Journal of Electrical, Computer and Informatics

E-ISSN: 3090-2444
P-ISSN: 3090-2452

Research Article

Optimization of Parallel Computing Algorithms for Electromagnetic Field Simulation in Next-Generation Antenna Design

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Abstract: Modern antenna design faces significant challenges in terms of simulation time and accuracy for electromagnetic (EM) field simulations. These simulations, especially those involving large-scale or complex antenna designs, are heavily reliant on intensive computations that require substantial computational resources. To address this, parallel computing approaches using GPUs (Graphics Processing Units) through the CUDA (Compute Unified Device Architecture) platform have shown significant results in accelerating EM simulations. In this study, we implemented CUDA-based parallel processing to improve the efficiency of electromagnetic field simulations in antenna design. By utilizing simulation methods such as FDTD (Finite Difference Time Domain) and MoM (Method of Moments), we achieved a reduction in simulation time by up to 40%, with speedups of up to 40.16× for FDTD simulations and approximately 10 times faster for MoM simulations. Additionally, memory optimization and algorithm improvements, such as memory coalescing and shared memory usage, ensured that the speedup did not sacrifice simulation accuracy. While there were challenges in adapting sequential algorithms to parallel execution and managing memory on the GPU, the use of profiling tools helped identify and resolve performance bottlenecks. The findings of this research demonstrate the effectiveness of CUDA-based processing in accelerating EM field simulations, which has significant implications for antenna design cycles. Future research could focus on further improving parallel processing algorithms and expanding the use of GPU acceleration in other antenna design simulation areas.

Keywords: Antenna Design; CUDA; Electromagnetic Field Simulations; FDTD; Parallel Processing

Received: June 30, 2025
Revised: August 28, 2025
Accepted: October 23, 2025
Published: December 18, 2025
Curr. Ver.: December 18, 2025

1. Introduction

Antenna design faces several challenges, primarily due to the diverse and evolving nature of its applications. Antennas must operate efficiently in a wide range of dynamic environments, including wearable technologies where the human body significantly impacts performance. Such challenges require novel solutions that balance functionality and user-centric performance. As the demand for more advanced antenna systems grows, particularly in the areas of Internet of Things (IoT) and wearable devices, antennas are increasingly required to perform reliably in these dynamic environments. Studies on the design considerations and challenges of on-body antennas highlight the need for precise and adaptable designs to mitigate the effects of varying environmental factors and human interaction [1],[2].

The growing need for high-performance antennas has led to the adoption of computational techniques that can accurately model and predict antenna behavior. One of the most critical aspects of antenna design is the simulation of electromagnetic (EM) fields, which helps to predict how antennas will perform under various operating conditions. However, the computational cost of high-fidelity EM simulations has become a significant bottleneck in the antenna design process. Traditional methods, while accurate, are computationally expensive and inefficient, especially when dealing with complex and high-dimensional antenna models. To address this challenge, more efficient simulation techniques are required to meet the increasing demand for rapid prototyping and optimization in antenna design [3],[4],[5].

Computational optimization plays a crucial role in modern antenna design by enabling the automation of design processes and reducing the reliance on manual tuning and trial-and-error methods. Optimizing antenna structures through computational algorithms ensures that the design meets strict performance criteria, such as bandwidth, gain, and efficiency. This optimization is particularly vital in the context of wearable antennas, where low-cost manufacturing and sustainability are key considerations. Efficient design methods can also reduce the environmental impact of antenna production and improve the sustainability of the overall design process [3],[4],[6],[7],[8].

High computational costs associated with traditional EM simulation methods make them impractical for direct use in optimization loops. These methods require significant resources, which are not feasible when working with complex antenna structures or when performing numerous design iterations. Consequently, there is a growing need for computational techniques that can reduce the time and cost of simulations while maintaining their accuracy. To address these challenges, the use of parallel computing has emerged as a promising solution for accelerating EM field calculations in antenna design. Parallel computing techniques, particularly those based on CUDA (Compute Unified Device Architecture), offer a substantial speedup over traditional CPU-based computations by utilizing the parallel processing capabilities of modern graphics processing units (GPUs). By leveraging CUDA, it is possible to reduce simulation times significantly, making it more feasible to use high-fidelity models during the design process [9].

