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Research on The Application of High-Performance Calculation in Real-Time Estimation Algorithm of Polarization Parameters of Conformal Arrays

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Abstract. In this paper, the application of high-performance computing technology in real-time polarization parameter estimation algorithm of conformal array is discussed, aiming at solving the problems of high computational complexity and poor real-time performance in traditional polarization parameter estimation methods. By introducing parallel computing and distributed computing technology, a new real-time polarization parameter estimation algorithm framework is proposed, which can significantly improve the calculation speed and data processing ability and meet the requirements of modern wireless communication systems for high-speed and accurate signal processing. The experimental results show that compared with the traditional algorithm, the time required by the proposed algorithm in this study is obviously reduced when processing the same amount of data, and it also shows significant advantages in accuracy. In addition, the algorithm shows good applicability and robustness in different scenarios, which provides an efficient and reliable solution for real-time estimation of polarization parameters of conformal array antennas.

Keywords: conformal arrays; high-performance calculation; polarization parameters; real-time estimation; Parallel computing; distributed computing.

1. Introduction

With the rapid development of wireless communication technology, conformal array antenna has been widely used in radar, wireless communication and other fields because of its unique structure and performance advantages [1-2]. Conformal array antenna can flexibly adjust the beam direction and shape, and improve the efficiency and accuracy of signal transmission. However, to give full play to the performance of conformal array antenna, accurate estimation of polarization parameters is the key. Polarization parameters describe the vector characteristics of electromagnetic waves, which have an important influence on the quality and stability of signal transmission.

Traditional polarization parameter estimation methods are often faced with the problems of high computational complexity and poor real-time performance, and it is difficult to meet the requirements of modern wireless communication systems for high-speed and accurate signal processing. Especially in the case of real-time beam tracking and adjustment, the limitations of traditional methods are more obvious [3]. Therefore, exploring a method that can estimate the polarization parameters of conformal arrays efficiently and in real time has become the focus of current research. In recent years, the rapid development of high-performance computing technology provides a new way to solve this problem. High-performance computing technology can significantly improve the computing speed and data processing ability by means of parallel processing and distributed computing, which provides strong support for real-time polarization parameter estimation [4-5]. Applying high performance computing technology to polarization parameter estimation can not only reduce the computational complexity, improve the real-time performance of the algorithm, but also further improve the accuracy of estimation.

The purpose of this paper is to explore the application of high performance calculation in real-time estimation algorithm of polarization parameters of conformal arrays. By introducing high-efficiency computing technology and optimizing the traditional algorithm, the polarization parameters can be estimated quickly and accurately to meet the requirements of modern wireless communication system for high efficiency and real-time signal processing. This research not only has important theoretical value, but also provides strong support for the practical application of conformal array antennas and promotes the technical progress in radar, wireless communication and other fields.

2. Application of high-performance calculation in polarization parameter estimation

High-performance computing technology is an important part of modern computing science, and its core idea is to significantly improve computing efficiency and data processing ability by using advanced computing methods and hardware resources. In polarization parameter estimation, the application of high performance calculation can greatly improve the performance of the algorithm and meet the needs of real-time processing.

The realization methods of high-performance computing technology mainly include parallel computing and distributed computing [6]. Parallel computing refers to the process of solving computing problems by using multiple computing resources at the same time. By decomposing a large computing task into several small tasks and distributing them to multiple processors for simultaneous processing, the computing speed is significantly improved. In polarization parameter estimation, multiple data samples can be processed simultaneously by using parallel computing technology to speed up the estimation process.

Distributed computing is a kind of computing method, which divides the problems that require huge computing power into many small parts, then distributes them to many computers for processing, and finally synthesizes these calculation results to get the final answer [7]. In the estimation of polarization parameters, distributed computing can make full use of the resources of many computers in the network, realize the rapid processing and analysis of large-scale data, and improve the accuracy of estimation.

Applying high-performance computing technology to polarization parameter estimation algorithm can significantly improve the calculation speed and accuracy (Figure 1).

