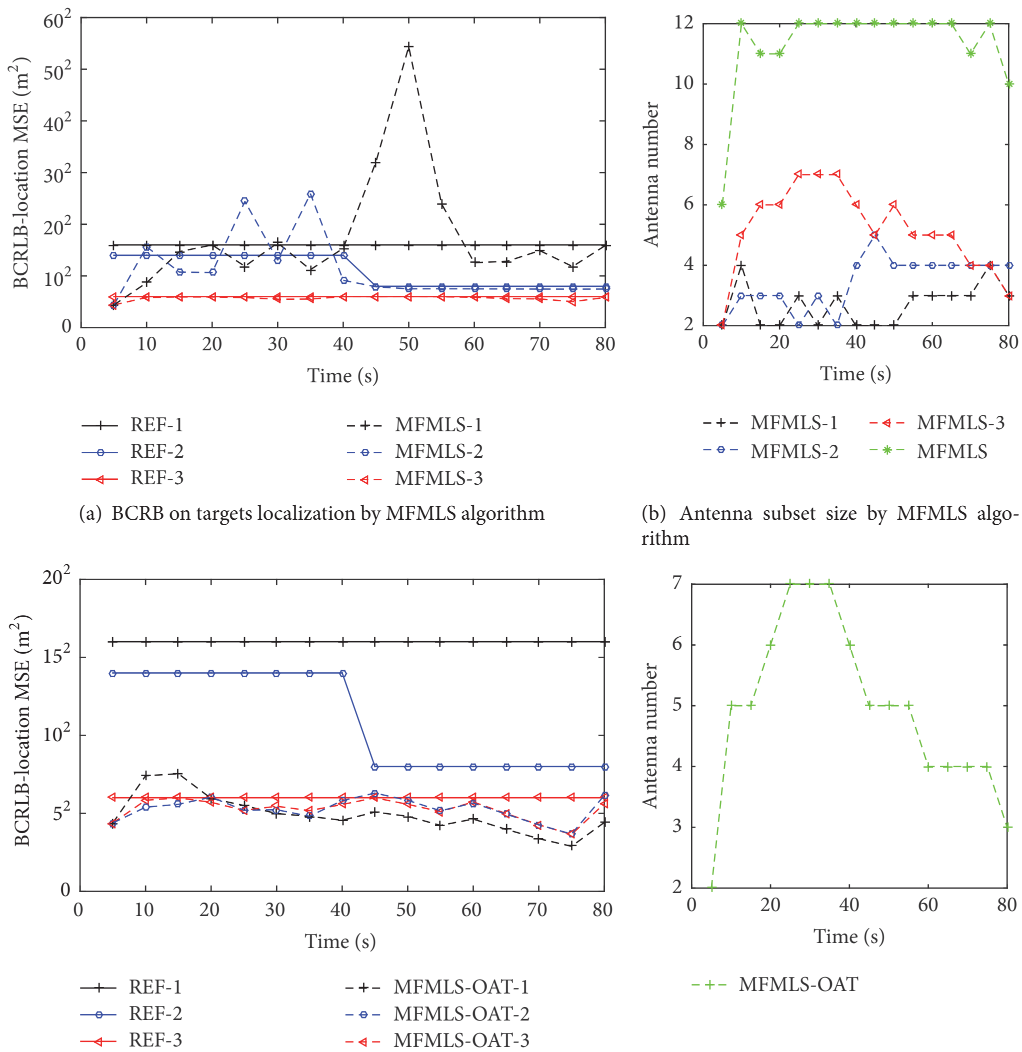


Figure 4: Optimal antenna selection result by MFMLS algorithm.

the relative few antennas, due to the exhaustive search for the best initial subset pairs.

Computational complexity is analyzed in Figure 3 where FMLS and MFMLS algorithm with exhaustive search for initial subset need higher computational complexity, though GMLS algorithm is much lower. When targets are in different priorities, MFMLS algorithm performs better selection performance for the implement of system tasks than others proposed in [18], which can contribute to practical application. Therefore, an optimal antenna selection result by MFMLS algorithm is presented in Figure 4 where the antenna number for each target is consistent with Figure 2(f).



(a) BCRB on targets localization by MFMLS algorithm

(b) Antenna subset size by MFMLS algorithm

(c) BCRB on targets localization by MFMLS_OAT algorithm

(d) Antenna subset size by MFMLS_OAT algorithm

Figure 5: BCRB on targets localization and antenna subsets by different algorithms with low MSE thresholds.

Table 3: Low MSE thresholds for multiple targets localization.

Target	MSE requirement 1 s~40 s (m^2)	MSE requirement 41 s~80 s (m^2)
Target 1	16^2	16^2
Target 2	14^2	8^2
Target 3	6^2	6^2

4.2. Resource Allocation for Low Location Estimation MSE. In order to further evaluate the performance of the MFMLS_OAT algorithm, the location tracking accuracy for three targets is set in Table 3 where all the targets are divided into suspicious targets and hot targets. With lower MSE thresholds, more antennas will be needed, where the transmit bandwidth is increased to 1.8 MHz.