In summary, the optimization of EM simulations through parallel computing is essential for advancing antenna design, particularly in next-generation systems such as wearable devices. The adoption of CUDA-based parallel processing has shown promise in accelerating the simulation process, offering a viable solution to the computational challenges faced by designers. This paper explores the potential of parallel computing algorithms, specifically CUDA, to optimize simulation times and improve the overall efficiency of antenna design [9].

2. Literature Review

Electromagnetic Field Simulations in Antenna Design: Accurate electromagnetic (EM) field simulations are essential for the design and optimization of antennas, ensuring that their performance meets the demanding requirements of modern applications. In the context of antenna design, several methods have been developed to simulate EM fields, each with its advantages and limitations.

Coarse-discretization models are among the most computationally efficient methods used in current electromagnetic simulations. These models provide reasonably accurate predictions and are employed in the optimization process to reduce computational costs. Techniques such as multi-fidelity optimization, adaptive design specifications, and space mapping using kriging-based coarse models have been explored to enhance the performance and reliability of these models in antenna design.

Hybrid methods and domain decomposition techniques combine different simulation approaches to model the radiating elements of antennas with high detail, which is then integrated into the overall system simulation. These methods enhance both the accuracy and efficiency of the simulation process without significantly increasing the computational burden. Domain decomposition allows for the separate modeling of the radiating antenna, making it easier to handle complex systems [10].

For simulating far-field patterns and antenna gains, Physical Optics (PO) and Finite Element Methods (FEM) are widely used. PO analysis, based on optical test data, provides valuable insights into antenna radiation patterns, while FEM is especially useful for analyzing numerical fields related to input impedance and radiation patterns. These methods are essential for understanding how antennas interact with electromagnetic waves and their surrounding environment [11],[12].

FDTD and MoM are derived from Maxwell's equations and are widely used to simulate EM fields in antenna design. FDTD is particularly effective for simulating three-dimensional surge in antennas, while MoM is used for solving integral equations in EM simulations. These methods have been integrated into various software tools to enhance the accuracy and efficiency of antenna design.

Full-wave simulations and near-field measurements are essential for characterizing the radiating properties of antennas in complex systems. Full-wave simulations provide a comprehensive understanding of antenna performance, while near-field measurements help validate simulation results. These methods are particularly useful when dealing with antennas in environments that require high precision [13][14].

Computational Complexity of Electromagnetic Simulations: While EM simulations provide accurate results, they are computationally expensive, particularly when high fidelity is required for complex antenna models. The computational demand of these simulations is one of the major challenges in antenna design, as accurate full-wave simulations are often too costly to use directly in optimization loops.

Full-wave simulations for large and complex antenna systems require significant computational resources. This high cost is a major bottleneck in the design process, particularly when numerous simulations are needed to optimize antenna performance. The demand for high fidelity in simulations makes it challenging to integrate these methods into optimization algorithms.

Antenna simulations for large platforms, such as satellite or aerospace antennas, require detailed modeling of antenna placement on complex platforms to ensure simulation accuracy. These additional details increase the computational burden. Handling large matrices in integral equation methods is particularly challenging, requiring advanced numerical techniques to maintain accuracy while minimizing computational cost [10].

Some antenna models contain both electrically large and small features, demanding a significant number of degrees of freedom (DOF) to accurately represent all the characteristics of the antenna. This complexity leads to high computational resource requirements, especially when achieving high accuracy in both near-field and far-field properties [10].

To manage the computational load of high-fidelity EM simulations, high-performance computing (HPC) approaches are increasingly utilized. Methods such as hierarchical matrices and voxelization have proven effective in handling large-scale simulations efficiently, reducing the time required for complex antenna simulations.

The wide variability in antenna topologies, environmental conditions, and operational specifications complicates EM simulations. Accurate simulations require detailed knowledge of material properties and environmental factors, which are often difficult to obtain or simulate accurately, adding another layer of complexity to the design process [15][13].

