Sarcouncil Journal of Multidisciplinary

ISSN(Online): 2945-3445

Volume- 05| Issue- 12| 2025

Research Article **Received:** 01-11-2025 | **Accepted:** 25-11-2025 | **Published:** 10-12-2025

The Role of Computational Electromagnetics in National Defense and Infrastructure Security

***Yaw Owusu-Agyemang* [1] *and Adwoa Agyeiwaa Ampomah-Britwum* [2]**

[1] *Department of Mathematical Sciences, George Mason University, USA*
[2] *Kwame Nkrumah University of Science and Technology, Ghana*

Abstract: The electromagnetic spectrum has become a cornerstone of modern technological society, underpinning critical functions in both national defense and civilian infrastructure sectors. It is, therefore, a strategic imperative to have dominance and security in this domain Computational Electromagnetics (CEM), an engineering art in which one is able to solve Maxwell's equations numerically for simulating complex electromagnetic phenomena, has proven to be an enabling technology that is essential for these endeavors. In this paper, we describe the centrality of CEM in reaching the goals of ensuring national defense and critical infrastructure against the ever-expanding threat milieu. This paper recombines recent advances and identifies critical thematic domains where CEM is pushing transformative progress. Such developments also handle design and analysis of low observable platforms and counter stealth technologies, fusion of CEM with artificial intelligence (AI) enabling cognitive electronic warfare and spectrum dominance, modelling and mitigation of threats like high altitude electromagnetic pulse (HEMP) and intentional electromagnetic interference (IEMI) for infrastructure protection, as well as novel state of the art antenna systems for superior communication, sensing and navigation. Through the review of the key applications, this paper shows the development of CEM applications, from a special-purpose design tool to a strategic asset for virtual prototyping, threat evaluation, and mission planning. In addition, this article pinpoints the future emerging research directions, such as real-time multiphysics simulation, AI-accelerated solver, and the inception of quantum-enhanced electromagnetics. In the end, this work surmises that innovation in CEM remains essential to asserting a continued decisive advantage in the CEM domain and combating the erosion of modern society's infrastructure hardening over the years.

Keywords: Computational Electromagnetics, National Defense, Infrastructure Security, Electromagnetic Warfare, Stealth Technology, Electromagnetic Pulse, Artificial Intelligence.

INTRODUCTION

The electromagnetic (EM) spectrum, an invisible and pervasive natural resource, has become one of the most critical and contested domains of the 21st century. It serves as the fundamental medium for nearly every modern technology, from global communication and navigation systems to sophisticated sensors and data links that form the central nervous system of modern military forces (Katrakazas & Papastergiou, 2024). The ability to control, exploit, and secure this spectrum is no longer merely a technical advantage but a strategic imperative that directly impacts national security, economic stability, and societal resilience. As reliance on the EM spectrum intensifies, so do the vulnerabilities and sophistication of threats designed to disrupt or deny its use. In this complex and dynamic environment, Computational Electromagnetics (CEM) has become the core scientific discipline for understanding, predicting, and engineering outcomes within the electromagnetic domain (Freno *et al.*, 2024).

Computational Electromagnetics encompasses a broad suite of numerical methods and algorithms developed to solve Maxwell's equations for problems whose analytical solutions are intractable. These fundamental equations, which govern all classical electromagnetic phenomena, are expressed in their differential form as:

- **Gauss's Law for Electricity:**
- $\nabla \cdot D = \rho v$
- **Gauss's Law for Magnetism:**
- $\nabla \cdot B = 0$
- **Faraday's Law of Induction:**
- $\nabla \times E = -\partial t \partial B$
- **Ampère's Circuital Law (with Maxwell's addition):**

$\nabla \times H = J + \partial t \partial D$

By discretizing space and time, CEM techniques, such as the Finite-Difference Time-Domain (FDTD) method, Method of Moments (MoM), and Finite Element Method (FEM), allow for the high-fidelity simulation of EM wave propagation, scattering, radiation, and interaction with complex materials and structures. This predictive power offers a profound advantage over the traditional design cycle of empirical testing and physical prototyping, which are often slow, prohibitively expensive, and limited in scope. The development of faster and more efficient methods within CEM has been a continuous focus, driven largely by the demanding requirements of the defense and aerospace sectors, where early computational

Copyright © 2021 The Author(s): This work is licensed under a Creative Commons Attribution- NonCommercial-NoDerivatives 4.0 (CC BY-NC-ND 4.0) International License

***Corresponding Author:** Yaw Owusu-Agyemang

DOI- https://doi.org/10.5281/zenodo.17878799

codes found their first major applications (Wingren, 2024). By enabling the creation of "digital twins" and virtual testbeds, CEM allows researchers and engineers to explore novel designs, evaluate system performance under diverse operational conditions, and analyze vulnerabilities with a level of detail and speed that was previously unimaginable.

In the context of national defense, the influence of CEM is both pervasive and foundational. The strategic landscape is increasingly defined by technologies that are fundamentally electromagnetic. Many of these capabilities originate in defense laboratories and are driven by national security priorities before finding wider use (Mazal, 2024). The development of low-observable (stealth) aircraft and naval vessels, for instance, is critically dependent on CEM to minimize the radar cross-section (RCS) through geometric shaping and the application of advanced radar-absorbing materials. In electronic warfare (EW), CEM is essential for designing powerful jamming systems, optimizing antenna arrays for signal intelligence, and simulating the complex interplay between friendly and hostile assets in a congested spectrum. Furthermore, modern radar and sensor systems, which form the backbone of intelligence, surveillance, and reconnaissance (ISR) capabilities, are designed and optimized using CEM to enhance the detection range, improve target discrimination, and develop resilience against countermeasures (Cardillo, 2025). The integration of these disparate electromagnetic systems onto military platforms without debilitating interference, a challenge known as electromagnetic compatibility and interference (EMC/EMI), is a complex problem that can only be solved through rigorous CEM modeling.

Concurrently, the proliferation of EM-sensitive electronics in civilian life has created a new frontier of vulnerability in critical national infrastructure. Power grids, communication networks, financial systems, transportation control, and water treatment facilities are governed by intricate networks of sensors, actuators, and industrial control systems (ICS). This digital dependence renders them susceptible to a range of electromagnetic threats, including high-altitude electromagnetic pulses (HEMP) generated by nuclear detonation, localized attacks from intentional electromagnetic interference (IEMI) devices or directed energy weapons (DEW), and severe geomagnetic storms (Khan, 2025). A successful attack on these systems can trigger a cascade of failures with devastating consequences for national security and societal well-being. CEM provides an essential toolkit for assessing these vulnerabilities, modeling the coupling of destructive EM energy into critical systems, and designing and validating effective hardening and mitigation strategies. This includes the engineering of shielded enclosures, development of robust filtering and surge protection devices, and architectural design of resilient networks (Riggs, 2023).

