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RESEARCH ARTICLE

Parameter Estimation of Communication Radar Fusion System Based on Orthogonal Frequency Division Multiplexing Technology

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ABSTRACT The development of communication and radar fusion systems is critical to enhancing sensor network security. However, in spectrum resource environments, the technology for processing fusion signals may face limitations due to multi-user access and interference issues. Traditional signal processing algorithms may also be influenced by waveform information. As a result, its implementation is limited in low-noise-ratio settings. Based on the advantages of multiple-input multiple-output technology in the field of communication and radar, in order to better ensure the non-interference between the communication and radar systems, the study introduces the orthogonal theory. It proposes a target detection and parameter estimation method based on orthogonal frequency division multiplexing (OFDM) technology in the signal modulation domain. It utilizes sparse tensor theory to obtain low rank features of signals, transform the dimensions of target parameter problems, and solve tensor rank 1 approximation problems. This can better improve the performance of target parameter estimation. The simulation analysis of the proposed method shows that the average error values of the improved decomposition method in Doppler frequency shift estimation and angle estimation are close to 10-2 and 10-1 respectively. The system runs for less than 5 seconds, and its average target detection accuracy exceeds 96%. The proposed orthogonal frequency division multiplexing technique can provide technical support for sensor networks in wireless communication and IOT networks, efficiently reducing computational complexity and interference among users. This can serve as a valuable reference for enhancing the security of communication radar fusion systems.

INDEX TERMS Orthogonal frequency division multiplexing technology, parameter estimation, sparse tensor theory, greedy CP decomposition, target scenario.

I. INTRODUCTION

As the boost of mobile communication and radar technology, communication radar fusion systems have attracted widespread attention in the fields of wireless communication and radar. It can provide more efficient, reliable, and flexible wireless communication services, while achieving functions such as object detection, tracking, and recognition. However, due to the limited signal resources and spectral efficiency requirements, achieving an efficient communication radar fusion system remains a challenge [1]. At present, the mainstream methods for communication radar fusion systems include time division multiplexing, frequency division multiplexing, and code division multiplexing. The time division multiplexing method can reduce the spectrum utilization of the radar system and is susceptible to multipath effects when the channel variance is high [2]. The frequency division multiplexing method requires precise frequency synchronization and channel estimation, which requires the complexity and real-time performance of the

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system. However, the code division multiplexing method also has limitations in terms of real-time performance and power efficiency [3]. To overcome the above challenges, orthogonal frequency division multiplexing (OFDM) technology has been proposed and applied to communication radar fusion systems. This technology utilizes different orthogonal sub-carriers to separate communication and radar signals, which can improve the efficiency of signal resource utilization. OFDM, as an efficient multi carrier modulation technology, has broadband characteristics and the ability to resist multi-path fading, and is widely used in wireless communication systems [4].Due to mutual interference between the communication system and radar radiation signal, it is necessary to use adaptive filtering and other methods to remove interference. This ensures optimal performance, stability, and effectiveness in the fusion process of the two signals. Additionally, the advantages and disadvantages of the communication signal's waveform and signal processing at the receiving end should be taken into account. Previous research on radar system design has faced limitations due to the power of communication signals. This is because radar experiences two-way fading field points during the detection process, and the receiver requires high-level processing in low signal-to-noise ratio (SNR) environments. For instance, Super-resolution algorithms such as periodograms and Estination of Signal Parameter via Rotational Invariance Techniaques (ESPIRT) for directional estimation suffer from spectral leakage and cannot be applied in multi-target and high SNR environments [5]. Therefore, careful consideration is necessary for effective design and implementation of radar systems. The application effect is good in multi-target and high SNR. To ensure proper integration between communication and radar systems and prevent signal interference, the implementation of orthogonal design is recommended. Therefore, the study proposes a communication and radar fusion system based on OFDM technology, which utilizes modulation symbol domain orthogonality to enhance technical performance and achieve parameter estimation. A certain solution for the development of the communication and radar fusion system application is also presented. The research idea is to introduce sparse tensor theory into the basic principles and structural analysis of communication radar fusion systems on the ground of the characteristics of OFDM technology in the fields of communication and radar. And it is optimized and improved in signal conversion, parameter estimation, target localization, and other aspects to better improve its target parameter detection performance. The development of information technology often features high-dimensional data. When synthesizing communication radar time-domain signals, OFDM technology will inevitably face fading in the multi-path channel and orthogonality problems between sub-carriers. Therefore, signal reconstruction is necessary. Communication radar in the transmission path experiences limitations in target identification resulting from signal fading, time delays, and equipment inaccuracies. Signal parameter estimation involves determining the frequency, time of arrival, pulse width, and amplitude. Tensor decomposition and complementation are vital in addressing the issue of high-dimensional signal reconstruction, enabling better estimation of target distance and speed. Through exploiting the structural features of tensor data, tensor decomposition ensures an effective representation of multiple dimensions of the data. Additionally, tensor complementation can handle the processing of incomplete tensors. Tensor decomposition and complementation provide higher flexibility and adaptability for parameter estimation, extracting more information from multidimensional data. The tensor's high-dimensional structure diversifies its decomposition model. The traditional higher-order tensor estimation problem is solved by transforming it with vectorization. However, the accuracy of the coefficient tensor's estimation is compromised by the vectorization operation, ultimately rendering it incapable of capturing the linear dependence within the response tensor. Therefore, the decomposition and complementation of the tensor problem show better analytical ability, enhancing parameter estimation accuracy by decreasing computational complexity while maintaining high-dimensional features. Improving parameter estimation can effectively enhance the performance and stability of communication radar system technology, enabling it to better adapt to complex working scenarios and equipment tasks, minimize internal interference, and reduce overall resource usage.

Unlike the traditional signal processing methods for fusion systems, which are based on vector or matrix modelling and the estimation of target parameters in dimensional order, the research is innovative in introducing the orthogonal frequency division multiplexing technique acutely in the analysis of communication radar fusion signals. The innovation of the study is to introduce the orthogonal frequency division multiplexing (OFDM) technique with multiple inputs and multiple outputs for the analysis of fused signals in communication radar, and to achieve the target parameter estimation in the fusion system from the tensor completion and decomposition, which reduces the waste of spectrum resources while taking the accuracy of the target parameter estimation into consideration. The traditional signal processing method of fusion system is easier to destroy the internal multi-dimensional structural characteristics of the signal, which leads to the loss of part of the information, and the additional parameter pairing problem also leads to the emergence of false targets. This study investigates the parameter estimation problem of communication radar fusion systems from four aspects. The first part is a literature review of the current research ideas and content of communication radar fusion systems. The second part is on the ground of OFDM technology to study from two aspects: tensor decomposition and completion. The third part analyzes the simulation results of the fusion system. The fourth part is a summary of the entire article and prospects for the future.

II. RELATED WORKS

The deployment of distributed networks plays an important role in improving the detection and parameter estimation capabilities of radar systems. Chalise BK scholars are considering deep learning improvements to networks without central coordinators, by introducing short-term and short-term memory networks to achieve compensation between different nodes. The results show that this method can effectively achieve parameter estimation and improve the robustness and synchronization problem of the algorithm. Sun Z scholars design detection methods in coherent radar systems that do not require searching for motion parameters, using trapezoidal transformations and function variation designs to estimate target maneuvering. The results show that the estimation method has good detection and estimation ability, and it can effectively avoid the influence of limited vision velocity sidelobes, with good effectiveness [6]. In radar network scenarios, both radar waveforms and broadcast signals can be sensed. Therefore, Temiz M scholars proposed a dual base underground boundary radar network target positioning algorithm, which ensures positioning accuracy through modeling and bistatic distance calculation. The results indicate that this method has good 3D positioning accuracy [7].Wu L scholar studied the resource allocation problem of distributed systems composed of heterogeneous radars and multi-layer communication, with a focus on resource allocation in multi target tracking (MTT) environments. Improving multi target tracking performance by allocating available power, dwell time, and shared bandwidth, and designing alternating optimization to monotonically improve Bayesian Cram é r Rao bounds to solve non convex problems. The results indicate that this method can significantly reduce tracking errors and exhibit good stability in different target scenarios and radar communication network distributions [8]. Regarding the sensitivity issue of OFDM signals, Liu G and other scholars proposed a new joint radar communication system on the ground of filter bank multi carrier and Doppler compensation algorithm under this waveform. This waveform can effectively combat multipath effects, improve spectral efficiency, and reduce phase errors through iterative supplementation. The results indicate that this method exhibits good effectiveness and robustness in imaging and communication [9]. Yang Y scholar utilized data level fusion for anti-interference target tracking algorithms in distributed radar networks, and improved performance with the help of consistent covariance intersection and unscented Kalman filters. On the ground of the differences in false target collaboration methods, two recognition schemes were designed on the ground of the nearest neighbor algorithm and consensus algorithm. The results indicate that this algorithm can effectively achieve physical target tracking and has good accuracy [10]. Cenkeramaddi L R scholar combines machine learning estimation with field of view enhancement technology to improve radar field of view performance. The results indicate that the root mean square error achieved by this angle estimation technique is less than three degrees, and it has good value in autonomous system applications [11]. To improve the signal recognition performance of radar and communication systems, Song X scholars have designed an adaptive OFDM technology that considers waveforms, ensuring system performance through two aspects: determining information categories and formulating optimization functions. The results indicate that this joint scheme exhibits high feasibility and effectiveness in waveform signal recognition and channel allocation [12]. Liu X scholar designed a new preamble to replace the original preamble in OFDM technology, and calculated the radar ambiguity function to improve its quality. And the application of point by point minimum processing can also improve the quality of communication frame sensing. Theoretical and simulation results indicate that this method improves the peak to maximum sidelobe ratio of the radar, and its fusion technology also improves the Doppler resolution of the joint radar access system [13].