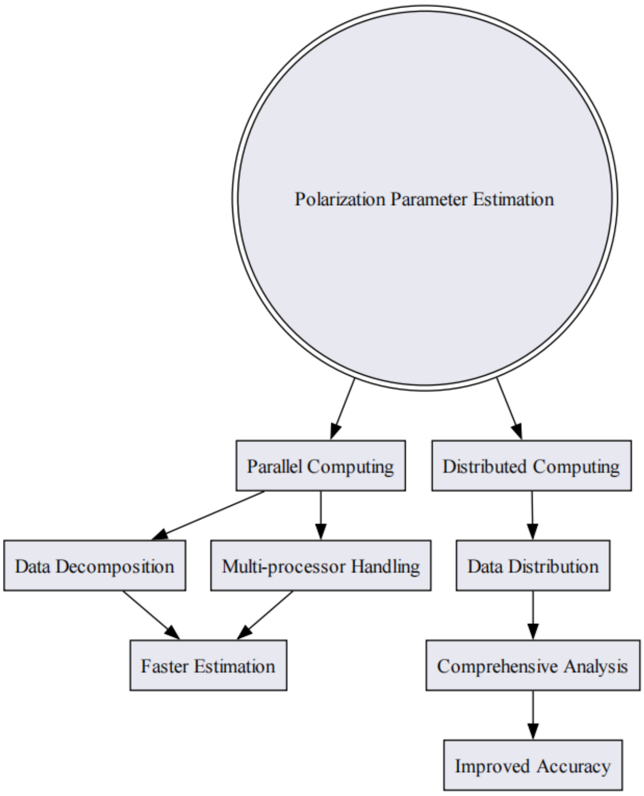

Figure 1 Application mode of high performance computing technology

Firstly, the polarization parameter estimation task is decomposed into multiple subtasks by parallel computing technology, and distributed to multiple processors for parallel processing. This can make full use of the computing power of multi-core processors or multiple computers and speed up the estimation. Secondly, using distributed computing technology, massive data samples are distributed to multiple computers in the network for processing. Each computer is responsible for processing a part of data and summarizing the processing results to the central node for comprehensive analysis. This method can not only improve the speed of data processing, but also make use of the storage and computing power of multiple computers to process larger data sets, thus improving the accuracy of polarization parameter estimation.

3. Design of real-time polarization parameter estimation algorithm

Aiming at the real-time estimation of polarization parameters of conformal array antennas, a real-time polarization parameter estimation algorithm framework based on high-performance computing is proposed in this study. This framework combines the advantages of parallel computing and distributed computing, and aims to realize fast and accurate polarization parameter estimation. The framework of this algorithm consists of the following key modules: data preprocessing module, parallelization strategy module, calculation task allocation module and polarization parameter estimation module.

3.1. Parallelization strategy

In the data preprocessing stage, the received original signal is mainly filtered, denoised and standardized to improve the data quality. In addition, the data should be segmented to facilitate the subsequent parallel calculation.

Parallelization strategy is the core of this algorithm, which decomposes the polarization parameter estimation task into several independent subtasks, and each subtask processes a part of data [8-9]. The preprocessed data is segmented according to time sequence or spatial order, and each segment of data contains a certain number of sampling points. Each data segment corresponds to a subtask, which is responsible for the polarization parameter estimation of the data segment. Using multithreading technology, these subtasks are executed in parallel on multiple processors.

Suppose a set of preprocessed data samples $D = d_1, d_2, \cdots, d_N$, where N is the total number of samples. The goal is to segment these data and assign a subtask to each data segment for polarization parameter estimation.

Divide the data into M segments in time sequence, each segment contains n_i sampling points, where $i = 1,2,\cdots,M$ and $\sum_{i=1}^{M} n_i = N$. Each piece of data can be expressed as:

$$D_i = d_{(i-1)n_i+1}, \cdots, d_{in_i} \tag{1}$$

Each data segment D_i corresponds to a subtask T_i, and the goal of this subtask is to estimate the polarization parameters of this segment of data. The estimation of polarization parameters is based on maximum likelihood estimation. The estimation method f is used to calculate the polarization parameters, namely:

$$\theta_i = f(D_i) \tag{2}$$

Where θ_i is the estimated polarization parameter of the data in the i section.