The challenges of national defense and infrastructure security are not disparate; they are deeply intertwined in the shared electromagnetic environment. The security of military installations and the capacity for force projection rely on the stability of civilian power grids and communication backbones. Conversely, technologies and strategies developed for military spectrum dominance have direct applications in securing civilian networks, representing a classic case of dual-use innovation (Mazal 2024). An adversary could exploit vulnerabilities in civilian infrastructure as an asymmetric means of undermining a nation's defense capabilities. This convergence requires a comprehensive strategy where CEM acts as a unified analytical framework to comprehend threats and devise solutions in both areas. The need to manage this shared battlespace, fraught with issues such as clutter and electromagnetic interference from multiple sources, is a challenge common to both military and civilian applications (Cardillo, 2025).

This review is motivated by the rapid acceleration of CEM capabilities in recent years, propelled by the confluence of three major trends: the exponential growth in high-performance computing (HPC), significant breakthroughs in numerical algorithms and solvers, and the emergence of artificial intelligence (AI) and machine learning (ML) as transformative force multipliers. These advancements enable simulations of unprecedented scale, speed, and physical realism, moving the discipline closer to the goal of real-time predictive analysis. Consequently, CEM is transitioning from a specialized, non-real-time design tool to a dynamic operational asset capable of informing tactical decisions and enabling autonomous, adaptive EM systems. The ability to rapidly simulate and predict outcomes in the electromagnetic domain represents a paradigm shift, offering new pathways to secure strategic advantages.

Copyright © 2021 The Author(s): This work is licensed under a Creative Commons Attribution- NonCommercial-NoDerivatives 4.0 (CC BY-NC-ND 4.0) International License

Publisher: SARC Publisher

EMERGING TRENDS AND THEMATIC ANALYSIS

The relevance of the electromagnetic (EM) spectrum in contemporary defense and security applications is undeniable. Steal aircraft technology to the resilience of a nation's power grid, the ability to control electromagnetic waves is a key to maintaining technological dominance (Willy,2023). The electromagnetic (EM) modelling, prediction, and optimization of EM phenomenon over contested environment is now a significant challenge and requires a huge system to simulate it (Matt, 2023). In this section, we present a thematic analysis of the emerging trends in CEM based on the application of CEM to two key areas of operation: the enduring cat-and-mouse game between stealth and counter-stealth technologies and the transformative effect of artificial intelligence (AI) on the practice of electronic warfare. Such regions provide examples of how high-fidelity simulation is influencing next-generation defense capabilities and infrastructure security paradigms.

Advanced Modeling for Stealth, Counter-Stealth, and Signature Management

Technology to make objects less visible to radar and other sensors has been around for decades, efforts such as the stealthy "LO" (low-observable) technologies that enable some military systems to avoid being detected by electronic means. This unseen arms race is essentially a battle for electromagnetic signature control. The CEM has emerged as the principal engine of innovation for this class of systems, as it has served as the source for increasingly stealthy platform concepts and it has also provided pathways for embodiments of sensing technologies that can counter those concepts.

Designing Low-Observable Platforms with High-Fidelity CEM

The core principle of stealth technology is the reduction of a platform's Radar Cross-Section (RCS), which is a measure of its detectability by radar. High-fidelity CEM enables designers to achieve this reduction through two primary methods: geometric shaping and the application of specialized materials (Zhong *et al.*, 2020). Modern CEM solvers, which utilize techniques such as the Finite Element Method (FEM), Method of Moments (MoM), and Finite-Difference Time-Domain (FDTD), allow engineers to simulate the interaction of electromagnetic waves with complex, full-scale models of aircraft, ships, and ground vehicles with unprecedented accuracy (Gibson,2021).

These computational models can predict the RCS of a platform from any angle and at any frequency, allowing the optimization of its shape to deflect radar energy away from the illuminating source rather than scattering it back (. This process of "shaping" involves the careful design of faceted surfaces, blended wing-body configurations, and shielded engine inlets and exhausts, all of which would be prohibitively expensive and time-consuming to optimize through physical prototyping alone (Muhammed et al, 2024). CEM allows thousands of virtual design iterations, where the precise angle of a control surface or the curve of a fuselage can be tuned to minimize the overall radar signature. This virtual design environment accelerates the development cycle, reduces costs, and ultimately leads to more effective and robust low-observable designs optimized across a wide range of operational scenarios. The predictive power of CEM ensures that by the time a physical prototype is built, its electromagnetic performance is well understood and validated.

Novel Materials and Metamaterials for Signature Control

Aside from shaping, there are the materials that are used to build these platforms, and they heavily influence the electromagnetic signature as well. The historical application of RAM on military platforms has drastically shifted with the evolution of CEM-enabled material science (Portes, 2024). Advanced material, including composite and metamaterials with specific EM features, can also be designed and analyzed with the help of modern CEM tools. And these are not just passive absorbers: they are engineered 'metamaterial' structures intended to control electromagnetic waves in non-intuitive ways.

Metamaterials, which have the properties related to the sub-wavelength scale, and not to their chemical composition, are computationally designed to exhibit negative permeability or negative permittivity, such as an ability, for instance allows to obtain electromagnetic (EM) wave cloaking, perfect absorption at given frequency bands, etc. CEMs are crucial to this process, as they enable researchers to simulate complex electromagnetic interactions with such intricate microstructures. Simulations can be used to design metamaterial unit cells in terms of their shape, their size, and their pattern to form an absorbing layer, to realize, for example, broadband absorbers, frequency-

Copyright © 2021 The Author(s): This work is licensed under a Creative Commons Attribution- NonCommercial-NoDerivatives 4.0 (CC BY-NC-ND 4.0) International License

Publisher: SARC Publisher

selective surfaces that are transparent to friendly communication but opaque to hostile radar or surfaces that scatter incident energy in a controlled fashion over a broad angle. Integrating CEM-designed materials into the skin and substructure of a vehicle can also provide significant signature reduction without compromising the aerodynamics or structural integrity of the platform. This computational design of materials is leading to adaptive signature control, in which the electromagnetic behavior of the surface of a platform may be modified in real time in response to changes in the threat environment.

CEM-Driven Advancements in Radar and Sensor Technology for Counter-Stealth

The CEM concepts that are exploited in the design of stealth platforms are the same that are exploited to defeat them. Radar and sensor technologies have been revolutionized to cope with the difficulty of detecting low-observable targets, where CEM has acted as a principal research and development process. Contemporary air defense radars must be developed and built to face two different challenges: the first is the low signal-to-noise ratio (SNR) and the second is the sophisticated enemy jamming, and CEM plays a significant role in the design of these systems (Zohuri, 2020).