In the context of communication radar processing structures, to avoid the problem of signal interference cancellation caused by traditional joint performance, Li C scholars propose a joint system that can receive and decode communication signals. By designing a form that can estimate target direction, distance, and speed, the signal scheme and its joint upper bound are derived. The results indicate that this method can effectively improve radar performance by utilizing target reflection signals [14]. The combination of communication and sensing systems can provide better spectral efficiency for 6G machine communication, but there is a problem of mutual interference between sensing signals. On the ground of this, Chen X proposed a code division multiple access OFDM system to connect communication sensors, which can achieve compatible code division multiple access gains and a new channel model. The experimental results show that this method can ensure the stability of radar sensing and performs well in low SNR situations [15]. Sakhnini A scholar proposed using OFDM waveforms to solve the radar perception problem of antennas. This shows that large arrays in multi input multi output communication can achieve precise positioning better, and they are to some extent less affected by narrow bandwidth conditions. The experimental results show that when the resolution increases by an order of magnitude, the radar and communication system under this design method can achieve better time division differentiation, with a capacity loss of less than 3%. The detection results of near-field radar can be well applied in low carrier frequency multi-input multi-output waveform (MIMO) systems [16].Knight C scholar introduced OFDM technology into MIMO design to achieve signal encoding and processing. This MIMO OFDM waveform can achieve broadband transmission of transmitting and receiving antennas under spatial environment perception, and its coding strategy has good radar signal recognition performance [17]. Scholar Liu Y proposed a dual function radar and communication system that considers orthogonality in a passive background, and improved it from two aspects:

constellation points and extended regions using a waveform design method with high applicability and low peak to average ratio. This is to make the system independent of channel state information. The results indicate that this method exhibits good comprehensive radar detection performance in communication verification [18]. Faced with the problem of dual function radar and communication optimization, Temiz M scholars designed a pre-encoder scheme using the downlink while considering the system's target rate and energy efficiency. This method is an optimization of multi input multi output OFDM technology. The results indicate that it can meet the data rate of each user and provide a new solution design for radar interference problems under OFDM technology [19]. In response to the interference management problem of waveform radar sensors used for speed and distance estimation in autonomous driving assistance systems, Basireddy A scholars use OFDM wave form to overcome ghost detection. It utilizes the maximum length sequence to achieve the orthogonality of the transmitted waveform. The simulation results show that this algorithm enables the scrambling sequence to effectively exert anti-interference performance, and performs better than other algorithms [20].

For the multiplexing technology in optical network and link design problems, many scholars have carried out research to better improve the signal transmission performance and the application of the system. Among them, J Wang scholars and P Wang scholars proposed inter-carrier interference parameter estimation to solve the OFDM radar distance-velocity estimation performance degradation in high manoeuvrability scenarios. This is feasible through the scale transformations and transformations of radar signals. The results show that this method can effectively improve the accuracy performance of orthogonal multiplexing technology radar system and show better robustness [21]. And Yousif B B scholars and Elsayed E E scholars combined RF with free space optical communication, leading to the proposal of an orthogonal amplitude modulation technique utilizing spatial mode multiplexing. To mitigate weak and strong turbulence distortion, a communication scheme is designed using a source Gaussian model. The simulation results show that when the propagation distance is greater than a specific threshold, the proposed improvement idea of the study has a better system capacity, exhibits a lower power loss scenario. Additionally, the proposed idea effectively enhances the system's robustness under angular error, serving as a reference for the design of a multiplexed RF link structure and the achievement of turbulence-resistant outcomes [22]. Aiming at the beam contradiction problem of radar communication system, Zhou et al proposed a bifunctional radar-communication system based on cyclic code arrays, which transforms the multidimensional orthogonal signal design problem into the base signal design problem by array processing and modulation of orthogonal frequency division multiplexed signals, resulting in significant improvements to the safe transmission and coverage of the signals [23]. To mitigate the effect of atmospheric cutoff, Yousif B B scholar and Elsayed E E scholar designed a multiplexed adaptive spatial optical link based on the spatial pattern of turbulent channel. The simulation results show that this design idea performs better for link transmission of signals, reducing power loss and SNR, and maintaining a low bit error rate [24]. Elsayed E E scholar and Kakati D scholar analyze the optimization of spatial multiplexing transmission technology in optical networks utilizing an improved digital pulse modulation scheme. The results indicate that the proposed improvement effectively reduces noise error and improves transmission performance under atmospheric turbulence. The power loss difference between the proposed and comparative algorithms is 0.2-3db [25]. Elsayed E E scholars and Yousif B B scholars proposed a spatial modulation idea for free-space optical communication systems with multiple-input-multiple-output links, combining a spatial exponential modulator with an improved pulse-position modulation scheme to compensate for performance degradation due to geometrical loss and atmospheric attenuation. The results show that the proposed design scheme exhibits excellent optical SNR and high sensitivity, and its improvement of SNR is more obvious in the turbulence-free case, which can better realise the hybrid spatial diversity of the link under atmospheric effects [26]. For free space optical fibre communication wavelength division multiplexing (WDM) technique for passive optical networks, Elsayed E E scholars and Yousif B B scholars have designed the digital pulse modulation scheme utilizing an enhanced moments function and modified Chernoff bounds. The results show that the modulation scheme exhibits high sensitivity and significant BER reduction performance under high gain network bandwidth conditions. Additionally, the improved scheme effectively improves the optical SNR of the link under strong turbulence, which is effective in application [27].

In summary, this study proposes a new improvement idea for the communication radar system using OFDM technology. It also introduces the tensor decomposition and complementation method for designing the system, taking into account the dimensional characteristics of the communication signal. For the purpose of enhancingthe performance of a communication radar system, Liu G and colleagues designed the Doppler compensation algorithm under waveform, and Yang Y and colleagues designed the anti-jamming target tracking algorithm with the aid of data fusion. These algorithms are crucial in signal filtering and frequency efficiency improvement, resembling the investigation of signal characteristic improvement. Chalise B K scholars introduced the long and short-term memory network to compensate for the nodes of the radar system, which to a certain extent can improve the detection ability of the system. However, it may encounter the issue of parameter changes.The research based on the system signal itself to improve the communication system is relevant to grasp and improve, and can effectively take into account the different parameters and signal dimensional structural characteristics of the change. The research based on the system signal itself to improve to grasp and improve the communication system is targeted, Knill C scholars will OFDM technology and waveform design, Temiz M scholars consider from the perspective of the target rate encoder design to achieve the optimization of the multiplexing technology, the above improvement ideas are mostly about the signal waveforms, sensors and other equipment, less involved in the parameter estimation problem. The above improvement ideas are mostly about signal waveforms, sensors and other devices, and less about parameter estimation. They do not take into account the signal changes of the communication system in different target scenarios, so they have certain limitations. The communication system improvement proposal presented in this study effectively satisfies the requirement for spectrum resources and signal characteristics while considering variations in the degree of freedom of parameters. The approach involves solving the problem from the perspective of functionalization tensor and appropriately configuring the encounter based on the SNR of the received signal, which significantly minimizes algorithmic computations and boosts overall performance. Moreover, the suggestion put forth offers valuable insights for ameliorating target detection accuracy of the communication radar system to some extent. This can also provide a reference idea for the improvement of target detection accuracy of communication radar system to some extent.