Using multithreading technology, these subtasks are executed in parallel on multiple processors. Each processor processes a subtask T_i and outputs the corresponding polarization parameter estimation value θ_i.

The estimated polarization parameters of each segment are combined to obtain the overall polarization parameters. The overall polarization parameter Θ is the average value of polarization parameters of all segments:

$$\Theta = \frac{1}{M}\sum_{i=1}^{M}\theta_i \tag{3}$$

In distributed computing environment, reasonable task allocation is very important to improve computing efficiency. This algorithm dynamically allocates subtasks according to the processing capacity of each computing node to achieve load balancing. Design a fault-tolerant mechanism, when a node fails, it can redistribute its tasks to other nodes.

3.2. Computational task assignment

There is a distributed system composed of P computing nodes, and the processing capacity of each node is expressed by $C_p,\ p=1,2,\cdots,P$. At the same time, there are M subtasks to be assigned, and the computational load of each subtask is represented by $L_m,\ m=1,2,\cdots,M$.

In distributed computing environment, the strategy of task allocation is very important to realize load balancing and improve computing efficiency. In order to allocate subtasks to each computing node reasonably and design an effective fault-tolerant mechanism to minimize the total load imbalance of all nodes [10]. Load imbalance is defined as the load difference between the node with the heaviest load and the node with the lightest load among all nodes.

x_{mp} indicates whether the subtask m is assigned to node p, if so, $x_{mp}=1$, otherwise, $x_{mp}=0$.

Optimization model:

$$\begin{aligned} &\text{minimize } \max_p\left(\sum_{m=1}^{M} L_m x_{mp}\right) - \min_p\left(\sum_{m=1}^{M} L_m x_{mp}\right) \\ &\text{subject to } \quad \sum_{\mathrm{p=1}}^{\mathrm{P}} x_{mp} = 1, \quad \forall m \\ &\qquad\qquad\quad x_{mp} \in \{0,1\}, \quad \forall m, p \end{aligned} \tag{4}$$

This model is solved by optimizing algorithm to simulate annealing.

Whenever a new subtask arrives, it is assigned to the node with the lightest current load. In order to deal with the situation of node failure, the status of each node is detected regularly. If a node is found to be unresponsive or the response is overtime, it is considered that the node has failed. When a node failure is detected, the unfinished tasks on the node are reassigned to other nodes. By maintaining a task queue in the system, whenever a node fails, put its tasks back in the queue, and then redistribute these tasks according to the load balancing strategy. In order to improve the reliability of the system, the same task is redundantly executed on multiple nodes. This way, even if a node fails, it will not affect the completion of the task.

3.3. Polarization parameter estimation

In each subtask, the polarization parameter estimation method is used for processing:

$$\hat{\theta} = \arg\min_{\theta} \sum_{i=1}^{N} \left\| S_i - A(\theta) E_i \right\|^2 \tag{5}$$

Where $\hat{\theta}$ is the estimated polarization parameter, S_i is the received signal sample, E_i is the estimated value of the transmitted signal, $A(\theta)$ is the array manifold matrix related to the polarization parameter θ, and N is the number of samples. The formula indicates that the polarization parameters are solved by minimizing the error between the received signal and the estimated signal.

By combining parallel computing and distributed computing, this algorithm realizes efficient polarization parameter estimation and meets the real-time requirements. Design flexible task allocation strategy, which can adapt to different scale and complexity of computing environment. Advanced polarization parameter estimation method is adopted to improve the accuracy of estimation.