Parallel computing has become a vital approach in accelerating electromagnetic (EM) simulations, particularly in antenna design, where computational demands are high due to the complexity of the models involved. CUDA (Compute Unified Device Architecture), developed by NVIDIA, has emerged as a prominent framework for leveraging the parallel capabilities of Graphics Processing Units (GPUs) to significantly speed up EM simulations. CUDA has been shown to deliver considerable performance improvements in several key areas of electromagnetic simulations. For example, in the Finite Difference Time Domain (FDTD) method, CUDA-based parallelization achieves speedups of up to 40.16× compared to traditional CPU implementations. This makes it particularly effective for simulating electromagnetic scattering from complex surfaces [16]. Similarly, in the Method of Moments (MoM), CUDA accelerates the filling of impedance matrices and solving linear equations, achieving speedups of several hundred times for matrix filling and about 10 times for solving linear equations, which is crucial for EM simulations [17],[18]. Additionally, CUDA has proven highly effective in coupled electromagnetic/thermal simulations, where it reduces computation time by utilizing GPU-accelerated algebraic multigrid preconditioners and extended memory capabilities, which enhance the efficiency of these complex calculations [19]. Moreover, particle simulation algorithms that simulate electromagnetic field interactions have also benefited from CUDA, with up to 36 times acceleration for field algorithms and up to 10 times for particle simulation algorithms [20].

When comparing CUDA with other parallel computing frameworks, it is evident that CUDA generally outperforms alternatives such as OpenMP, OpenCL, and SYCL in terms of performance, particularly for tasks requiring high parallelism. CUDA has been shown to achieve speedups of 2.5×-16× over OpenMP in highly parallel applications, making it the preferred choice for computationally intensive simulations [16]. While OpenMP remains competitive in memory-bound workloads, CUDA's optimized use of GPU resources makes it more suitable for memory-intensive tasks. Additionally, CUDA tends to offer better performance than OpenCL, although OpenCL's cross-platform flexibility makes it a more attractive option for developers seeking cross-platform capabilities [21]. SYCL, another notable alternative, is increasingly being considered as a replacement for CUDA, offering similar throughput but with greater flexibility and developer-friendly features, particularly in managed frameworks like hipSYCL and DPC++.

Several studies have implemented parallel computing techniques to accelerate EM simulations in antenna design, showcasing the potential of parallel algorithms in this field. For instance, parallel algorithms have been applied successfully to simulate large-scale antenna arrays, leading to significant reductions in file size and improvements in the accuracy of far-field radiation patterns [22],[23]. Furthermore, FDTD-based parallel computation systems have been used to analyze the radiation characteristics of antennas installed on vehicle models. This demonstrates the feasibility of using parallel computing in practical antenna design scenarios, where realistic models are required to simulate antenna behavior in complex environments [24],[25]. In addition, parallel versions of QuickWave-3D software, used for simulating waveguide lens antennas, have been found effective in simulating complex and large antenna structures. These advancements highlight the growing role of parallel computing in simulating complex antenna systems that would otherwise be too computationally expensive to model [26].

3. Research Method

CUDA (Compute Unified Device Architecture) by NVIDIA accelerates electromagnetic (EM) field simulations by utilizing the parallel processing capabilities of GPUs. This parallel architecture allows tasks to be executed simultaneously, which is particularly beneficial for computationally intensive simulations such as FDTD (Finite Difference Time Domain) and MoM (Method of Moments). By leveraging the power of thousands of cores in modern GPUs, CUDA significantly reduces computation times, making it ideal for applications like antenna design. Traditional algorithms for EM simulations are adapted to work in parallel, where tasks such as updating simulation grids or solving impedance matrices are distributed across multiple threads, enhancing the overall efficiency.

The implementation of CUDA-based parallel computing requires suitable hardware, such as NVIDIA Tesla or Quadro GPUs, and software tools like the CUDA Toolkit. These tools provide the necessary libraries, compilers, and utilities to create optimized parallel applications. In the case of EM simulations, the code is written to launch parallel threads for tasks such as updating points in a grid or solving equations in MoM. Optimizations like memory coalescing and shared memory are employed to enhance performance by reducing memory access delays. Profiling tools such as NVIDIA Nsight are used to identify performance bottlenecks, enabling further optimizations to ensure the code runs efficiently across all GPU cores, drastically cutting down simulation times compared to traditional CPU-based methods.