III. DESIGN OF PARAMETER ESTIMATION FOR COMMUNICATION RADAR SYSTEM BASED ON OFDM TECHNOLOGY

The communication radar system can provide a wider communication coverage range and higher communication capacity, while also possessing the ability to perceive obstacles and targets. It has been applied in fields such as intelligent transportation, military operations, and logistics management. However, communication radar systems often exhibit limitations in communication signal power and low SNR signal processing during the design process. To ensure the accuracy of parameter estimation in communication radar systems, this study designs estimation algorithms on the ground of OFDM technology from two aspects, and estimates target parameters from tensor decomposition and tensor completion. The optimization problem is solved by considering the characteristics of target scenarios and signal nodes.

A. ESTIMATION OF COMMUNICATION RADAR TARGET PARAMETERS BASED ON TENSOR DECOMPOSITION REPRESENTATION

OFDM technology is a multi carrier modulation technology. It transmits data by dividing the signal into several narrow sub-carriers, and the spectra of each sub-carrier are orthogonal to each other, making the transmission process more stable. Due to the characteristics of anti multi-path propagation and spectrum equalization, OFDM technology can reduce the complexity of communication channels. OFDM technology is different from the range Doppler coupling of traditional radar waveforms, as its range and Doppler are independent of each other. OFDM technology can achieve low-speed transmission of high-speed data streams and modulate them using different orthogonal subcarriers, thereby avoiding the problems of spectrum overlap and mutual interference. The core of this method for symbol domain modulation is to transform the received signal in the frequency domain and use a divider to eliminate the interference of the transmitted signal on the information. Furthermore, it can transform the research on radar target parameter estimation into the estimation of sine wave frequency parameters. The periodogram method can utilize the special orthogonal time-frequency structure of OFDM to estimate its frequency. Its structure can be demonstrated using Figure 1.

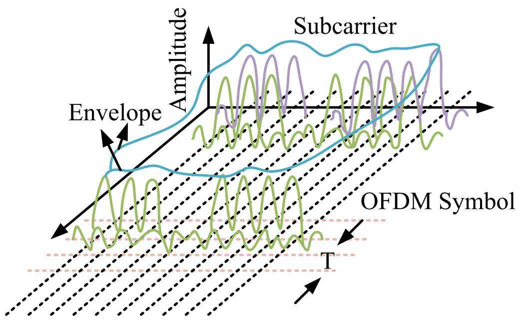


FIGURE 1. **Orthogonal time-frequency structure of OFDM signal.**

In Figure 1,OFDM divides the input digital signal into multiple parallel low-speed sub-carriers, and utilizes orthogonal sub-carriers to achieve spectral utilization of different data. At the sending end, the raw data is converted into a frequency domain signal through Inverse Fast Fourier Transform (IFFT), and then modulated into sine waves with different phases and amplitudes onto parallel subcarriers.The frequency domain representation of the original communications radar signal is the Fourier transform. The Fourier inverse transform is typically used to convert the frequency domain signal back into a time domain signal. This process, the Fourier inverse transform converts the amplitude and phase information of the frequency domain representation back into the waveform of the time domain representation, allowing us to regain the waveform characteristics of the original data [28]. These sine waves undergo serial parallel conversion and are transmitted in parallel to the receiving end. At the receiving end, the received signal undergoes parallel serial conversion and is divided into different sub-carriers using orthogonal frequency division multiple access technology. Then, it demodulates and reverses Fourier transform on each sub-carrier, converts the signal back to the time domain, and extracts the original data. OFDM can effectively utilize frequency domain resources and provide high-speed data transmission and anti-interference capabilities. The figure 2 is a schematic diagram of signal processing in a single substrate OFDM fusion system.

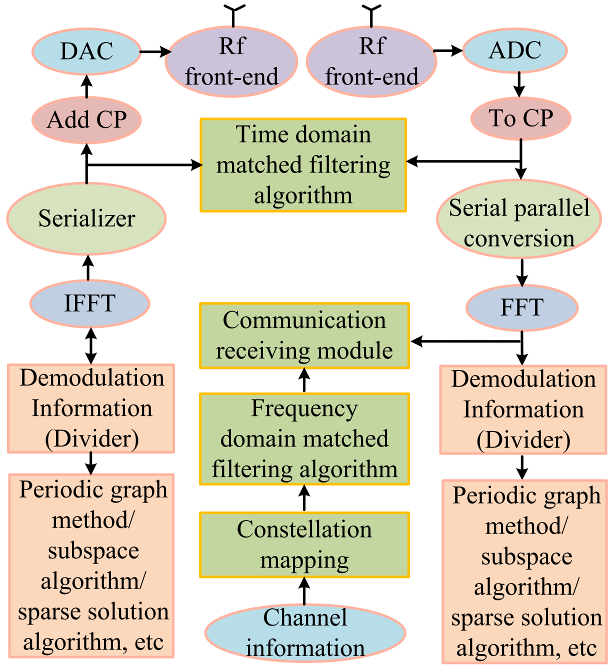


FIGURE 2. Signal processing process of OFDM based fusion system.

In Figure 2, in the actual signal processing process, it is necessary to select a certain length of signal for OFDM symbol representation. The transmission signal in the OFDM time-frequency structure can be represented in matrix form, as shown in equation (1).

$$DTX = \begin{bmatrix} d0,0 & \dots & \text{d0,M-1} \\ d1,0 & \dots & \text{d1,M-1} \\ \dots & \dots & \dots \\ dK-1,0 & \dots & dK-1\text{,M-1} \end{bmatrix} \tag{1}$$

In equation (1), M represents the number of OFDM symbols. T represents the duration of the unit code. $\mathrm{d}K-1$,M-1 is the transmitted data symbol. K represents the number of sub-carriers. Subsequently, after determining the waveform of the OFDM symbol and the orthogonality of the rectangular filter in the time-frequency domain, the waveform of the corresponding symbol can be represented, as shown in equation (2).

$$s(t) = \sum_{m=0}^{M-1} \sum_{k=0}^{K-1} sk, m \tag{2}$$

In equation (2), sk, m is the waveform corresponding to the OFDM symbol. When synthesizing OFDM time-domain signals, to ensure the integrity of orthogonality between subcarriers in multipath delay situations, it is necessary to add cyclic prefixes between each symbol. The length of the prefix is usually one fourth or one eighth of the symbol length. After removing the prefix, OFDM signals need to be demodulated, while radar detection does not require signal demodulation to complete synchronization and carrier frequency offset correction. The current OFDM fusion system rarely considers angle estimation when estimating target parameters, and the original methods are prone to damaging the internal structural features of multidimensional signals. The false pairing of the original parameters can also lead to the loss of SNR. A common solution is to use subspace estimation to achieve parameter estimation, but it is difficult to analyze the low SNR impact of target parameters and has a high cost. Therefore, to ensure the structure of data in the fusion system, this study proposes a target parameter estimation method on the ground of tensor decomposition using sparse and low rank theory. This method transforms multidimensional problems into one-dimensional problems and approximates them with tensor optimal rank.

Sparse and low rank theory is a mathematical theory used to process high-dimensional data, which can be represented by fewer non-zero elements or lower ranks. In OFDM, the signal is divided into multiple orthogonal sub-carriers in the frequency domain, which makes the signal sparse in the frequency domain. The data on each sub-carrier can be represented by the position and amplitude of non-zero elements. Therefore, sparse representation can achieve OFDM signal processing and parameter estimation [29]. Tensor decomposition also includes factor decomposition models that possess high-dimensional structural characteristics. The canonical multivariate decomposition in tensor decomposition is commonly used as a model, and the tensor is decomposed into the form of a sum of rank 1 tensors in some columns to achieve the decomposition effect. The factor matrix resulting from tensor decomposition requires only element scale transformation and permutation transformation models. When the tensor is decomposed with other rank R decomposition, a diagonal matrix exists between its factor matrices, uniquely describing the scale ambiguity of the decomposition. The essence of tensor decomposition is to focus on the estimation accuracy and information acquisition of each factor matrix for complete tensor data.In the tensor decomposition description problem, the guidance vector of a uniform linear array composed of antennas can be expressed as equation (3).

$$aR(z) = [a_R^0(z)a_R^1(z)\dots a_R^{NR-1}(z)]^T \tag{3}$$

In the formula, NR represents the antenna array element. z represents the signal. T is the transposed symbol. R is the given rank and aR is the oriented vector.Meanwhile, sub-carriers in single user mode can be allocated using orthogonal frequency division multiple access. When there is an ideal elimination of coupling between the receiving antennas, signal noise in the environmental target is the main receiving content. The target parameter estimation of the fusion system aims to balance signal design and resource allocation efficiency, but due to the sparsity of targets in the scene and their limited display compared to the overall detection area. To better describe the problem of target parameter estimation, this study performs OFDM fine-tuning on the received signal, which uses tensor form to adjust the information under the target channel response, and obtains equation (4).

$$\hat{D} = D * V + \tilde{W} \tag{4}$$

In equation (4), V is a tensor. $\tilde{W}$ is Gaussian white noise. D is the tensor obtained by expanding the emission data matrix. The parameter estimation process diagram is shown in Figure 3.

