Guest Editorial Frontiers in Computational Electromagnetics—Part II

I. INTRODUCTION

THIS is a continuation of Part I of the Special Issue of IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION (TAP) on Frontiers in Computational Electromagnetics (CEM) at the intersection of methods, computing, and applications [1]. Its principal goal is to showcase the most recent developments, ideas, and results constituting the state-of-the-art CEM techniques to simulate problems of antennas and propagation and discuss the best and most visionary approaches as we move forward. To address the challenges of ever-increasing problem sizes and complexities, as well as the diversity of AP applications and modeling requirements, a range of electromagnetic simulation strategies and numerical discretization techniques are essential, with no single approach being universally optimal. CEM is both an art and a science, focusing on the development of these approaches.

Part II of the TAP CEM Special Issue features 15 papers. It starts with five papers on integral equations, then proceeds with four on the finite element method (FEM), followed by two works on time-domain techniques and two on optimization techniques, and finishes with two contributions to ray tracing (RT) methods.

II. INTEGRAL EQUATIONS

The first two papers focus on multilevel fast multipole algorithm (MLFMA)-based acceleration of surface integral equation (SIE) solvers. Kalfa et al. [A1] apply a multiple-arithmetic framework to the MLFMA hierarchical tree structure. This approach alleviates the low-frequency breakdown and the efficiency limitations of MLFMA for electrically large problems with fine geometrical details. Zhu et al. [A2] improve the MLFMA by making use of the recently developed directional fast multipole methods. However, unlike these methods, their method relies on plane-wave-based exponential expansions instead of equivalent source-based sampling. The resulting method achieves the optimal computational complexity irrespective of the dimensional features of the objects.

The remaining three papers are on various uses of integral equation formulations in electromagnetics. Ylä-Oijala et al. [A3] review the integral operator-based theory for characteristic mode analysis (CMA) of conducting, composite, and lossy structures. They compare the advantages and disadvantages of surface and volume integral operators for CMA in different scenarios and discuss the presence of spurious modes observed in the solutions of the generalized eigenvalue equation (GEE) constructed using these operators. Konno et al. [A4] propose an SIE solver to analyze antennas above a 2-D infinite periodic array of scatterers. The array is not meshed but modeled as an infinite reflecting plane that contributes to the matrix entries of the SIE solver with a reflected wave component (similar to the use of layered medium Green's function). Several numerical results are presented to demonstrate the effectiveness of this new method. Tihon et al. [A5] developed a method to efficiently compute the dispersion surfaces of printed periodic structures in layered media. This method uses a periodic SIE solver and a tracking algorithm to represent the dispersion surface as a superposition of parameterized iso-frequency curves. The authors validate their method against commercial software and show it to be accurate and efficient.

III. FINITE ELEMENT METHOD

In Part II of this Special Issue, there are four papers focusing on FEM. Zhao et al. [A6] combine hybridizable discontinuous Galerkin (HDG) and boundary integral (BI) methods to efficiently analyze electromagnetic scattering from inhomogeneous and composite objects. The coupling between the two formulations is carried out using numerical flux and the resulting coupled system of equations is solved using an MLFMA accelerated iterative solver. Within the matrix-vector multiplication subroutine of the iterations, the inverse of the HDG matrix is efficiently accounted for using a sparse direct matrix solver. Numerical experiments demonstrate the accuracy and efficiency of this HDG-BI solver. Tóth et al. [A7] present a general and efficient method to calculate mass and stiffness matrices of H(curl)-conforming finite elements in both curvilinear geometries and inhomogeneous materials. This method preserves the null space of the curl operator and relies on the expansion of finite element integrals in a series of multivariate polynomials. The resulting element matrices can be integrated analytically using predefined universal matrices. Amor-Martin et al. [A8] integrate a nonoverlapping, nonconformal, and cement-element-based domain decomposition method (DDM) into FEM to efficiently solve Maxwell equations for large-scale problems. They use the method of manufactured solutions (MMS) to implement DDM in a step-by-step manner: decouple subdomains using absorbing boundary conditions, introduce different transmission conditions to couple them, and combine direct/iterative schemes to solve

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resulting matrix equations. The results show that this DDM-FEM achieves the theoretically predicted convergence rate in accuracy. Wu et al. [A9] propose a goal-oriented adaptive FEM to analyze electromagnetic radiation problems involving complex geometries. The new error indicator, which enables refinement of mesh in regions that are selected based on the parameters of interest, helps to improve FEM's accuracy and efficiency. Numerical simulations of two practical antennas demonstrate the advantages of this new goal-oriented adaptive FEM over existing h-adaptive FEM used in commercial software packages.