4. Experimental verification and performance analysis

In order to verify the polarization parameter estimation algorithm proposed in this study, a cluster environment with five high-performance computing nodes is built. Each node is configured as follows:

Processor: Intel Xeon Gold 6230, with 18 cores and 36 threads, has a basic frequency of 2.1GHz and a maximum turbine frequency of 3.9GHz to support high-intensity parallel computing requirements.

Memory: equipped with 128GB DDR4 ECC memory to ensure the processing ability of large data sets and the stability of multi-task parallel operation.

Storage: Each node is equipped with 1TB NVMe SSD for fast data reading and writing, and 4TB SATA hard disk for data storage.

Network: Nodes are connected through 10Gbps Ethernet to ensure high efficiency and low delay of data transmission.

In addition, the whole cluster is connected by high-performance network switches to realize fast communication between nodes. Professional cluster management software is also deployed to facilitate the distribution, monitoring and management of tasks.

In order to comprehensively evaluate the performance of the algorithm, a specific data set is prepared, which comes from the conformal array antenna receiving system in the laboratory environment and contains data sets of various polarization states and signal conditions. The data set is divided into training set and test set, in which the training set is used to train and optimize the model of the algorithm and the test set is used to evaluate the performance of the algorithm. Several groups of comparative experiments are carried out, and the proposed algorithm is compared with the traditional polarization parameter estimation algorithm. In the experiment, two algorithms were run on different data sets, and their running time and estimation error were recorded.

The experimental results show that compared with the traditional algorithm, the time required by the proposed algorithm in this study is significantly reduced when processing the same amount of data.

Thanks to the application of high-performance computing technology, the algorithm can make full use of the advantages of parallel computing and distributed computing, thus improving the computing speed (Figure 2).

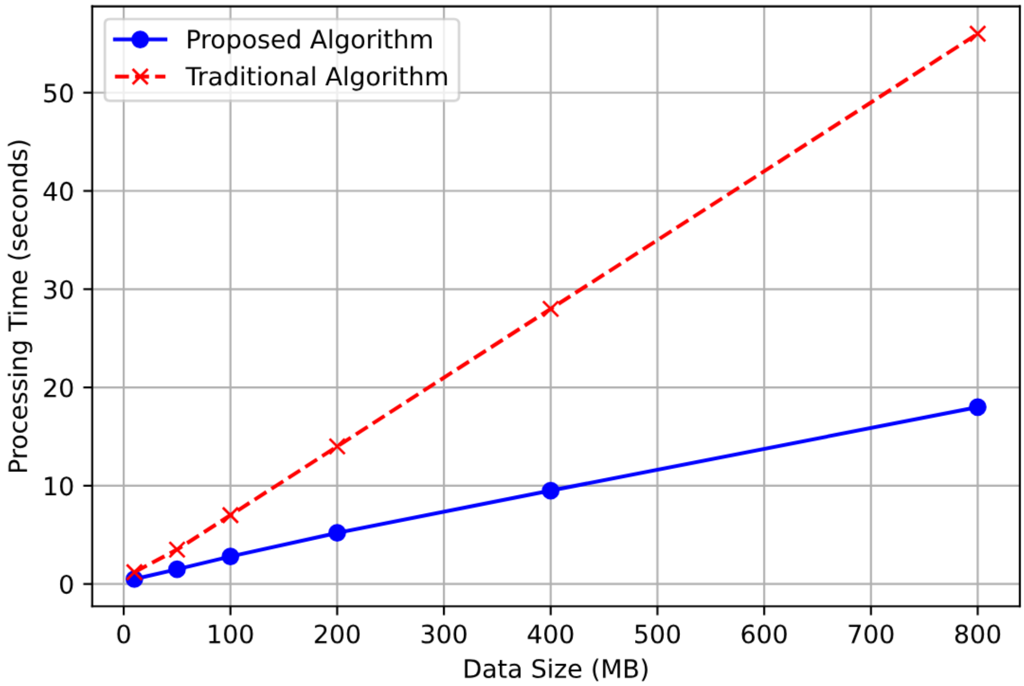

Figure 2 The changing trend of algorithm processing time with the increase of data volume