In Figure 3, due to the fact that the received signal can be represented in the form of tensor decomposition, its inherent low rank structure makes its decomposition results unique.Therefore, the correspondence between the target parameters and the tensor decomposition factor matrix can be represented by defining the objective parameters to signify the variant connection between the decomposition factor and the matrix. The estimation of target parameters refers to using data obtained from sensors or systems, analyzing and processing this information to infer some important features or attributes of the target object. The estimation of target parameters can be achieved by separating the relevant parameters and separately estimating them in two aspects.For the separation part, the tensor decomposition problem with noise can be used to achieve it, and its mathematical expression is shown in equation (5).

$$\min_{A,B,C} \left\| \breve{D} - \sum_{h=1}^{H} ah \circ bh \circ ch \right\|_F^2 \tag{5}$$

In the equation, ah, bh, ch represent diagonal matrices on the three dimensions of the tensor. H is the permutation matrix that describes the fuzziness of permutation. F is the relationship representation function. $\breve{D}$ is the matrix form of the tensor factor, A, B, C represent the given rank. Tensor decomposition is different from matrix decomposition in that its solution is unique and needs to satisfy the Kruskal condition. The mathematical expression of the Kruskal condition is shown in equation (6).

$$kA + kB + kC \geq 2H + 2 \tag{6}$$

In the equation, k represents the number of columns, and. When non coherent targets in the scene have different time delays, frequency shifts, or angles, then the matrices in equation (6) in the decomposition problem are all full rank matrices, otherwise, this equation does not hold. The traditional Alternating Least Squares (ALS) algorithm for tensor decomposition problems often has limitations in accuracy due to scenario limitations. This study proposes the use of calibration models for target parameter problem analysis, and proposes to perform multi-channel random initialization processing on the local optimal problem when solving tensor rank 1 approximation problems. This is to achieve the global optimal solution while ensuring algorithm convergence. The mathematical expression for the approximate optimal value is Equation (7).

$$(\hat{a}, \hat{b}, \hat{c}) = \arg\min_{\hat{a}\tau, \hat{b}\tau, \hat{c}\tau} \left| T(\hat{a}\tau, \hat{b}\tau, \hat{c}\tau) \right| \tag{7}$$

In equation (7), $(\hat{a}, \hat{b}, \hat{c})$ represents a vector. τ is the number of randomly initialized paths. The optimal rank 1 approximation may not necessarily have a corresponding relationship with the true value during the decomposition process, as it may be affected by interference from other factors. Therefore, this study utilizes greedy canonical factorization (Parallel factor, CP) to eliminate the estimated rank 1 components and residuals. The greedy CP decomposition algorithm processes the dimensions of the tensor one by one, and designs the corresponding factor matrix by selecting the dimension with the maximum variance. Its main function is to find, eliminate, and iterate the approximate optimal value during the iteration process. When calculating the rank 1 approximation, the residual tensor and noise tensor may not necessarily correspond completely, so additional iterative training is required. The mathematical expression of the iterative conditions is shown in equation (8).

$$\left\| \varepsilon R - \varepsilon R' \right\| \leq tG \tag{8}$$

In equation (8), $\varepsilon R'$ represents the residual tensor at the end of the current round. εR is the residual tensor at the end of the previous iteration. tG is the iteration termination threshold. In greedy iterative algorithms, each functionalized tensor calculation requires fast Fourier transform 3D operations, which can incur significant computational costs in the case of multiple objective numbers. Therefore, this study proposes to pre-process the fast Fourier transform domain to reduce duplicate calculations. The algorithm flowchart is shown in Figure 4.

In Figure 4, the transformation domain algorithm is mainly achieved through three data exchanges, namely 3D Fourier transform, coarse estimation result transfer, and rank 1 tensor transformation. 3D-DFT can be expressed as equation (9).

$$\tilde{\chi} = [\alpha; F1a, F2b.F3c] \tag{9}$$

In equation (9), $F1, F2.F3$ represent three dimensional Fourier transform matrices, $\tilde{\chi}$ is the given vector. Considering the constraint of factor vectors in the decomposition problem, this study conducts parameter correction from two aspects: parameter estimation and factor vector reconstruction. It is mathematical expression is shown in equation (10).

$$\begin{cases} \hat{\tau} = \arg\max\limits_{\tau} \dfrac{\left|\hat{a}^H a(\tau)\right|}{\left\|\hat{a}\right\| \left\|a(\tau)\right\|} \\ \hat{f} = \arg\max\limits_{f} \dfrac{\left|\hat{b}^H b(f)\right|}{\left\|\hat{b}\right\| \left\|b(f)\right\|} \\ \hat{\theta} = \arg\max\limits_{\theta} \dfrac{\left|\hat{c}^H c(\theta)\right|}{\left\|\hat{c}\right\| \left\|c(\theta)\right\|} \end{cases} \tag{10}$$

In equation (10), $\hat{\tau}$ represents the target delay. $\hat{f}$ represents the Doppler frequency shift. $\hat{\theta}$ represents the target angle.

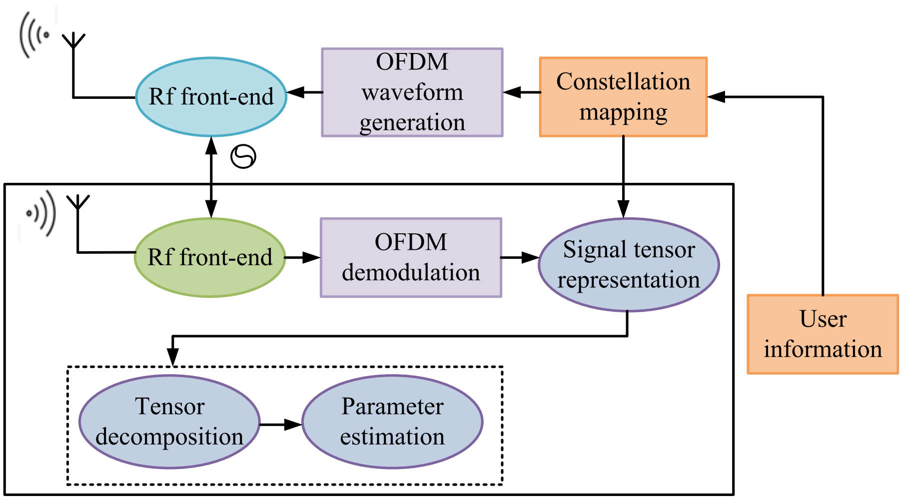


FIGURE 3. Schematic diagram of the estimation process of system target adoption number under tensor decomposition.

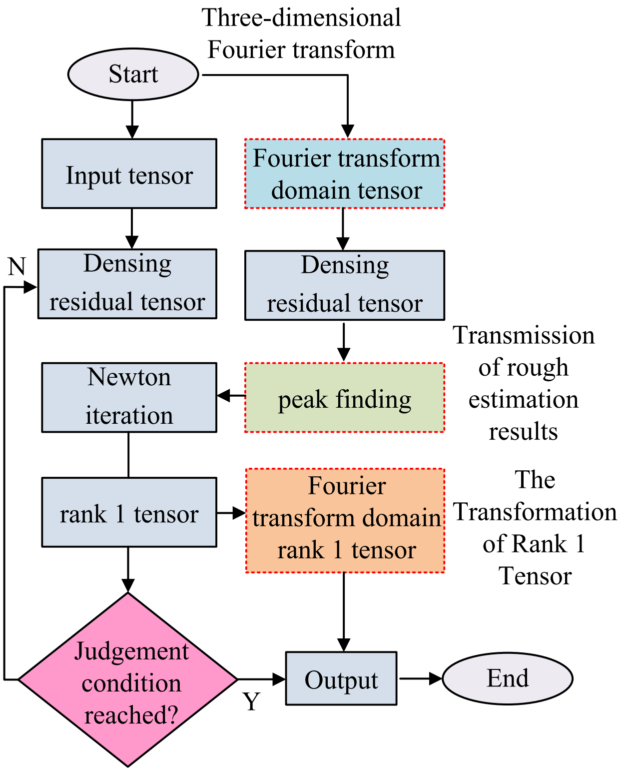


FIGURE 4. Schematic diagram of Fourier transform domain flow.