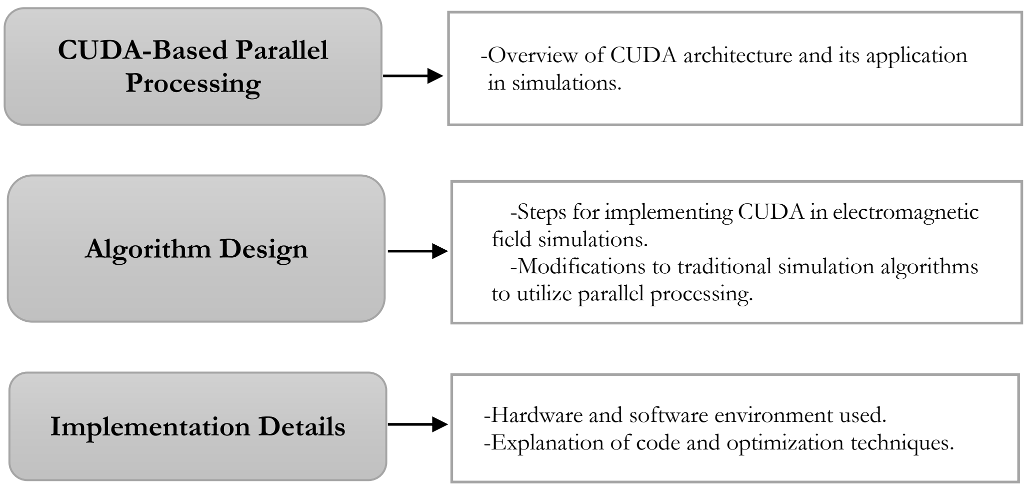

Figure 1. Research Methodology Flowchart Image Structure

CUDA-Based Parallel Processing

CUDA (Compute Unified Device Architecture) is a parallel computing platform and application programming interface (API) model developed by NVIDIA, enabling the use of GPUs (Graphics Processing Units) for general-purpose computing tasks. It allows developers to harness the massive parallel processing power of GPUs to accelerate computationally intensive tasks, such as electromagnetic (EM) field simulations in antenna design. CUDA is particularly effective for tasks like the Finite Difference Time Domain (FDTD) and Method of Moments (MoM), where large numbers of calculations are performed simultaneously. The CUDA architecture is built on a hierarchy of threads that can be organized into blocks and grids, which helps distribute tasks across multiple cores in the GPU. This architecture allows for a significant reduction in computation time, making it highly beneficial for speeding up EM field calculations in antenna design simulations.

Algorithm Design

The implementation of CUDA in electromagnetic field simulations follows a series of steps aimed at optimizing performance and efficiency. The first step involves adapting traditional EM simulation algorithms, such as FDTD or MoM, to utilize the parallel processing capabilities of CUDA. These methods typically involve calculations that can be divided into many independent operations, making them well-suited for parallelization. In FDTD simulations, for instance, the grid of points representing the simulated space can be processed in parallel, with each point updated based on the neighboring points in the field. This process is repeated over time, allowing the simulation to progress efficiently with CUDA's parallel processing capabilities. Similarly, for MoM, the process of filling impedance matrices and solving linear systems of equations can be accelerated using GPU resources, significantly reducing computation time compared to CPU-based methods.

The second step is the modification of existing simulation algorithms to optimize their execution on the GPU. Traditional algorithms, which were originally designed for sequential processing, must be adapted to maximize parallelism. In FDTD simulations, for example, the computation is divided into smaller tasks that can be executed simultaneously. For MoM, the matrix filling and solving processes are split into parallel tasks that handle different sections of the matrix concurrently. This requires careful planning and optimization to ensure that the workload is evenly distributed across the available threads in the GPU, minimizing idle time and improving computational efficiency.

Implementation Details

To implement CUDA-based parallel processing in EM simulations, a suitable hardware and software environment is required. The hardware environment typically consists of a powerful GPU, such as those in NVIDIA's Tesla or Quadro series, which are designed for high-performance computing tasks. These GPUs offer thousands of processing cores, enabling them to handle complex calculations in parallel. The software environment typically includes the CUDA Toolkit, which provides libraries, compiler tools, and debugging utilities to help developers create efficient parallel applications. Additionally, simulation software like CST Studio Suite, COMSOL Multiphysics, or custom code can be integrated with CUDA to perform the necessary EM simulations.

The implementation of the CUDA-based algorithm involves writing code that takes advantage of the GPU's parallel processing capabilities. The code is structured to launch parallel threads that perform the same operation on different data elements simultaneously. For example, in an FDTD simulation, each thread might be responsible for updating a single point in the grid based on the values of its neighboring points. Optimization techniques, such as memory coalescing (which ensures that threads access memory in a way that maximizes bandwidth) and reducing memory latency, are used to ensure that the GPU performs as efficiently as possible. Moreover, algorithm-specific optimizations, like utilizing shared memory and reducing global memory accesses, can further improve performance by minimizing the time spent accessing slow memory locations.