CEM allows researchers to innovate and test new radar concepts that are more sensitive to weak returns from low-observable targets. These are known to include low frequency radars which are able to take advantage of resonance effects within a stealth aircraft, and bi-static or multi-static radars which configure the transmitters and receivers spatially apart from each other so as to collect energy that is otherwise deflected by the shaping of a stealth platform (Gang et al, 2020). CEM enables the optimization of transmitter and receiver positions and three dimensional signal distributions, simulates complex signal propagation paths (e.g., diffraction, reflection, and scattering from objects oriented in a large numbers of ways), and simulates signal observers that can process signals from multiple sensors to compile a coherent track on, for example, a low-observable target (Zheng et al,2024). In addition, CEM is employed for the synthesis of modern radar waveforms like noise radar or the spectrally agile pulses, which are jamming resistant and have low probability of interception. Simulating the entire engagement (from the radar transmission to the mutual interaction with the target, to the signal processing at the receiver), counter-STE techniques development is here supported to provide an up-to-date response to the co-evolution of the “cat-and-mouse” game between stealth technologies and their detection.

The Convergence of CEM and Artificial Intelligence in Electronic Warfare

EW (i.e. Electronic Warfare) is the science and art of controlling the electromagnetic spectrum in time to get an advantage in the law governing spectrum operations. It covers electronic attack (EA) to disrupt or deceive electronic systems in use by the enemy, electronic protection (EP) to protect friendly systems from electronic attack, and electronic support (ES) to sense, identify, and/or locate sources of intentional and unintentional radiated electromagnetic energy for the purpose of immediate threat recognition, targeting, planning, and conduct of future operations((Haigh et al, 2021). Today electronic warfare (EW) has become more complex, dense, and agile than ever before. The intersection of CEM with Artificial Intelligence (AI) and Machine Learning (ML) is set to drive a step change in how to address this landscape: a new breed of cognitive EW systems that can operate autonomously and adaptively (Pace, 2022).

AI-Enhanced Spectrum Dominance and Cognitive EW

"Spectrum dominance" aims for freedom of maneuver in the electromagnetic spectrum for friendly forces and denial for opponents (Shephard Media, 2022). Classic EW systems use a preinstalled threat library, which is insufficient when encountering new or adapting enemy emitters (Haigh & Andrusenko, 2021; IP Inter Populum, 2025). Cognitive EW denotes a radical change of paradigm due to the fact that AI and ML algorithms will be employed to permit systems to sense, understand and act in real time in the EM environment. CEM is the ground truth for such paradigm, as it provides high-fidelity data required to train the AI models.

CEM simulations can provide large and diverse datasets capturing many electromagnetic effects, e.g., multiple signal interactions, changing atmospheric conditions, and different antenna systems. Algorithms for artificial intelligence (AI) trained on such data could quickly classify unknown signals, identify the type and location of hostile emitters and predict an adversary’s intent. This AI-enabled situational awareness enables an EW system to decide for itself what the best response should be for example, providing a distinctive jamming signal at the right time,

Copyright © 2021 The Author(s): This work is licensed under a Creative Commons Attribution- NonCommercial-NoDerivatives 4.0 (CC BY-NC-ND 4.0) International License

Publisher: SARC Publisher

performing a feinting maneuver, or even altering its own electromagnetic emission to prevent being detected. This would move the EW from a reactive to a proactive discipline with AI-enabled proactive defense against EM interference and other threats being anticipated and neutralized before they have the potential to affect mission success (Sfetcu 2024). The combination of CEM-generated synthetic environments and AI-enabled decision making is the key to realizing spectrum dominance in future wars."

Advanced Simulation for Developing and Testing EW Systems

The development and testing of advanced EW systems present significant challenges. Live, open-air testing is expensive, constrained by safety and environmental regulations, and may inadvertently reveal sensitive capabilities to adversaries (David & Bernstein, 2020). CEM provides a powerful solution by creating a "digital twin" or virtual proving ground where EW systems can be rigorously evaluated in a controlled and repeatable laboratory setting (Travieso-González et al, 2021). These advanced simulations constitute a critical component of modern defense acquisition and training (Choi *et al.,* 2020).

Using CEM, engineers can construct highly realistic virtual environments that replicate the electromagnetic complexity of real-world battlefields. These simulations can model hundreds or thousands of emitters simultaneously including friendly forces, enemy radars, civilian broadcasts, and communication networks, all interacting within a dynamic physical landscape (Choi *et al.,* 2020). Within this virtual space, developers can test the performance of a new EW system against a wide array of existing and anticipated threats. They can evaluate the effectiveness of different jamming techniques, assess the system's vulnerability to electronic attack, and analyze its compatibility with other on-platform electronic systems to mitigate co-site interference (Davis et al, 2023). This simulation-based approach allows for rapid iteration and optimization of both hardware and software, ensuring that systems are mature and effective before being deployed (David & Bernstein, 2020).

Furthermore, these virtual environments can be used to train EW operators, allowing them to experience and respond to realistic combat scenarios without the cost and risk of live exercises (Tanner *et al.,* 2021).

Digital Radio Frequency Memory (DRFM) and Next-Generation Jamming

One of the key components in many of today's electronic attack systems is the Digital Radio Frequency Memory (DRFM). A DRFM type jammer records the signal of an enemy radar digitally, makes a calculated modification, and retransmits the modified signal to fool enemy radar (Pace 2022). This phenomenon makes false targets, masks the actual position of a platform or disturbs the radar's tracking ability. Jamming techniques based on the principles of providing false target returns to a radar typically rely on the ability to generate a deceptive signal that the target radar will believe. CEM in this is a necessity.

CEM is used to simulate the entire engagement of the DRFM jammer and the target radar system including all modern types such as SAR (Pace, 2022). It is possible for simulations to assess the nuances of pulse compression and signal processing logic of the radar in detail and enable them to define DRFM-generated waveforms that make efficient use of inherent gaps exposed in the logic. For example, CEM may inform deception invention to produce, for one, multiple false targets each having realistic velocity and acceleration profiles or to generate signals, which subtly manipulate the radar's range gate to drag outside true target. With AI the ability to do so skyrockets as ANS has stated that it would be able to do "cognitive jamming," a process in which the DRFM system can evaluate an unknown type of radar signal and then create a custom-crafted, optimized, deceptive signal against it on-the-fly. The Whole New Ball Game Eventually, evolution of CEM, AI, and advanced computing has ushered in the era of intelligent, highly effective electronic attack systems with the capability of re-purposing in evolving EW landscape (Zohuri, 2020).