B. PARAMETER ESTIMATION OF COMMUNICATION RADAR TARGETS BASED ON TENSOR COMPLETION REPRESENTATION

When conducting high-resolution estimation of targets, it is inevitable to involve antenna arrays with larger bandwidth and longer coherent accumulation time. Moreover, in antenna array configuration, the contradiction between data sampling processing and communication spectrum requirements leads to the waste of antenna spectrum resources. Inconsistency in data resolution and differences in evaluation criteria or objective functions can lead to base mismatch problems in target estimation, which refers to the mismatch of target parameters between model training and practical applications. In the design of communication radar systems, considering the authenticity and continuity of target parameter selection, a tensor completion method is proposed to achieve parameter estimation in response to the problem of base mismatch. Tensor completion refers to the reconstruction of a complete tensor from partially observed tensor data by filling in missing or incomplete elements. Tensor completion techniques are frequently utilized for handling missing data and making predictions. The primary emphasis of these techniques is on the reconstruction impact of absent data, including the filling of gaps in missing interactive data and conducting predictive analysis on missing sequence data. Due to the limitations of sampling methods or resources, it is difficult to obtain complete tensor data. In order to better recover the original signal from a small amount of data, completion techniques have emerged. During the collection of information, signal transmission faults, irregular collection methods, and different sampling frequencies can all lead to the generation of missing values in data. These factors may have a notable impact on the algorithm's performance [30]. This study focuses on the problem of communication radar systems. In the scenario of multiple input multiple output (MIMO), to reduce the number of antennas and achieve sparse antenna arrays, the number of transmitting and receiving antennas is designed to be less than or equal to their corresponding array element spacing, and the frequency diversity array form is used to represent the frequency domain orthogonality between antennas. Figure 5 is a schematic diagram of the MIMO antenna array configuration.

In Figure5, the MIMO system utilises multiple transmit antennas and multiple receive antennas to achieve

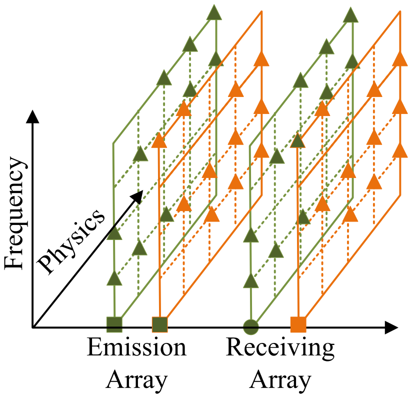


FIGURE 5. **MIMO antenna configuration.**

communication, the system is capable of achieving higher transmission rates and more reliable data transmission with limited spectrum and transmit power, and the multiple antennas are capable of spatially separating and processing interference on the signal.Considering the time-varying waveform, the transmission signal of the transmitting antenna can be expressed as equation (11).

$$sm(t) = \sum_{p=0}^{P-1} \delta m\,[p] \cdot hm(t - pT) \tag{11}$$

In equation (11), p represents the OFDM symbol interval sequence number. T is the symbol length. $\delta m\,[p]$ is the pulse control factor. m is the transmitting antenna. pT is the emission forming filter. t is the time. The received signals are orthogonal to each other within the OFDM symbol, so they can be demodulated and data symbol separated. When the transmitted signal is a time-frequency agile waveform, only a portion of the data is valid, so it is necessary to perform under-sampling tensor design on it. There are differences in the missing situations caused by different types of sampling methods. In the fusion system studied, to improve the positioning accuracy of the target, it is usually necessary to transmit a large bandwidth signal. Therefore, this study utilizes a multi band signal model for time-frequency sampling analysis, which mainly moves a limited number of broadband signals generated by the transmitter to a specific frequency and synthesizes broadband signals through frequency hopping. Figure 6 shows the time-frequency representation of multi band signals.

In Figure 6, the time-frequency representation of multi band signals is different from traditional under-sampling methods. Its blocky distribution on the time-frequency plane is limited, and it corresponds to the base-band in multi-band transceivers. Meanwhile, considering that due to different target scenarios, the tensor completion problem can lead to some data becoming unusable in the face of sensor failure. This will make it difficult to ensure a balance between performance and other factors after sampling some tensor data. Therefore, this study proposes to use weighted CP decomposition to give the rank on the ground of the above content, thereby achieving the solution of non convex optimization problems.

$$\min_{A,B,C} \left\| P\Omega(\breve{D} - [E, F, G]) \right\|_F^2 \tag{12}$$

In equation (12), E, F, G represent factor matrices. The common solution for tensor rank is to use maximum likelihood estimation for functional solution. However, considering the large search range and computational complexity faced by this method during the calculation process, a combination of finite grid search and Newton iteration is proposed to achieve accurate estimation. In the tensor problem with noise functionalization, the likelihood function can be represented using the vectorization calculation method to obtain the estimated parameters under the optimization problem, as shown in equation (13).

$$(\varpi, \alpha) = \arg\max_{\varpi,\alpha} p(y\,|\varpi, \alpha\,) \tag{13}$$

In equation (12), ϖ represents the noise vector. α is the parameter. When the noise is zero mean Gaussian white noise, the estimation problem of target parameters can be represented using third-order tensors, and equation (14) is obtained.

$$Gy(\tau, f, \theta) = \frac{\left|x(\tau, f, \theta)^H y\right|^2}{\|x(\tau, f, \theta)\|^2} \tag{14}$$

Considering that equation (14) is highly nonlinear, it is necessary to construct a discrete parameter network to obtain rough estimation results and calculate the corresponding amplitude using oversampling factors. On the basis of rough estimation, the estimation results are represented using the Newton iterative algorithm, which is mathematically expressed as equation (15).

$$(\hat{\tau}, \hat{f}, \hat{\theta})^T = (\hat{\tau}, \hat{f}, \hat{\theta})^T - \delta \frac{\Lambda J(\hat{\alpha}, \hat{\tau}, \hat{f}, \hat{\theta})}{\Lambda^2 J(\hat{\alpha}, \hat{\tau}, \hat{f}, \hat{\theta})} \tag{15}$$

In equation (15), δ is the iteration step size. $\Lambda J(\hat{\alpha}, \hat{\tau}, \hat{f}, \hat{\theta})$ is the gradient vector of the objective function. $\Lambda^2 J(\hat{\alpha}, \hat{\tau}, \hat{f}, \hat{\theta})$ is the Hessian matrix of the objective function. In each iteration, to reduce computational complexity, one parameter can be estimated each time and other parameters can be assumed to be known. Subsequently, estimation of different parameters can be achieved.

IV. APPLICATION TEST AND ANALYSIS OF PARAMETER ESTIMATION METHODS FOR COMMUNICATION RADAR SYSTEMS

To better validate the performance of the parameter estimation algorithm proposed in the study, an experimental environment and testing scenarios were designed for simulation analysis. In the experimental testing environment, the iteration termination threshold in the CP decomposition algorithm is set to 10-9, and the tensor power method termination threshold is set to 10-10. The average value after

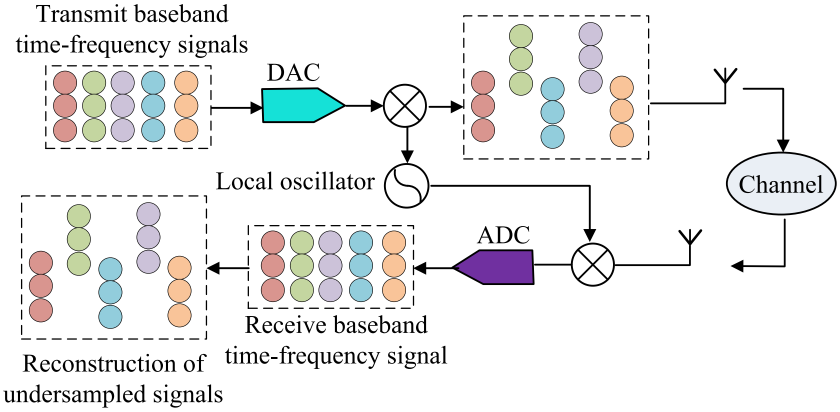
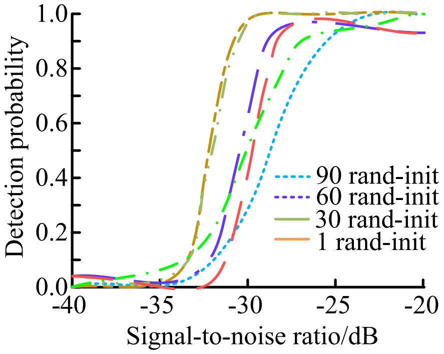


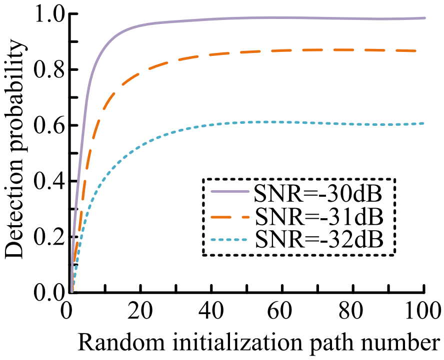
FIGURE 6. Time frequency representation of multi band signals.