IV. Time-Domain Techniques

The next part of the Special Issue consists of two papers focusing on time-domain techniques. Štumpf et al. [A10] investigate the transient excitation of a narrow slot on a perfectly electrically conducting that separates two homogeneous dielectric half-spaces. The problem is formulated using the time-domain Lorentz reciprocity theorem and numerically solved using the Cagniard–De Hoop method of moments. Nayak et al. [A11] developed a data-driven reduced order model (ROM) for rapid analysis and extrapolation of the time-domain response in resonant cavities. They apply the Hankel-dynamic mode decomposition (DMD) algorithm on the FDTD data to extract the spatial and temporal mode features and build an accurate and predictive ROM. This ROM is then used to forecast the cavity electric field at any time instant with a very small computation cost.

V. Optimization Techniques

This is followed by two papers advancing optimization techniques. Lim et al. [A12] propose a physics-based approach inspired by the statistical mechanics of correlated spins and adiabatic quantum computing to optimize phase configurations of intelligent surfaces. The problem of optimizing a phase configuration is transformed into the problem of finding the ground state of the target Ising Hamiltonian, which can be solved very efficiently using heuristic quantum optimization algorithms. The authors demonstrate the feasibility of combinatorial optimization for weighted beamforming and diffusive scattering applications using this new method. Papathanasopoulos et al. [A13] introduce an optimization assisted by a neural network (ONN) predictor and demonstrate its effectiveness in antenna design. ONN is a surrogate model-based optimization approach that utilizes a neural network to efficiently approximate the objective function. The results presented in the paper demonstrate that ONN requires fewer objective function evaluations and achieves better optimal points compared to baseline optimization algorithms. This new method is used in the design of two practical antennas: a Yagi–Uda antenna and a dual-band slotted patch antenna.

VI. Ray Tracing Methods

Finally, there are two papers dealing with ray tracing (RT) methods. Kasdorf et al. [A14] propose a novel unified parallelization framework, consisting of algorithms, strategies, and data structures, to radically enhance the efficiency of the shooting and bouncing ray (SBR) method for RT propagation modeling. The authors perform comprehensive parallelization on graphics processing units (GPUs) of all components of the SBR algorithm, including electric field computation and post-processing tasks being traditionally limited to sequential operation. With this, the new SBR methodology achieves massive parallel versus serial speedups and upwards of 99% parallelism under Amdahl's parallelization scaling law, without sacrificing the previously advanced and established accuracy of the method. Na et al. [A15] propose a new ray tracing framework that uses Huygens surfaces to divide complex environments into smaller subdomains and Huygens sources to connect the ray-based field representations in neighboring subdomains. This approach is more accurate than the conventional SBR methods since it reduces errors caused by ray misses. It is more efficient than the methods that rely on the uniform theory of diffraction (UTD) since it separates diffraction edges into different subdomains and avoids the exponential increase in the number of diffracted rays. The authors implement the method on GPUs, which enables massively parallelized simulations.

These papers, along with those published in Part I of this Special Issue, clearly demonstrate that the state of CEM for antennas and propagation, as well as other applications, is indeed very strong. While this Special Issue highlights significant advancements in the field, many challenges and open problems remain in CEM-based analysis, modeling, and design. We anticipate the emergence of numerous ground-breaking CEM approaches in computational methodologies, numerical discretization techniques, and harnessing the ever-increasing computing power, all fueled by future applications and evolving challenges. So, until the next TAP CEM Special Issue. Are those four, now more than 150 years old, Maxwell's equations ever going to be definitely solved?

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Appendix: Related Articles

[A1] M. Kalfa, Ö. Ergül, and V. B. Ertürk, "Multiple-precision arithmetic implementation of the multilevel fast multipole algorithm," *IEEE Trans. Antennas Propag.*, vol. 72, no. 1, pp. 11–21, Jan. 2024.

[A2] G.-Y. Zhu, W.-D. Li, W. E. I. Sha, H.-X. Zhou, and W. Hong, "A directional multilevel complex-space fast multipole algorithm for electrically large problems of various dimensions," *IEEE Trans. Antennas Propag.*, vol. 72, no. 1, pp. 22–36, Jan. 2024.