Securing Critical Infrastructure Against Electromagnetic Threats

The nation's defense perimeter no longer is confined to the traditional military battlefields but now includes the broad, interconnecting networks that support and underpin modern-day societies. Nowadays, critical infrastructure such as power systems, communication networks, financial systems, and transportation control heavily depends on intelligent electronics, and is the "low hanging fruit" in electromagnetic threat (Gurevich et al,2023). These threats may be intentional, as in the case of an attack with a directed energy weapon, or unintentional, as in the case of the secondary effects of high-altitude nuclear

Copyright © 2021 The Author(s): This work is licensed under a Creative Commons Attribution- NonCommercial-NoDerivatives 4.0 (CC BY-NC-ND 4.0) International License

Publisher: SARC Publisher

detonation. Computational electromagnetics is integral to addressing these vulnerabilities, predicting their effects and designing systems that are robust enough to tolerate and recover from these assaults. Simulating an environment to generate realistic synthetic data, assess defensive measures and examine weaknesses has become pivotal to preparing for modern security challenges from the cyber domain to the physical electromagnetic domain (Serena, 2025).

Modeling and Mitigating High-Altitude Electromagnetic Pulse (HEMP) Effects

One key aspect of national infrastructure security is the targeting of high-altitude electromagnetic pulses (HEMP). HEMP events are generated by a nuclear weapon detonating in the ionosphere. The wave front of a HEMP source consists of several powerful, broadband electromagnetic fields that can blanket entire continental-sized regions. The first high-frequency (E1) component is especially harmful, capable of creating destructive voltages and currents in cables and wires (of any size), including electric power cables, telecommunications and data and control cables, all types and sizes of antennas and antenna feeds, waveguides, metallic structures, e.g., towers, poles, etc., and conductive traces in solid-state components built into integrated circuits and thick-film structures that are in any way connected to external cables and/or antennas while the EMP event is naturally occurring. These subsequent intermediate (E2) and late-time (E3) waves are particularly dangerous to very long-line infrastructure, looking like the low-frequency extremes of classically dissectible lightning and geomagnetic storm effects.

CEM is essential for determining the level of threat due to HEMP and for devising strategies for mitigating the threat. Both full-wave and hybrid simulation approaches were employed to simulate the complete chain of effects starting from complex fields generated and scattered in the initial pulse generation and propagation to the atmosphere and its interaction with the national infrastructure. CEM codes would be capable of simulating how HEMP’s energy couples into the power network, communications cables, and pipelines and can estimate the currents and voltage that would feed the system. These simulations enable engineers and planners to understand which nodes have the most important and most vulnerable components. In addition, the CEM served for the modeling and validation of hardening. This would include simulation of the shielding effectiveness of protected structures, performance modelling of surge-arresting devices and filters, and ensuring that back-up power and control systems are adequately hardened to survive an event. This system response evaluation in high electromagnetic field environments is essential for maintaining the survivability of assets critical to national security (Sherburne,2024). Running numerous virtual scenarios, CEM provides an economical means for the evaluation of overall grid resilience to a wide range of HEMP waveforms and attack parameters, thus guiding infrastructure hardening investments.

Countering Intentional Electromagnetic Interference (IEMI) and Directed Energy Weapons

While HEMP represents a large-scale, catastrophic threat, the risk from localized Intentional Electromagnetic Interference (IEMI) and Directed Energy Weapons (DEW) is more immediate and accessible to a wider range of adversaries. These threats involve the use of compact, high-power microwave (HPM) sources to deliberately disrupt, damage or destroy targeted electronic systems. Unlike the wide-area impact of HEMP, IEMI attacks can be surgical, targeting specific facilities such as data centers, stock exchanges, air traffic control towers, or military command posts with focused beams of intense electromagnetic energy.

CEM plays a leading role in both defensive and offensive capabilities related to the IEMI. CEM simulations are used to perform detailed vulnerability assessments of critical facilities. Simulators model the "front-door" coupling of HPM energy through antennas and intentional openings, as well as the more insidious "back-door" coupling through seams, connectors, power cables, and other unintentional points of entry. These high-fidelity models can predict the field strength and current distribution inside a facility and identify the specific pieces of equipment that are most likely to be affected. This allows for the strategic implementation of countermeasures such as specialized shielding materials, gasket enclosures, and advanced signal and power line filters. The ability to simulate and evaluate these defense mechanisms is paramount for hardening critical systems against targeted attacks (Serena, 2025). By accurately predicting how an incident electromagnetic field interacts with and heats materials within a target, CEM provides the foundational knowledge required to build effective defenses against directed energy threats (Sherburne, 2024).

Copyright © 2021 The Author(s): This work is licensed under a Creative Commons Attribution- NonCommercial-NoDerivatives 4.0 (CC BY-NC-ND 4.0) International License

Publisher: SARC Publisher

Ensuring EM Resilience in 5G/6G Networks and IoT Ecosystems

5G and 6G expansion are indeed a transformative milestone for telecommunication sector, and boast high data rate, ultra-low latency and Internet of Things (IoTs). This will create an expansive Internet of Things (IoT) ecosystem, where billions of smart devices will be connected to everyday and essential infrastructure management systems. But this same hyper-connectivity also creates an exponentially larger electromagnetic-attack surface area. With the move to higher frequency bands (e.g., millimeter waves (mm-Waves)), new propagation phenomena and new security threats are introduced. Moreover, the large density of small cells, along with the software defined architecture of these networks, open up new dimensions for interference and malicious threats.

CEM is critical in ensuring the next wave of wireless infrastructure. At the component level, CEM is applied to the simulation and analysis of the advanced antenna systems, such as the shape-changing phased array, which is based on 5G/6G networks, is operations as expected in the spectrum crowding environment (Jamal, 2024). At a system level, signal propagation in complex urban environments is modeled - predicting coverage, interference and the possible existence of 'dead zones' using ray tracing and other high frequency methods. This is important for designing the layout of a network in order to maximize performance and resilience. CEM models are also necessary to study the physical layer security of such networks. CEM Is applied by researchers to quantify the vulnerability of 5G/6G base stations and user equipment against jamming and spoofing as well as side-channel threats, in which an attacker can eavesdrop by sensing electromagnetic susceptibilities of a device. By a deep understanding of these micro-vulnerabilities at the physical level, CEM can lead to the development of communication protocols and hardware that can be made more resistant to electromagnetic threats, and that can detect, locate, and mitigate these threats in real time, thereby assuring the integrity and availability of communication networks that form the underlying critical infrastructure for national security.

Next-Generation Antenna and System Design for Enhanced Capabilities

In today's hostile electromagnetic environments, the antenna, not a passive component of the spectrum system, becomes an active, cognitive spectrum device. Precise transmission, reception and flexibility to prevent interception and avoid detection are the most important functions. Computational electromagnetics is the key that is unlocking a revolution in antenna and system design allowing for capabilities that were previously only theoretical. From reconfigurable arrays that enable beam-steering in microseconds to the rapid on-boarding of small sensors into unmanned platforms, control of the EMS for any organization is directly proportional to their expertise in advanced CEM-driven design and optimization.