1000 independent simulations is used as the experimental result. The uniform spacing of the receiving antennas in the communication radar fusion system is 15, and the carrier frequency and sub-carrier spacing of OFDM are 5.9GHz and 90.909kHz, respectively. The symbol length and cyclic prefix length of the OFDM signal are 11us and 1.375us, and the total bandwidth of the antenna is 93.1MHz. During the experiment, evaluation was conducted using indicators such as SNR, root mean square error, and detection probability. Parameter estimation performance tests were conducted in different target scenarios, and the effectiveness of the proposed algorithm was studied through algorithm comparison results. In the analysis of error in signal-to-noise results, the algorithm proposed in the study is compared with greedy CP algorithm, ALS algorithm, particle filtering algorithm, and maximum likelihood estimation algorithm. When conducting target detection probability analysis, theZiw Zakai bound, Cramerow bound, and tensor completion algorithm proposed in the study are selected for comparison.Figure 7 shows the target detection probability of the tensor decomposition method proposed in the study on different random initialization paths.

In Figure 7 (a), the tensor decomposition algorithm proposed in the study exhibits an upward trend in target detection probability under different path numbers when the SNR is greater than −35dB, and is relatively stable when the path numbers are 1 and 30, respectively. Its maximum target detection probability reaches a stable value of 100% when the SNR reaches −30dB. When the number of paths is 100, the tensor decomposition algorithm reaches its maximum value at a SNR of −18dB. Overall, the target detection probability demonstrated by this decomposition algorithm is generally good, and the overall fluctuation is relatively small. Figure 7 (b) shows that when the number of initialization paths is large enough, the decomposition algorithm exhibits relatively stable target detection performance. When the SNR is −30dB, −31dB, and −32dB, the average target detection probabilities are 96.13%, 85.12%, and 59.34%, respectively. Object detection probability is usually used to evaluate the accuracy of object detection algorithms in identifying and locating objects, referring to the probability that the algorithm correctly recognizes the target on a given test set. The higher the detection probability, the better the algorithm performs in target recognition. The results in Figure 7 show that the tensor decomposition algorithm proposed in the study shows an increasing trend in target detection probability under different path numbers under high SNR, and there is no significant



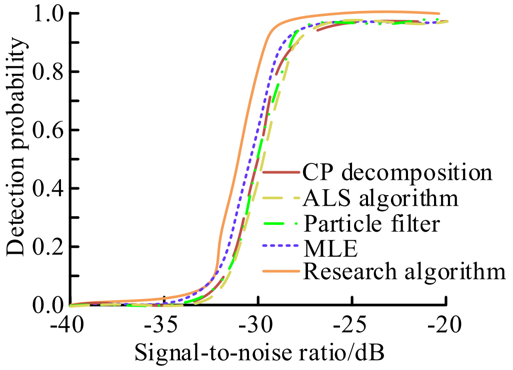
(a) Target detection probability of algorithms under different path numbers



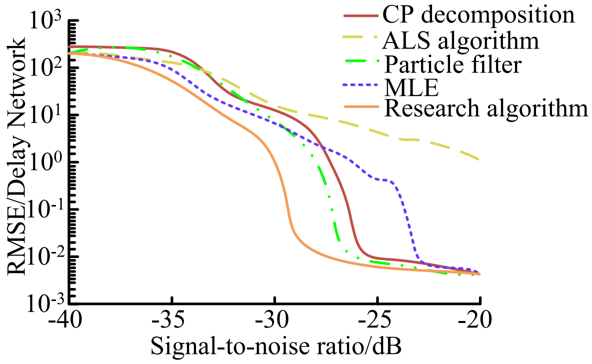
(b) Target detection probability of algorithms under different signal-to-noise ratios

FIGURE 7. Target detection probability of the proposed algorithm under different path numbers and SNRs.

change in the overall numerical difference. The detection probability continues to perform favorably despite varying signal noise powers.Subsequently, the error situation of the proposed algorithm under changes in SNR was analyzed, and the results are shown in Figure 8.

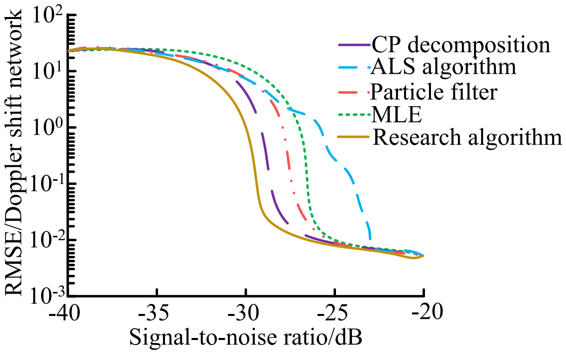


(a) Detection accuracy

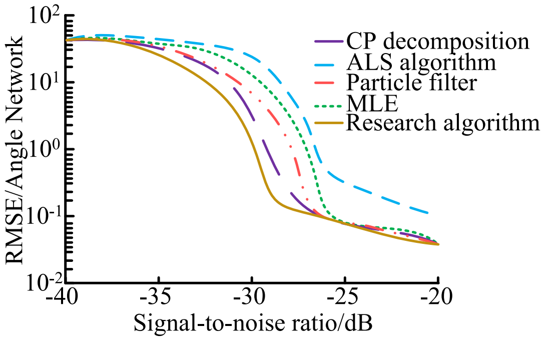


(b) Target delay estimation

FIGURE 8. Target detection accuracy and error results of different algorithms.

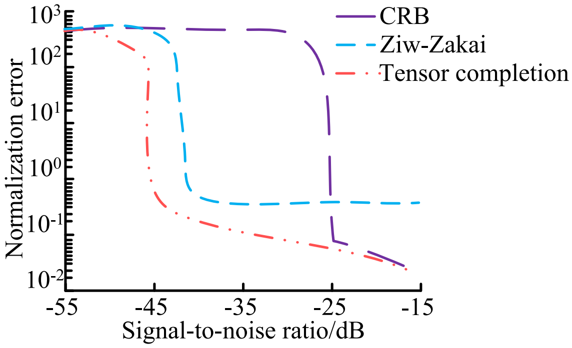


(a) Target Doppler shift estimation

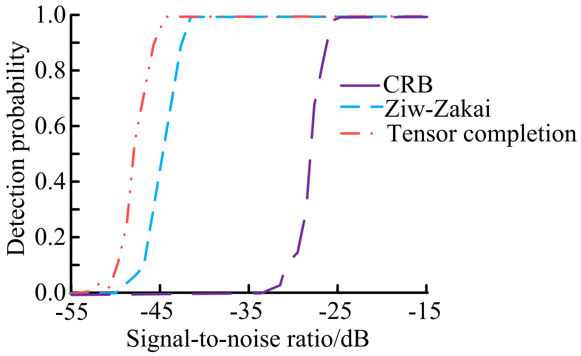


(b) Target angle estimation

FIGURE 9. Doppler frequency shift estimation and angle estimation performance of different algorithms.



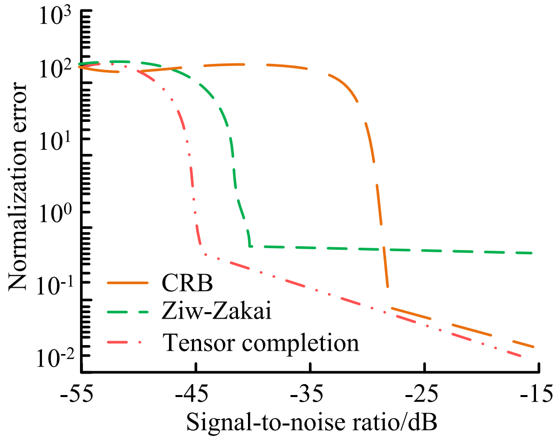
(a) Target delay estimation(RMSE)



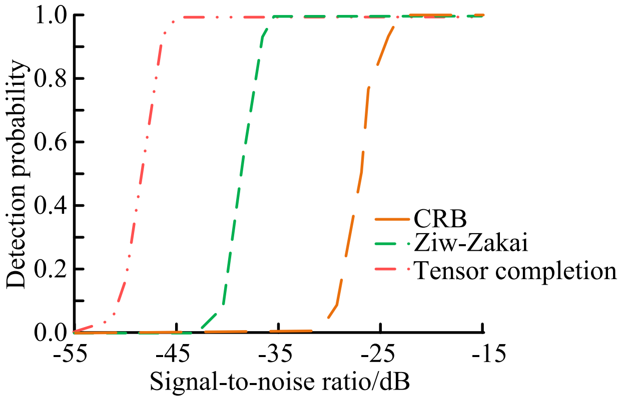
(b) Target detection accuracy

FIGURE 10. Target detection results of different completion algorithms in a single target scenario.