Considering that every antenna can be used to track all the targets by MFMLS_OAT algorithm, which can obtain higher localization performance, location estimation accuracy and tracking antenna number performed by MFMLS and MFMLS_OAT algorithm are, respectively, presented in Figure 5. Computation complexity is presented in Figure 6. As we can see, with low location estimation MSE, the proposed MFMLS_OAT algorithm can outperform the MFMLS algorithm with fewer tracking antennas and less computation complexity.

Though the MFMLS_OAT algorithm outperforms MFMLS algorithm on computational complexity and antenna utilization compared with MFMLS algorithm, there is still a difficulty in the signal back-end processing for practical engineering application where it is not easy for receivers to divide the signals from three targets. Therefore, when the MFMLS algorithm can fail to meet the demands for higher location accuracy, the MFMLS_OAT algorithm will

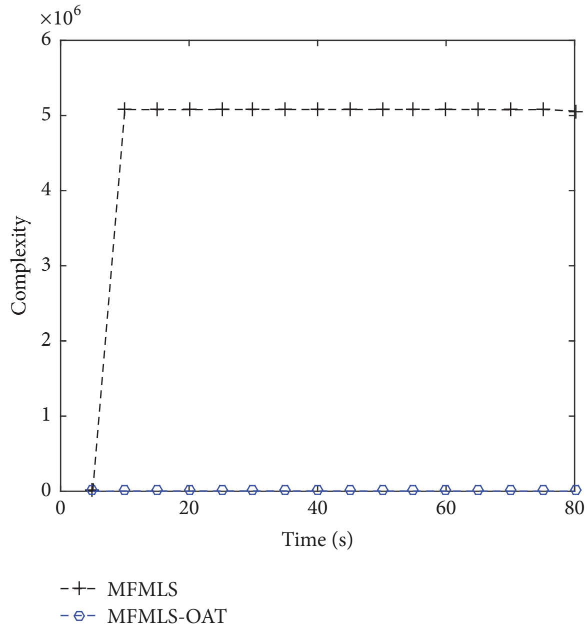


FIGURE 6: Computational complexity by different algorithms with low MSE thresholds.

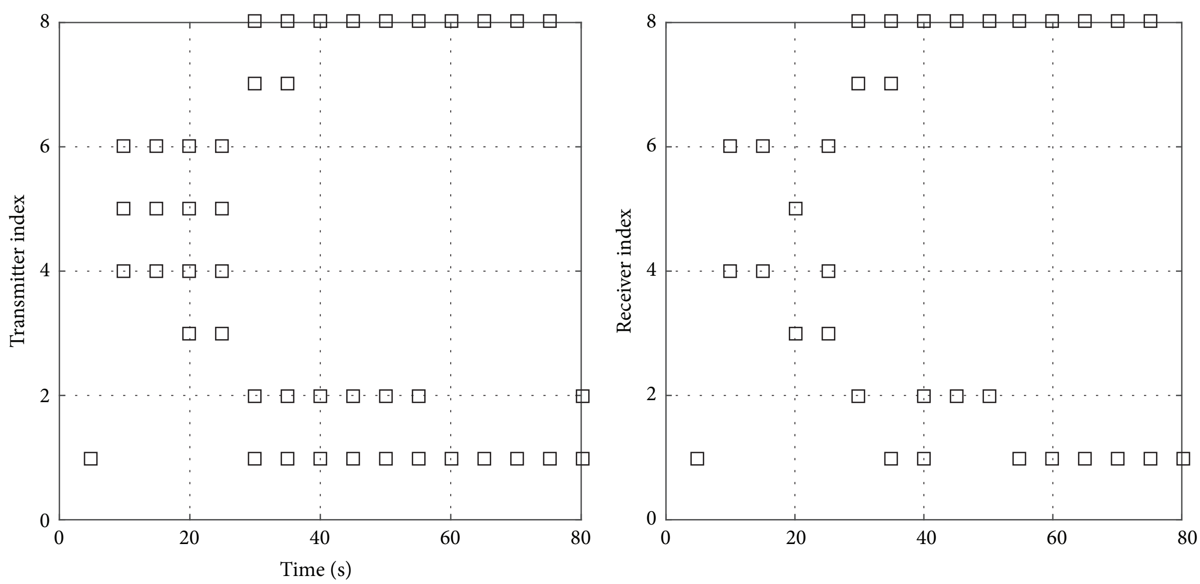


FIGURE 7: Optimal antenna selection results by MFMLS_OAT algorithm.

be the best choice. An optimal antenna selection result by MFMLS_OAT algorithm is presented in Figure 7.

5. Conclusions

In order to strengthen the practicability of the resource allocation schemes in distributed MIMO radar system, antenna selection schemes for multiple targets tracking with different location estimation MSE and targets priorities are proposed in this paper. The MFMLS algorithm and MFMLS_OAT algorithm are presented and employed to describe the antenna selection process in detail. With high location estimation MSE, the proposed MFMLS algorithm can meet the localization demands of different target priorities better than GMLS and FMLS algorithm proposed in [18]. Restricted by tracking antenna utilization, the MFMLS_OAT algorithm with fewer antenna numbers and lower computational complexity can achieve lower location estimation MSE and ensure the demands of multiple system tasks. In fact, location accuracy is related not only to antenna selection, but also to the parameter allocation on transmit power, effective bandwidth, and illumination time. A joint resource allocation algorithm for multiple targets tracking will be further explored in later research work.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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