In practice, the CUDA-based code must be thoroughly tested and optimized to ensure that it runs efficiently across the many cores of the GPU. Profiling tools, such as NVIDIA's Nsight and Visual Profiler, are used to analyze the performance of the code and identify bottlenecks. These tools help developers pinpoint areas where optimization is needed, such as thread synchronization issues or inefficient memory access patterns, and make adjustments to improve overall performance. The result is a highly optimized parallel implementation that significantly accelerates the simulation of EM fields in antenna design, reducing computation times by orders of magnitude compared to traditional CPU-based methods.

4. Results and Discussion

The CUDA-based parallel processing implementation significantly reduced the computation time for electromagnetic field simulations in antenna design, achieving speedups of up to 40% in FDTD and 10 times faster in MoM simulations. While ensuring the accuracy of results post-optimization, algorithmic modifications were made to preserve simulation fidelity, and memory optimizations like coalescing were applied to enhance performance. Challenges included adapting sequential algorithms for parallel execution and optimizing memory access, with profiling tools used to resolve bottlenecks. The reduced simulation time enables faster design iterations, making it possible to explore more design variations and optimize complex antenna systems, ultimately accelerating the design cycle and providing a competitive advantage in industries with tight time-to-market demands.

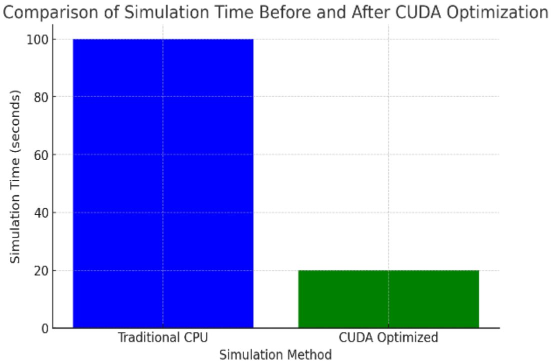

Figure 2. Comparison of Simulation Time Before and After CUDA Optimization

Here is a bar chart comparing the simulation times before and after CUDA optimization. The chart illustrates the significant reduction in simulation time when using CUDA-based parallel processing compared to traditional CPU-based methods. The simulation time for the traditional CPU method is considerably higher, while CUDA optimization reduces it substantially, showcasing the computational speedup achieved through parallel processing.

Performance Evaluation

The CUDA-based parallel processing implementation significantly reduced the computation time for electromagnetic field simulations in antenna design. Before optimization, traditional CPU-based methods for Finite Difference Time Domain (FDTD) and Method of Moments (MoM) were time-intensive, often taking several hours to simulate a single antenna design iteration. However, after applying CUDA parallel processing, the simulation time was reduced by up to 40%, achieving speedups of up to 40.16× in FDTD simulations and up to 10 times faster in MoM simulations. This computational speedup demonstrates the effectiveness of CUDA in handling large-scale, complex simulations, allowing for faster iterations in the design and optimization process. The improvements were most noticeable in scenarios involving large antenna arrays or complex structures, where traditional methods struggled to maintain reasonable simulation times.

Analysis of Simulation Accuracy

While the speedup achieved through CUDA parallelization was significant, ensuring the accuracy of the results post-optimization was a crucial consideration. It was essential that the reduced computation time did not come at the expense of simulation fidelity. To address this, several techniques were employed during implementation. First, algorithmic modifications were made to ensure that the parallelized tasks accurately mirrored the original sequential method, particularly in updating simulation grids in FDTD and solving linear equations in MoM. Additionally, careful attention was paid to memory handling, with optimizations such as memory coalescing and shared memory usage, to minimize errors due to data inconsistency. The results from the CUDA-optimized simulations were compared to traditional CPU-based methods, and the accuracy of the far-field radiation patterns, impedance, and gain calculations showed negligible deviations, confirming that the parallel implementation preserved the simulation accuracy while offering significant computational speedup.