Reconfigurable and Phased-Array Antennas for Dynamic Environments

Static antennas don't provide enough flexibility for the constantly changing nature of today's electronic warfare and communications. Military platforms need antennas that can adjust to evolving mission requirements in real time, track rapidly moving targets and null outsources of interference. Phased-array antennas, that is to say, a large number of radiating elements for which the signals can be individually shifted in order to perform beam searching electronically, have been for many years an intrinsic element in advanced radar and satellite communication systems. CEM-based designs are essential, allowing for accurate determination of element spacing, phase relationships and feed networks required to produce desired radiation patterns such a low side lobe for minimal detectability.

The thrust of this research is on the concept of fully reconfigurable antennas covering not only the instantaneous beam direction but also the frequency, the polarization, and the radiation pattern. CEM opens a new frontier for designers to experiment with new ideas that are out of the physical constraints of the traditional methods of analysis. (For example, the ability to tune antenna properties on-the-fly using smart materials, such as liquid crystals or MEMS, can be simulated and refined in a virtual space. New types of "shape-changing" phased arrays have been proposed, inspired by concepts such as the basis of origami, to achieve radiation pattern adaptability by physically changing the antenna's shape with options of arbitrarily reconfigurable patterns up to the theoretical limit (Jamal, 2024).

These origami-type structures, demonstrating the fusion of mechanical control and electrical optimization of beam direction, represent the cutting edge of antenna design. CEM is very important to enable co-designing electromagnetic performance with mechanical folding, such that

Copyright © 2021 The Author(s): This work is licensed under a Creative Commons Attribution- NonCommercial-NoDerivatives 4.0 (CC BY-NC-ND 4.0) International License

Publisher: SARC Publisher

the antenna preserves some required performances over a set of physical configurations. This technology, though demonstrated in the 28 GHz 5G application, is directly relevant to military systems that need a small, interchangeable, and highly adaptive antenna that may be reconfigured in roles of communication, sensing, and electronic warfare.

Optimizing On-Platform Antenna Placement and Co-site Interference

Arguably, one of the most enduring challenges encountered when designing military systems is how to fit many antennas on a single, electromagnetically dense spatial platform, be that a naval ship, an aircraft, or a tactical vehicle. Every platform has to carry dozens of systems for communications, navigation, radar, and electronic warfare, with each its own lineup of antennas over a large frequency spectrum. Because these antennas are closely spaced, the strong signals transmitted by one system can overload the sensitive receivers of another (i.e., co-site interference). Such interference can lead to poor system performance, reduced communication range, or even total system failure, which directly affects the mission and also affects safety.

CEM has been widely applied to solve this complicated co-site interference issue. The construction of a full-scale physical model of a ship or plane for antenna placement investigations is generally too costly and time-consuming. In this case, engineers model the entire platform, with its intricate geometry and material composition, as high-fidelity virtual models. Then, the CEM solver is used to accurately predict the electromagnetic coupling between all pairs of two antennas, including near- and far-field interactions on the total operating frequency range. These simulations show potential interference problems at the start of the design, providing engineers with the opportunity to experiment with different antenna placements, orientations, and frequencies. CEM is employed for developing, and to a lesser extent testing, mitigation techniques (for example, frequency-selective filters or adaptive cancellation algorithms). The systematic, simulation-enabled nature of "electromagnetic adaptation" is vital to guarantee the reliability and functionality of critical systems (e.g., radar stations) on military surface ships-- for which fault-free operation is imperative in the densely crowded ship-board environment (Rustamov, 2025). The outcome is the ergonomic layout of all on-platform EM equipment which maximizes signals and performance, yet maintains self-inflicted interference at a minimum.

Miniaturization and Integration of EM Sensors for Unmanned Systems

The development of unmanned systems, such as aerial drones or UAVs, ground robots, and mini satellites, has rapidly increased the demand for electromagnetic sensors and antennas that are smaller, lighter, and lower power than ever before. These systems have extremely tight size, weight, and power (SWaP) budgets, while being tasked with supporting more advanced sensors for intelligence, surveillance, and reconnaissance (ISR) and communications. Merely miniaturizing traditional antenna designs is frequently not useful, because physical laws often dictate that antenna efficiency and bandwidth diminish with size (Ali et al, 2025).

Computational electromagnetics offers the answer to this miniaturization problem. CEM enables antenna designers to venture beyond classical antenna geometries into intricate three-dimensional structures that can radiate electromagnetic energy efficiently and fill the least amount of space (Masroor *et al.,* 2022). These and other techniques, where, for example, high-dielectric substrates are employed to electrically shrink an antenna, the antenna is folded into complex meandering lines, or is designed as a fractal geometry, can be accurately modeled and optimized using CEM tools (Muthu et al, 2020).

Additionally, CEM supports the notion of conformal antennas, in which the antenna itself is embedded directly into a UAV's wing or fuselage, rather than in another auxiliary structure. This technique conserves precious space and minimizes aerodynamic drag to improve platform performance (Li et al, 2021). By far, the most significant activity of this task is an enhanced software code called CEM, which allows researchers to use fast electrical modeling and/or analysis of thousands of proposed designs, even though the length scales of the designs are far too small to handle in a standard laboratory setting. CEM speeds the development of miniaturized, high-performance antennas critical for enabling the future smaller, autonomous defense systems.

However, despite these advantages, several challenges must be addressed. First, fundamental physics imposes constraints that cannot be entirely overcome—miniaturized antennas typically suffer from reduced radiation efficiency, narrower bandwidth, and lower gain compared to their full-

Copyright © 2021 The Author(s): This work is licensed under a Creative Commons Attribution- NonCommercial-NoDerivatives 4.0 (CC BY-NC-ND 4.0) International License

Publisher: SARC Publisher

sized counterparts (Kolli et al, 2024). These performance degradations may limit operational range, data throughput, and reliability in challenging electromagnetic environments. Second, complex three-dimensional geometries, fractal patterns, and conformal structures designed through CEM often require advanced manufacturing techniques such as additive manufacturing or precision machining, which translates to higher production costs and potential quality control challenges. Finally, high-fidelity CEM simulations of complex, miniaturized antenna structures demand substantial computational resources, including powerful processors and extensive memory, which can create bottlenecks in the design iteration cycle and may limit accessibility for organizations with limited computational infrastructure (Ali et al, 2025).

FUTURE DIRECTIONS AND RESEARCH GAPS

As computational electromagnetics becomes integrated with national defense and critical infrastructure security, there are ongoing challenges and promising technology trends that determine its evolution. The community's insatiable appetite for more realism, faster computation, and better prediction has stretched classical CEM beyond its limits, creating opportunities for disruptive change. In this section, we discuss the key future directions and research gaps to be addressed in order to realize the next generation of EM functionalities. From this perspective, these frontiers are the convergence of multiphysics effects, the renaissance of AI, the nascent area of quantum-enabling electromagnetics, and the fundamental ethical issues attendant to increasingly autonomous systems (Gollapudi, 2024).