Figure 8 shows the SNR error results of different algorithms, and the comparison algorithms are greedy CP algorithm, ALS algorithm, particle filtering algorithm, maximum likelihood estimation algorithm, and the improved CP algorithm proposed by the study. The study assumes that the target parameters are randomly distributed in the detection area, and the SNR is defined as the ratio between the received signal tensor power and the noise tensor power. A smaller error result corresponds to a lower signal time delay.By utilizing root mean square error for analysis, especially in terms of overall detection accuracy, the proposed greedy CP decomposition algorithm that combines multi-channel randomness and parameter correction exhibits the lowest error delay. When the signal-to-noise ratio is −35dB, the target detection accuracy curve significantly decreases, and this is even more so in subsequent studies to achieve delay grid smoothing less than 10-2. The other four comparison algorithms have more similar detection probabilities, but their SNR to reach a smooth situation are basically close to −25dB, with an average detection accuracy of no more than 95%. From the target delay estimation situation, the research algorithm obviously has a faster descending trend than the other algorithms, and the noise value required for



(a) Target delay estimation(RMSE)

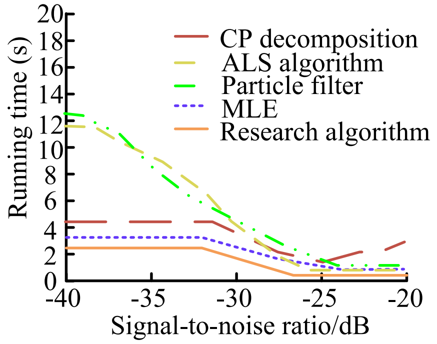


(b) Target detection accuracy

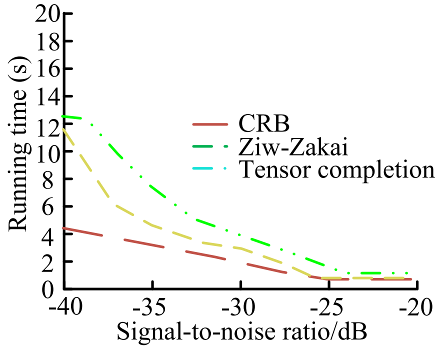
FIGURE 11. Target detection results of different completion algorithms in a single target scenario.

its error value to reach a smooth state is smaller. After the SNR is less than −30dB, its average error accuracy performs better than the research algorithm and the particle filtering algorithm, whose values all converge to 10-2, but the improved algorithms proposed by the research have a stronger convergence. The improved CP decomposition algorithm proposed in this study can perform vectorization on the rank 1 approximation problem of noisy functionalized tensors. The updating of residual tensors and Fourier transform processing can also enhance the processing of the original data, leading to a better estimation effect on signal accuracy. The different algorithms' Doppler frequency shift and angle estimations are then tallied, and the results are presented in Figure 9.

In Figure 9, in high dynamic environments, the presence of large radial velocities between the transmitter and receiver makes it inevitable for the receiver to generate large Doppler shifts during signal reception. The estimation of Doppler shift is the change in frequency resulting from the motion of the target object. Doppler shift conveys information regarding the velocity and direction of the observed object. This method is applicable in radar systems for determining the motion status and positional data of the target object, with the alteration in the target's angle estimation playing a vital role in inferring its trajectory. The results in Figure 9 show that the improved target detection algorithm proposed by the study exhibits better detection results and its frequency shift estimation and angle estimation errors are significantly better than the other algorithms at different SNR, with the average error values converging to 10-2 and 10-1. In contrast, the other comparative algorithms had error margins of at least 3% compared to the study algorithm, with the ALS algorithm performing the poorest.Subsequently, the effectiveness of the completion algorithm in parameter estimation was analyzed, and the results are shown in Figure 10.



(a) Tensor decomposition

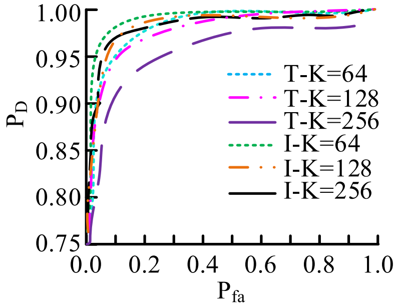


(b) Tensor completion

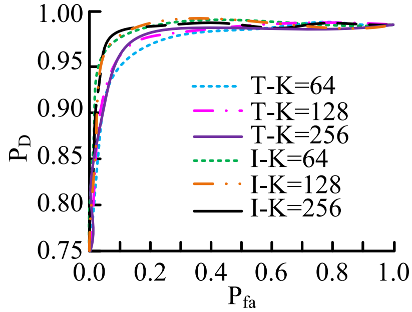
FIGURE 12. Comparison of runtime of different algorithms.

Figure 10 shows the Ziw Zakai bound and the Cramero bound (CRB) for target parameter estimation. The results show that CRB reflects a lower SNR result when detecting targets, and its target delay estimation error exceeds 102 when the SNR is between (−55, −25) dB. However, the error value of Ziw Zakai still has an average value of 10-0.5 under high SNR. The error value exhibited by the proposed algorithm is less than 10-1 when the SNR is greater than −45dB, and its target detection probability can perform well at low SNR. The performance of the algorithm in non coherent scenarios was analyzed, and the results are shown in Figure 11.

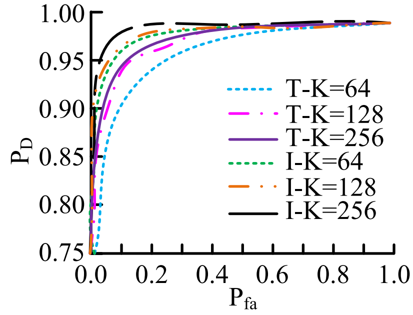
The results in Figure 11 indicate that the proposed parameter estimation completion algorithm can demonstrate good detection performance, which is less affected by SNR, and its processing gain value can reach 15dB. This indicates that it has a high degree of freedom when solving parameters. The other two algorithms are difficult to evaluate their



(b) Goal A

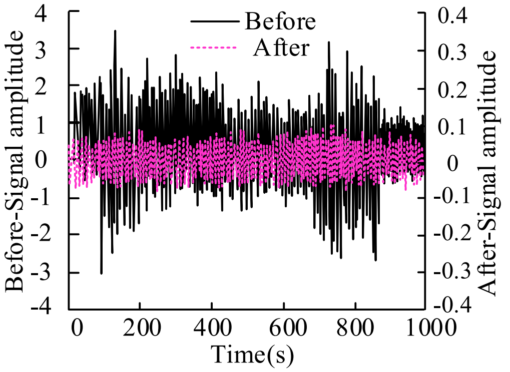


(c) Goal B

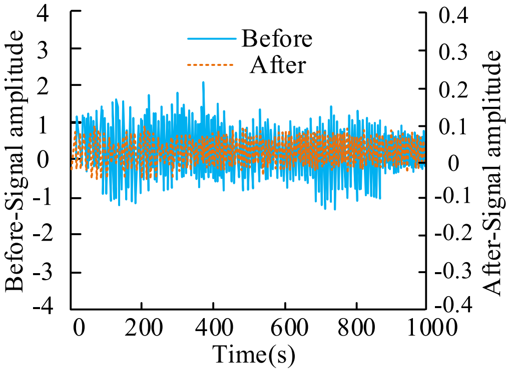


(d) Goal C

FIGURE 13. Performance evaluation of target detection under two algorithms.



(a) Large radial velocity target



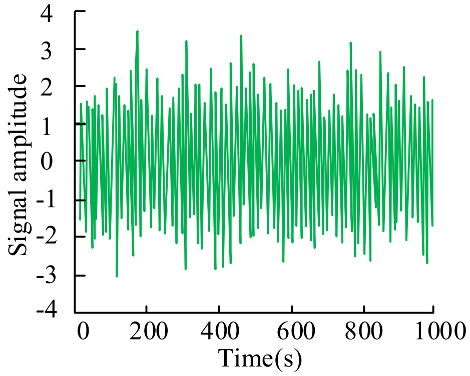
(b) Small radial velocity target

FIGURE 14. Simulation effect of parameter estimation algorithm with different radial velocity targets.