[A3] P. Ylä-Oijala, M. Kuosmanen, and H. Wallén, "Integral operator-based characteristic mode theory for conducting, material, and lossy structures," *IEEE Trans. Antennas Propag.*, vol. 72, no. 1, pp. 37–49, Jan. 2024.

[A4] K. Konno, N. Haga, J. Chararothai, Q. Chen, N. Nakamoto, and T. Takahashi, "A novel method of moments for numerical analysis of antennas over two-dimensional infinite periodic arrays of scatterers," *IEEE Trans. Antennas Propag.*, vol. 72, no. 1, pp. 50–60, Jan. 2024.

[A5] D. Tihon, S. N. Jha, M. Bodehou, and C. Craeye, "Efficient tracking of dispersion surfaces for printed structures using the method of moments," *IEEE Trans. Antennas Propag.*, vol. 72, no. 1, pp. 61–74, Jan. 2024.

[A6] R. Zhao, M. Dong, L. Chen, J. Hu, and H. Bagci, "A coupled hybridizable discontinuous Galerkin and boundary integral method for analyzing electromagnetic scattering," *IEEE Trans. Antennas Propag.*, vol. 72, no. 1, pp. 75–88, Jan. 2024.

[A7] L. L. Tóth, A. Amor-Martin, and R. Dyczij-Edlinger, "Hierarchical universal matrices for curvilinear tetrahedral $H(curl)$ finite elements with inhomogeneous material properties," *IEEE Trans. Antennas Propag.*, vol. 72, no. 1, pp. 89–99, Jan. 2024.

[A8] A. Amor-Martin, L. E. Garcia-Castillo, L. L. Tóth, O. Floch, and R. Dyczij-Edlinger, "A rigorous code verification process of the domain decomposition method in a finite element method for electromagnetics," *IEEE Trans. Antennas Propag.*, vol. 72, no. 1, pp. 100–109, Jan. 2024.

[A9] H. Wu, K. Fu, S. Zuo, Z. Lin, X. Zhao, and Y. Zhang, "An efficient goal-oriented adaptive finite element method for accurate simulation of complex electromagnetic radiation problems," *IEEE Trans. Antennas Propag.*, vol. 72, no. 1, pp. 110–122, Jan. 2024.

[A10] M. Štumpf, G. Antonini, and I. E. Lager, "Pulsed electromagnetic excitation of a narrow slot between two dielectric halfspaces," *IEEE Trans. Antennas Propag.*, vol. 72, no. 1, pp. 123–130, Jan. 2024.

[A11] I. Nayak, F. L. Teixeira, and R. J. Burkholder, "On-the-fly dynamic mode decomposition for rapid time-extrapolation and analysis of cavity resonances," *IEEE Trans. Antennas Propag.*, vol. 72, no. 1, pp. 131–146, Jan. 2024.

[A12] Q. J. Lim, C. Ross, A. Ghosh, F. Vook, G. Gradoni, and Z. Peng, "Quantum-assisted combinatorial optimization for reconfigurable intelligent surfaces in smart electromagnetic environments," *IEEE Trans. Antennas Propag.*, vol. 72, no. 1, pp. 147–159, Jan. 2024.

[A13] A. Papathanasopoulos, P. A. Apostolopoulos, and Y. Rahmat-Samii, "Optimization assisted by neural network-based machine learning in electromagnetic applications," *IEEE Trans. Antennas Propag.*, vol. 72, no. 1, pp. 160–173, Jan. 2024.

[A14] S. Kasdorf, B. Troksa, C. Key, J. Harmon, S. Pasricha, and B. M. Notaroš, "Parallel GPU optimization of the shooting and bouncing ray tracing methodology for propagation modeling," *IEEE Trans. Antennas Propag.*, vol. 72, no. 1, pp. 174–182, Jan. 2024.

[A15] H. Na, M. M. Taygur, and T. F. Eibert, "A multiple Huygens surface based ray tracing framework with GPU acceleration," *IEEE Trans. Antennas Propag.*, vol. 72, no. 1, pp. 183–196, Jan. 2024.

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[1] B. M. Notaroš, F. P. Andriulli, and H. Bagci, "Guest editorial frontiers in computational electromagnetics," *IEEE Trans. Antennas Propag.*, vol. 71, no. 12, pp. 9175–9177, Dec. 2023.