From the overall trend, the processing time of the two algorithms increases with the increase of data volume. This is because with the increase of data, the amount of information that the algorithm needs to deal with increases, and the computational complexity also increases, which leads to the extension of processing time. The algorithm proposed in this study has significant advantages in processing time. Under the same amount of data, the processing time of the proposed algorithm is always lower than that of the traditional algorithm. This advantage has been reflected when the data volume is small, and with the increase of data volume, this gap becomes more obvious. This shows that the algorithm proposed in this study can deal with large-scale data more effectively and has higher computational efficiency.

In terms of accuracy, the algorithm proposed in this study also shows significant advantages. By comparing the estimation errors of the two algorithms, it is found that the proposed algorithm can estimate the polarization parameters more accurately in most cases (Table 1).

Table 1 Estimation errors of different algorithms on different data sets

Dataset number	Data set description	Estimation error of the algorithm proposed in this study (%)	Estimation error of traditional algorithm (%)
DS1	Low SNR environment	2.3	4.8
DS2	Medium SNR environment	1.6	3.5
DS3	High SNR environment	1.1	2.7
DS4	Multipath interference environment	2.8	5.2
DS5	Dynamic polarization state change	2.1	4.1
DS6	Complex signal condition	2.5	4.6
DS7	Weak signal receiving condition	3.2	6.0
DS8	Interference signal exists	2.9	5.3

On the whole, the estimation error of the proposed algorithm on each data set is generally lower than that of the traditional algorithm. This shows that under the same experimental conditions, the proposed algorithm can estimate the polarization parameters more accurately, showing its remarkable advantages in accuracy. In the environment with low SNR (such as DS1 data set), the estimation errors of the two algorithms are relatively high, but the error of the algorithm proposed in this study is still significantly lower than that of the traditional algorithm. In the medium SNR(DS2) and high SNR(DS3) environments, the errors of the two algorithms are reduced, but the algorithm proposed in this study still keeps ahead. When faced with data sets with special signal conditions, such as multipath interference environment (DS4), dynamic polarization state change (DS5), complex signal condition (DS6), weak signal receiving condition (DS7) and interference signal existence (DS8), the proposed algorithm also shows lower estimation error. This shows that the algorithm is more robust and accurate when dealing with complex and unfavorable signal conditions.

To sum up, the experimental verification and performance analysis prove that the real-time polarization parameter estimation algorithm framework proposed in this study has obvious advantages in real-time and accuracy, and has good applicability and robustness in different scenarios. This provides an efficient and reliable solution for real-time estimation of polarization parameters of conformal array antennas.

5. Conclusion

By introducing parallel computing and distributed computing technology, the real-time estimation ability of polarization parameters of conformal array antenna is significantly improved. Experimental results show that compared with traditional methods, the proposed algorithm not only has shorter processing time, but also has a significant improvement in accuracy. Through parallel computing technology, a large task is decomposed into several small tasks and distributed to multiple processors for simultaneous processing, thus greatly improving the computing speed. This method makes it possible to process multiple data samples at the same time and speeds up the whole estimation process. Secondly, the application of distributed computing allows massive data to be distributed to multiple computers for processing, which not only accelerates the data processing speed, but also utilizes the storage and computing resources of more computers, thus improving the accuracy of polarization parameter estimation. The algorithm design proposed in this paper includes key modules such as data preprocessing, parallelization strategy, calculation task allocation and polarization parameter estimation. The cooperation of these modules ensures the efficiency and accuracy of the algorithm. In particular, the parallelization strategy and reasonable task allocation mechanism effectively meet the needs of large-scale data processing and ensure the reliability and robustness of the system. The framework of real-time polarization parameter estimation algorithm based on high-performance computing proposed in this study not only meets the requirements of modern wireless communication system for high efficiency and real-time signal processing, but also shows good applicability and robustness in different scenarios. This achievement provides an efficient and reliable solution for the practical application of conformal array antenna.

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