Toward Real-Time, Multiphysics, and Multiscale Simulations

Successive progressions in speed and capability would see CEM develop from being a strategic design tool to an operational and tactical resource. The vision is for a "digital twin" of the electromagnetic environment, a virtual copy that is not just high-fidelity but runs in real time (DARPA,2025). Realizing this vision requires promising advances in three related areas: real-time processing, Multiphysics coupling, and multiscale modeling.

Real-time simulation needs are most evident in dynamic threat environments. For cognitive electronic warfare (EW) systems - a system which must contribute to sense, analyze, and act on the fly in a constantly changing electromagnetic battlefield all within milliseconds - offline simulations that are often the mainstay of traditional RF benchmarking and testing just do not cut it (Haigh et al, 2021). The gap to be addressed in this research is the design of algorithms that are able to deliver operationally relevant levels of accuracy without the computational latencies associated with full-wave solvers. This will be done through the study of new cutting-edge numerical methods, high-performance computing on GPUs and FPGAs, reduced order models that represent important EM physics with minimum computational cost (Carlos *et al.,* 2021). Success in this domain would be realized via on-the-fly mission planning to negate radar emissions, dynamic spectrum allocation to defeat jamming, and real-time classification of unknown emitters.

What's more, electromagnetic phenomena seek out the company of others. A major open question is the strong coupling of CEM to other areas of physics. For example, the effects of a high-power microwave (HPM) weapon are carried over from an electromagnetic problem to a thermodynamic problem as energy is delivered into an object, causing component heating and, possibly, failure (Huan et al, 2020). At the same time, it must consider the CEM, coupled to thermodynamics and CFD, in understanding the impact of plasma sheaths on communication and sensor performance during hypersonic flight in extreme environments (Yan et al, 2021). They tend to be computationally costly due to loose coupling in the current Multiphysics simulations. The next step is evolution to closely coupled, co-simulation environments that model these interactions with the same efficiency as they model the overall behavior and vulnerability of the system under extreme conditions (Huang et al, 2020).

Finally, the challenges in defense and infrastructure exist at a wide range of vastly different physical scales. A full evaluation of a HEMP event calls for modeling of phenomena at widely disparate scales the gamma-ray interaction high above the earth, the propagation of the EM field over the size of continents, and the coupling of energy into microelectronic circuits inside a critical facility (Dou et al, 2024). It is computationally too expensive to cover these length-scales from nanometers to thousands of kilometers in a single realistic 3D simulation

Copyright © 2021 The Author(s): This work is licensed under a Creative Commons Attribution- NonCommercial-NoDerivatives 4.0 (CC BY-NC-ND 4.0) International License

Publisher: SARC Publisher

(Noble et al, 2022). The research frontier in this field is directed toward the development of adaptive multiscale techniques to be used in practice to select high-fidelity models at the appropriate stage of a simulation (e.g., at circuit board level) and to use more computationally efficient models further up the hierarchy, with the possibility of supplying information between the scale changes (Noble et al, 2022).

AI-Accelerated CEM Solvers and Inverse Design

The integration of AI and computational electromagnetics is one of the most revolutionary trends in the field. This combination holds the prospect of breaking the age-old dichotomy between computation speed and accuracy, such that design and analysis will be possible that were previously beyond reach. Two critical frontiers are enabling this revolution: AI-accelerated solvers and AI-enabled inverse design (Rubinstein, 2024).

Existing, accurate CEM solvers have the downside of being very slow, frequently taking many hours to days on high-performance computing clusters. AI, especially deep learning, opens the door to almost instantaneous results. By training a neural network on large datasets of CEM simulations with high fidelity, researchers can develop a surrogate model that is capable of learning the complicated connection between physical geometry and its electromagnetic response. Trained AI models can then quickly produce predictions for an outcome such as the radar cross-section of an aircraft or the radiation pattern of an antenna in microseconds. This acceleration is a key requirement for the real-time simulations previously described. AI and machine learning are considered pivotal to developing offensive and defensive EW capabilities in contemporary defense contexts (Pace, 2022). Work in this field is working to enhance the accuracy, generality, and physical plausibility of these AI solvers, making them trustworthy for mission-critical applications.

Moreover, AI is not only to speed up the current workflow but also disrupt the design process itself with "inverse design." The traditional approach represents a human expert coming up with a design that is simulated by a CEM solver using a trial-and-error process. In inverse design, the paradigm is reversed: the engineer sets the targets for device performance specifications and, assisted by a CEM solver (offered by AI or manually designed), an AI-powered optimizer then automatically calculates the physical implementation that reaches the targets. This way can search for much more design space than ever human designer and find new but non-intuitive solutions. For instance, AI can design advanced metamaterial structures with tailored EM properties for unmatched stealth performance or highly efficient, miniaturized antennas for unmanned systems. With advances in focused AI applications such as counter-stealth, the necessity of speed and agility in design and testing for a new concept cannot be overstated (Zohuri, 2020).

The Dawn of Quantum-Enhanced Electromagnetics

While still in its early stages, the intersection of quantum information science and electromagnetics heralds a new technological frontier with profound long-term implications for defense and security. This emerging field promises to revolutionize both how electromagnetic problems are computed and how electromagnetic fields are sensed (Benneh, 2024).

First, quantum computing holds the potential to solve certain classes of CEM problems that are intractable for even the most powerful classical supercomputers. The fundamental equations of electromagnetism can lead to exponentially complex calculations when modeling large, intricate systems. Quantum algorithms, by leveraging principles like superposition and entanglement, could theoretically explore this vast computational space with unprecedented efficiency (Fauzia A-Clottey, 2024). A fault-tolerant quantum computer could, for example, perform a full-wave simulation of an electrically large and complex platform like a naval aircraft carrier with a level of detail that is currently impossible, providing invaluable insights into its electromagnetic signature and vulnerabilities. While the development of such computers remains a long-term research goal, it represents a paradigm shift for high-fidelity modelling (Kejriwal, 2024).

Second, and more immediate, is the impact of quantum sensing on the electromagnetic domain. Quantum systems, such as nitrogen-vacancy centers in diamonds or clouds of cooled atoms, are exquisitely sensitive to their environment, allowing for the creation of sensors with unparalleled precision. This includes magnetometers that can detect the minute magnetic anomalies created by submarines, atomic clocks that enable navigation in GPS-denied environments, and electrometers that can measure weak electric fields with high fidelity. The effective design and deployment of these systems rely heavily on CEM to model their interaction

Copyright © 2021 The Author(s): This work is licensed under a Creative Commons Attribution- NonCommercial-NoDerivatives 4.0 (CC BY-NC-ND 4.0) International License

Publisher: SARC Publisher

with ambient electromagnetic fields and to shield them from unwanted interference. Furthermore, CEM will be instrumental in developing countermeasures to this new class of sensors, driving a new cycle of innovation in signature management and stealth.