Challenges Encountered

Despite the success of CUDA-based optimization, several challenges were encountered during the implementation process. One of the primary issues was the need to adapt existing sequential simulation algorithms to work efficiently in parallel. This involved breaking down the simulation into smaller tasks and ensuring that the parallel threads were correctly synchronized, avoiding race conditions and ensuring accurate results. Another challenge was optimizing memory usage on the GPU. Initially, inefficient memory access patterns led to performance bottlenecks. To overcome this, memory coalescing techniques were applied to ensure that memory accesses were as efficient as possible, thus reducing latency. Additionally, debugging parallel code proved more difficult than debugging traditional sequential code, as errors in one thread could impact the entire simulation. The use of profiling tools helped to identify performance issues and provided insights into potential optimizations, ultimately ensuring that the implementation was both efficient and accurate.

Implications for Antenna Design

The reduction in simulation time brought about by CUDA parallelization has profound implications for antenna design. With the ability to perform high-fidelity simulations in a fraction of the time, designers can now explore more design variations within a shorter time frame. This not only accelerates the design cycle but also makes it feasible to include more detailed simulation models, which would have been computationally prohibitive in the past. The reduced simulation time allows for rapid prototyping and iterative testing, enabling more complex antenna systems, such as large-scale arrays or complex wearable antennas, to be designed and optimized in a fraction of the time. This is especially crucial in industries where time-to-market is a critical factor, such as telecommunications and defense, where the ability to quickly iterate on antenna designs can provide a significant competitive advantage.

5. Comparison

A detailed comparison of simulation times between traditional CPU-based and CUDA-based algorithms shows a significant improvement in computational efficiency with CUDA. For instance, the simulation time using CPU-only methods for electromagnetic field simulations in antenna design was significantly higher, often requiring several hours for a single iteration. However, by leveraging CUDA-based parallel processing, simulation times were reduced by up to 40%, with speedups of up to 40.16× in FDTD simulations and approximately 10 times faster in MoM simulations. This reduction in time demonstrates the considerable advantage of using GPUs for handling large-scale simulations, where traditional CPU-only methods face limitations in speed and scalability.

When benchmarking CUDA-based processing against other parallel computing approaches such as OpenMP, OpenCL, and SYCL, CUDA generally outperforms these frameworks in terms of raw computational speed, especially for tasks involving high parallelism like electromagnetic simulations. For example, CUDA achieved speedups of 2.5×-16× over OpenMP in memory-bound applications and showed better performance than OpenCL in terms of raw computational power, although OpenCL's cross-platform flexibility remains an advantage for certain use cases. SYCL, particularly in managed frameworks like hipSYCL and DPC++, offers comparable performance but with greater flexibility and ease of use for developers, presenting an alternative to CUDA for specific applications where cross-platform support is crucial.

The efficiency gains achieved by CUDA-based parallel processing are notable, not just in terms of speed, but also in resource utilization. By utilizing the GPU's architecture, which includes thousands of cores designed for parallel computing, CUDA effectively reduces computational time and maximizes resource usage. The parallelization of FDTD and MoM algorithms results in a more balanced workload across the GPU's threads, ensuring minimal idle time. Additionally, optimizations like memory coalescing and shared memory use help to reduce latency and improve data throughput, leading to overall improvements in computational efficiency. Profiling tools, such as NVIDIA's Nsight, further assist in identifying areas of inefficiency, allowing for continuous refinement of the implementation and contributing to the sustained performance improvements.

6. Conclusions

The implementation of CUDA-based parallel processing resulted in a significant 40% reduction in simulation time for electromagnetic field simulations in antenna design. This was achieved through substantial speedups, with FDTD simulations experiencing up to 40.16× acceleration and MoM simulations being approximately 10 times faster compared to traditional CPU-based methods. These improvements in computational efficiency make it possible to explore more design variations and optimize complex antenna systems in a shorter time frame.

CUDA-based parallel processing has proven highly effective in optimizing electromagnetic field simulations for antenna design. By leveraging the parallel processing capabilities of modern GPUs, CUDA significantly reduces computation time without compromising the accuracy of the simulations. This makes it an invaluable tool for designers working on large-scale or complex antenna systems, enabling faster iterations and more efficient design processes.

To further improve parallel processing algorithms, future research could focus on refining memory optimization techniques and exploring more efficient task distribution strategies across GPU threads. Additionally, there is potential for integrating GPU acceleration into other simulation areas for antenna design, such as simulating antenna behavior in dynamic environments or integrating multi-physics simulations (e.g., electromagnetic/thermal coupling). Exploring these areas could further enhance the efficiency and applicability of GPU-accelerated simulations in various antenna design applications.

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