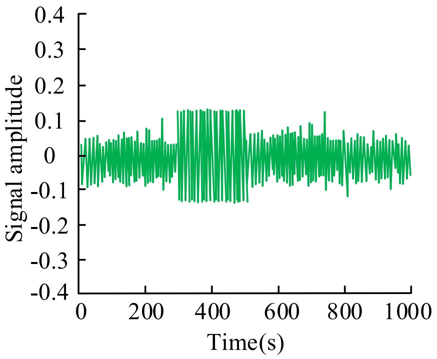
performance well. Subsequently, the runtime of the proposed parameter estimation algorithm was analyzed, and the results are shown in Figure 12.

The results in Figure 12 indicate that the tensor decomposition and tensor completion proposed in the study have a relatively low running time, which is generally less than 4 seconds and 5 seconds. And when the SNR is −25dB, it exhibits runtime of 0.5s and 0s, which is much less than other comparison algorithms. The method proposed in the study can effectively reduce computational complexity and runtime, and is significantly superior to other algorithms. The algorithm primarily employs 3D Fourier transform preprocessing to convert and combine tensor factor vectors, enhancing data processing efficiency.Subsequently, in a multi-objective scenario, the receiver operating characteristic (ROC) was used to describe the algorithm performance, and three targets with the same amplitude were designed with randomly distributed parameters. The study sets these three targets as targets A, B, and C. The difference between the targets lies in the differences in Doppler, distance, and velocity. When the number of subcarriers is set to 64, 128, and 256, the ROC curves corresponding to the three targets are obtained, as shown in Figure 13.

In Figure 13, "T" and "I" respectively represent the traditional target parameter estimation methods and the improved estimation methods used in the study. The results in the figure indicate that the detection accuracy of traditional parameter estimation methods on different targets is lower than that of improved estimation algorithms. Specifically, when the number of sub-carriers is 64, the average detection accuracy of the traditional algorithm on the three targets is 92.23%, 95.16%, and 94.37%, respectively. The average detection accuracy of the improved algorithm exceeds 96%, and it shows significant performance improvement as the number of sub-carriers increases. Among the three detection targets, the improved algorithm proposed in the study has a small difference in accuracy and overall stability, and is less affected by Doppler frequency shift and distance.For motion target detection is an important part of radar signal processing, in order to further detect the parameter estimation algorithm proposed in the study, the design of the radar large radial velocity and small radial velocity target two cases to be analysed, and the results are shown in Figure 14.

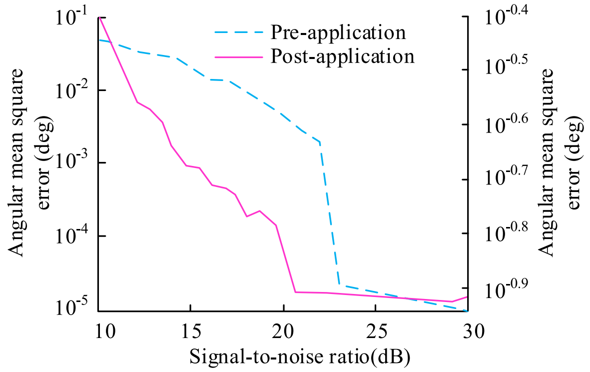


(a) Pre-application

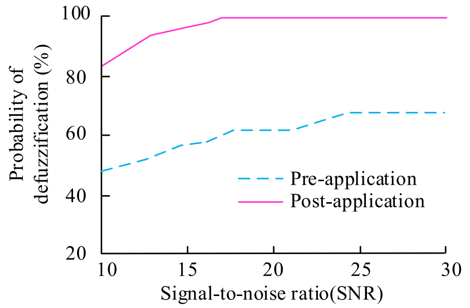


(b) Post-application

FIGURE 15. **Simulation results before and after applying parameter estimation to the target signal.**



(a) Target azimuth measurement results



(b) Fuzzy probability of target elevation angle solution

FIGURE 16. **Target angle case under parametric estimation.**

The results in Figure 14 show that the improved parameter estimation algorithm proposed by the study, after its application, has a lesser degree of signal loss for both large and small velocity targets, and its overall signal retention is better and less limited by the size of the velocity target.The study further illustrates the effectiveness of the proposed parameter estimation method in processing system signals. The results are shown in Figure 15.

Figure 15 represents the results of the echo signal at the target position, and the results show that Figure 15(a) shows the waveform of the target echo signal received by the radar at the initial moment, and Figure 15(b) shows the situation of the target echo signal after the parameter estimation. The figure's results demonstrate that after canceling the noise, the clutter signal is eliminated and the overall echo signal is largely preserved.This suggests that the velocity target can be effectively intervened by parameter estimation. Subsequently the target angle situation under parameter estimation is analyzed and the results are shown in Figure 16.

The results displayed in Figure 16 indicate a noteworthy enhancement in the angular measurement performance of the transmit signal carrier frequency under parameter interference conditions. Additionally, with the variation in SNR, the angular mean square error results exhibited a significant reduction. The de-fuzzification probability of azimuthal angle surpassed 80%, which is evidently superior compared to the results pre-improvement.

V. CONCLUSION

Research is conducted on the estimation of target parameters in communication radar systems, and a tensor CP decomposition method is proposed for calculation to better improve target detection accuracy. The simulation analysis of the proposed method shows that the target detection probability of the tensor decomposition algorithm under different path numbers shows an upward trend when the SNR is greater than −35dB, and is relatively stable when the path numbers are 1 and 30, respectively. Its maximum target detection probability reaches a stable value of 100% when the SNR reaches −30dB. When the number of initialization paths is large enough, the average probability of target detection for the decomposition algorithm at SNRs of -30dB, −31dB, and −32dB is 96.13%, 85.12%, and 59.34%. The improved greedy CP decomposition algorithm proposed in the study exhibits the lowest error delay, and its target detection accuracy curve shows a significant decline when the SNR is −35dB. The average detection accuracy of greedy CP algorithm, ALS algorithm, particle filter algorithm, and maximum likelihood estimation algorithm does not exceed 95%. The average error values of frequency shift estimation and angle estimation of the improved target detection algorithm proposed in the study approach 10-2 and 10-1 under different SNRs, with an error margin of at least 3% compared to other algorithms. And in multi-objective scenarios, the tensor decomposition and completion algorithms proposed in the study have a running time of basically less than 4 seconds and 5 seconds, and exhibit running times of 0.5 seconds and 0 seconds at a SNR of −25dB, far less than other comparative algorithms. Compared to traditional parameter estimation methods. The average detection accuracy of the improved algorithm proposed in the study on different targets exceeds 96%, far higher than the 92.23%, 95.16%, and 94.37% of traditional algorithms. The study's proposed information processing technology efficiently resolves multi-user access interference issues in fusion systems by analyzing the interference power distribution characteristics among users. And while ensuring communication capacity, it reduces computational complexity and achieves good detection results, avoiding the influence of signal waveform information on the algorithm. Most current signal processing algorithms are more susceptible to waveform information and perform poorly at low signal-to-noise ratios. The signal received by radar detection is the target reflected back, with two-way attenuation and other characteristics, which leads to its performance is extremely limited. The problem of parameter estimation under low signal-to-noise ratio is of great significance to the performance of the technology as well as to the effect of signal processing. Specifically, improving parameter estimation can improve the performance and accuracy of the system, enhance the detection capability of the radar system and the accuracy of target tracking, which means that the recognition rate of the target object will be greatly improved in the complex environment. And improved parameter estimation can also optimise the signal processing algorithm, thus improving the anti-interference ability and working efficiency of the radar system. These applications will help to improve the overall performance of the communication radar system and provide more reliable data and information processing capabilities for the wide application of software radio technology, which can also better cope with the increasing complexity of the communication radar working scenarios and equipment tasks, and is of great significance in promoting the convergence design of electronic equipment and the use of system resources to ensure system performance and stability.The channel state information reflects the impact of the signal during transmission, including propagation delay, multipath effects, and distortion due to interference. It is worth noting that incomplete or inaccurate channel state information does affect the performance of algorithms for communication radar parameter estimation. In parameter estimation, inaccurate channel state information may lead to the accumulation of errors and can affect the accuracy of parameters such as the position, velocity and shape of the target. Therefore, in future research, special attention needs to be paid to the acquisition, updating and accuracy of channel state information. On the one hand, further research is needed on methods to improve the efficiency and accuracy of channel state information acquisition, including the use of more advanced channel estimation techniques, in order to more accurately reflect the effects of the actual signal transmission process. On the other hand, there is also a need to investigate how to make the radar parameter estimation algorithm robust to the incompleteness and inaccuracy of the channel state information, for example, by introducing adversarial learning or non-deterministic modelling techniques to mitigate the impact of inaccurate channel state information. Overall, it shows good application performance in communication radar systems.

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