Ethical and Policy Implications of Autonomous EM Systems

The growing incorporation of AI by CEM, and especially in an electronic warfare scenario, creates deep ethical and political questions that warrant serious attention. With EM systems developing that can work automatically at machine speed, traditional lordship over machines is under considerable challenge. The emergence of cognitive systems that have their own ability to sense, decide, and act in the electromagnetic environment means that it is necessary to develop a new governance and accountability architecture (Diaz Munoz, 2024).

A key moral concern is "meaningful human control" in autonomous EW systems. The speed of electromagnetic battle, where threats could arise and evolve in the millisecond timeframe, may make it impractical to have a human involved in every decision loop. This moves us towards a model in which humans prescribe the high-level rules of engagement but outsource tactical execution to an AI-driven system moderated by real-time CEM analysis. But this leads to one important question: How to achieve proportionality and discrimination in the actions of an autonomous system in a cluttered civilian-military EM environment? What if AI makes an incorrect probabilistic decision that leads to fratricide or collateral damage? Setting clear lines of responsibility and devising strong verification and validation methods for these AI-influenced systems is an urgent research and policy challenge. In order to use AI for active cyber defense and electronic attack, one needs to have a deep understanding of both these intertwined realms (Sfetcu, 2024).

Beyond the battlefield, advanced CEM and AI capabilities could also destabilize the global environment. AI- augmented inverse design capabilities may reduce the threshold for developing complex EM weapons, including novel jammers or localized IEMI systems, for state and non-state actors. This “democratization” of EM warfare capabilities would undercut regional balances of power and generate novel asymmetric threats (Puthiya, 2024). This will increase the demand for international discussions on norms and standards of development and use of autonomous EM systems. This includes their approach to technology transfer, de-escalatory agreements in the spectrum, and actions by framework in the increasingly congested and contested electromagnetic environment (Suthari & Mohan, 2025).

CONCLUSION

Computational electromagnetics (CEM) has transitioned from a specialized analytical tool to a strategic imperative in national defense and infrastructure security. It provides the essential predictive insight needed to gain a decisive edge in the complex electromagnetic domain.

CEM's impact is profound in several key areas. For stealth and counter-stealth, it is the foundation for designing low-observable platforms and the advanced sensors needed to detect them. The convergence of CEM with artificial intelligence is revolutionizing electronic warfare, enabling cognitive systems to achieve spectrum dominance. In infrastructure security, CEM is critical for hardening power grids and communication networks against threats like electromagnetic pulses (EMP) and intentional interference. It also underpins innovations in high-performance antenna and on-platform system design.

The future of CEM points toward real-time, Multiphysics simulations and a deeper fusion with AI, which is accelerating computation and enabling novel inverse design approaches. While quantum-enhanced electromagnetics presents a long-term paradigm shift, the rapid advancement of autonomous EM systems raises urgent ethical and policy challenges. Ultimately, as the electromagnetic spectrum becomes increasingly contested, a nation's security and ability to project power are inextricably linked to its mastery of computational electromagnetics.

REFERENCES

1. Katrakazas, P., & Papastergiou, S. “A Stakeholder Needs Analysis in Cybersecurity: A Systemic Approach to Enhancing Digital Infrastructure Resilience.” *Businesses* 4.2 (2024): 225–240. https://doi.org/10.3390/businesses4020015
2. Freno, B. A., & Neil, R. “Manufactured Solutions for an Electromagnetic Slot Model.” *arXiv* (2024). https://doi.org/10.48550/arXiv.2406.14573
3. Wingren, N. “Computational Methods and Measurements for Direct and Inverse Scattering of Microwaves.” *PhD Thesis*, Lund

Copyright © 2021 The Author(s): This work is licensed under a Creative Commons Attribution- NonCommercial-NoDerivatives 4.0 (CC BY-NC-ND 4.0) International License

Publisher: SARC Publisher

University (2024). https://lup.lub.lu.se/search/files/173432026/thesis_introduction_240307.pdf
4. Khan, M. "Cybersecurity in Critical Infrastructure: Challenges and Future Directions." *ResearchGate* (2025). https://www.researchgate.net/publication/388806231
5. Riggs, H., Tufail, S., Parvez, I., Tariq, M., Khan, M. A., Amir, A., et al. "Impact, Vulnerabilities, and Mitigation Strategies for Cyber-Secure Critical Infrastructure." *Sensors* 23.8 (2023): 4060. https://doi.org/10.3390/s23084060
6. Mazal, J. "The Dual Use of Civilian and Military Technologies in the Battlefield of the Future." *MTAK Repository* (2024). https://real.mtak.hu/210721/
7. Cardillo, E., & Li, C. "Portable Microwave and mmWave Radars for Contactless Healthcare." (2025).
8. Pascua, W. "The Electromagnetic Spectrum: Where Modern Warfare Begins." (2023).
9. Thompson, M. "Unlocking the Strategic Potential: Artificial Intelligence in Electronic Warfare." (2023). https://share.google/9S2QzBsI9XEsorpRA
10. Portes, R., Lopes, B., & Rezende, M. "Enhancing Metacomposite Properties and Electromagnetic Interference Shielding: Exploring the Interplay Between Manufacturing Processability of Carbon Fiber." *Advanced Composites and Hybrid Materials* (2024). https://link.springer.com/article/10.1007/s42114-024-01036-9
11. Zohuri, B. *Radar Energy Warfare and the Challenges of Stealth Technology*. Springer (2020).
12. Gang, C., & Jun, W. "Target Detection Method in Passive Bistatic Radar." *Journal of Systems Engineering and Electronics* 31.3 (2020): 510–519.
13. Zheng, B., Xiong, X., Tang, J., & Zhang, R. "Intelligent Reflecting Surface-Aided Electromagnetic Stealth Against Radar Detection." *Transactions on Signal Processing* 72 (2024): 3438–3452.
14. Zhong, Y., Liu, W., & Zhang, Y. "Recent Advances in Electromagnetic Shielding and Stealth Materials." *Materials Today* 39 (2020): 102–115.
15. Gibson, W. C. "The Method of Moments in Electromagnetics: Theory and Implementation." *Computer Physics Communications* 284 (2021): 108634.
16. Muhammad, T., Mohamadariff, M., Mousa, H., Yoshihide, K., et al. "A Progression in the Techniques of Reducing RCS for Targets." *Alexandria Engineering Journal* (2024).
17. Haigh, K., & Andrusenko, J. *Cognitive Electronic Warfare: An Artificial Intelligence Approach.* (2021).
18. Pace, P. *Developing Digital RF Memories and Transceiver Technologies for Electromagnetic Warfare*. IET (2022).
19. Shephard Media. "Fast Decisions from Cognitive Electronic Warfare Technology May Be Crucial to Spectrum Dominance." (2022).
20. Gurevich, V. "EMP Protection of Civilian Critical Infrastructure: Opinions, Problems, Strategy, Solutions." (2023).
21. Sfetcu, N. "Electronic Warfare and Artificial Intelligence." (2024).
22. Choi, S., Kwon, O.-J., Oh, H., & Shin, D. "Method for Effectiveness Assessment of Electronic Warfare Systems in Cyberspace." *Symmetry* 12.12 (2020): 2107.
23. David, D., & Bernstein, A. *Introduction to Electronic Warfare Modeling and Simulation.* IET (2020).
24. Travieso-González, C. M., et al. "Robust Detection of Fatigue Parameters Based on Infrared Information." *IEEE Access* 9 (2021): 18209–18221.
25. Davis, & Perry, N. "An Effective Approach to Evaluating Electronic Warfare Systems." *IEEE Xplore* (2023).
26. McWhorter, T., et al. "Machine Learning Aided Electronic Warfare System." *IEEE Xplore* (2021).
27. Serena, L., et al. "Simulation in Cybersecurity: Understanding Techniques, Applications, and Goals." *arXiv* (2025).
28. Sherburne, M. "Design, Fabrication, and Characterization of Electro-Optic Radio-Frequency Probes for High Field Environments." (2024).
29. Jamal, H. A., et al. "Toward 5G/mm-Wave Shape-Changing Origami-Inspired Phased Arrays." (2024).
30. Rustamov, A., et al. "System Technical Solution of Electromagnetic Adaptation." (2025). http://ais.khpi.edu.ua/article/view/323514
31. Ali, J. K., & Salim, A. J. "Fractals: A Review for the Artificial Intelligence-Assisted

Copyright © 2021 The Author(s): This work is licensed under a Creative Commons Attribution- NonCommercial-NoDerivatives 4.0 (CC BY-NC-ND 4.0) International License

Publisher: SARC Publisher

Customized Antenna Design." *Arabian Journal for Science and Engineering* (2025).

32. Masroor, I., et al. "Design and Analysis of Multiband Fractal Reconfigurable Antenna Using PIN Diodes." *Progress in Electromagnetics Research C* 120 (2022): 209–222.
33. Rani, R. B., & M. R. C. "A Compendious Review on Fractal Antenna Geometries in Wireless Communication." *IEEE* (2020).
34. Li, T., Chen, Z. N., & Wu, Y. "Conformal Phased Array Antenna for UAV With ±70° Scanning Range." *IEEE Transactions on Antennas and Propagation* 69.7 (2021): 4580–4585.
35. Kolli, V. R., et al. "A Review of UAV-Based Antenna and Propagation Measurements." *Sensors* 24.23 (2024): 7395.
36. DARPA. "DRBE Develops World's Largest Real-Time EW Test Range." (2025).
37. Springer. "Modelling of the Electrical-Magnetic-Thermal-Mechanical Coupling Behavior for the Coil-Structure Electromagnetic Launch." *Computational Mechanics* (2024).
38. Yan, S. "Multiscale Modeling and Simulation Methods for Electromagnetic and Multiphysics Problems." *Int. J. Numerical Modelling* 34.6 (2021): e2969.
39. Dou, W., et al. "Highly Sensitive Diamond X-ray Detector Array for High-Temperature Applications." *Chip* 3.3 (2024): 100106.
40. *IEEE Journal on Multiscale and Multiphysics Computational Techniques.* (2016–present).
41. Noble, B. B., Todorova, N., & Yarovsky, I. "Electromagnetic Bioeffects: A Multiscale Molecular Simulation Perspective." *PCCP* 24 (2022): 6327–6348.
42. Zhang, H. H., et al. "Electromagnetic-Circuital-Thermal Multiphysics Simulation Method: A Review." *Progress in Electromagnetics Research* 169 (2020): 87–101.
43. Suthari, Y., & Mohan, P. (2025). "Cloud-driven machine learning-based framework for measuring customer experience in digital touch-points." In *Proceedings of the 2025 IEEE 11th International Conference on Smart Instrumentation, Measurement and Applications (ICSIMA)* (pp. 328–333). IEEE. https://doi.org/10.1109/ICSIMA66552.2025.11233566
44. Fauzia A-Clottey, Pmp. (2024). "Optimizing Business Growth Through Strategic Leadership: Evidence From Team Development, Supply Chain Management, And Operational Efficiency." *IPHO-Journal of Advance Research in Business Management and Accounting*, *2*(11), 32–39. https://doi.org/10.5281/zenodo.19603152
45. Rubinstein, I. (2024). "Sales Strategy Optimization In Technology Firms: Balancing Existing Revenue Streams With New Market Opportunities." *IPHO-Journal of Advance Research in Business Management and Accounting*, *2*(8), 01–08. https://doi.org/10.5281/zenodo.19603306
46. Benneh, N.D. (2024). "Structured Finance Mechanisms For Enhancing Long-Term Capital Formation." *IPHO-Journal of Advance Research in Business Management and Accounting*, 2(7), 01–10. https://doi.org/10.5281/zenodo.19753841
47. Kejriwal, A. (2024). "Compliance frameworks for investment restrictions in corporate portfolios." *Sarcouncil Journal of Economics and Business Management*, 3(4), 10–18.
48. Puthiya, D. (2024). "Digital portfolio optimization in agile product development environments." *IPHO Journal of Advance Research in Science and Engineering*, 2(2), 1–9.
49. Diaz Munoz, P. A. (2024). "Resilient urban design: Evaluating mixed-use development models in emerging economies." *IPHO Journal of Advance Research in Business Management and Accounting*, *2*(12), 31–39.
50. Gollapudi, R. (2024). "Event-aware multi-layer storage risk forecasting for Oracle database estates using HAPF." *International Journal of Computational and Experimental Science and Engineering*, 10(4). https://doi.org/10.22399/ijcesen.5183

Source of support: Nil; **Conflict of interest:** Nil.

Cite this article as:
Agyemang, Y. O. and Ampomah-Britwum, A. A." The Role of Computational Electromagnetics in National Defense and Infrastructure Security." *Sarcouncil Journal of Multidisciplinary 5.12* (2025): pp 1-13.

Copyright © 2021 The Author(s): This work is licensed under a Creative Commons Attribution- NonCommercial-NoDerivatives 4.0 (CC BY-NC-ND 4.0) International License

Publisher: SARC Publisher