EPH-International Journal of Science and Engineering
ISSN (Online): 2454-2016
Volume 10 Issue 4 December 2024

DOI: https://doi.org/10.53555/ephijse.v10i3.314

MODELING AND ANALYSIS OF HALF-WAVE DIPOLE ANTENNAS IN MATLAB: A COMPREHENSIVE REVIEW

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Abstract

Radio frequency (RF) and electromagnetic (EM) systems still rely heavily on half-wave dipole antennas due to their practical design, reliable operation, and adaptability to a variety of communication applications. The development of contemporary wireless technologies such as 5G, the Internet of Things (IoT), and wearable technology has led to a growing demand for accurate dipole antenna design and analysis to fulfill performance requirements. Because simulation tools may save development cycles and improve the accuracy of design forecasts, RF engineers are increasingly using them to do this. Of them, MATLAB has emerged as a popular platform for antenna modeling because it provides a very flexible environment that accommodates both sophisticated, algorithm-level modifications and streamlined design procedures. This article provides a thorough analysis of MATLAB-based methods for half-wave dipole antenna modeling. Antenna Toolbox, user-developed solutions using the Method of Moments (MoM), and hybrid approaches that combine MATLAB with full-wave solvers like CST Microwave Studio and Ansys HFSS are all covered. Each method is evaluated based on its precision, processing requirements, flexibility, and applicability to certain use cases. The balance between usability, level of control over the modeling process, and the accuracy of the simulated outcomes is among the trade-offs included in the analysis. The study discusses the shortcomings of these approaches as well as their advantages, including the lack of generally recognized benchmarking standards, the abstraction level of solvers, and the low precision of near-field modeling. This review is useful for both academic researchers and professionals in the business since it provides a comprehensive assessment of existing procedures and identifies areas that require improvement. It attempts to guide anyone looking for dependable and effective MATLAB antenna modeling solutions, as well as suggestions for future advancements in simulation-driven antenna design.

Keywords: *Half-wave dipole antenna, MATLAB simulation, Method of Moments, Antenna Toolbox*

1. Introduction

Half-wave dipole antennas have been important in electromagnetic (EM) and radio frequency (RF) engineering (Belous, 2021). Because they are well-designed, predictable and can be analyzed easily, they are very useful in both teaching and practical situations (Cleves, 2020). These antennas are used in many areas such as wireless communication, radar and the new Internet of Things (IoT), because they operate on frequencies ranging from HF to UHF and into the microwave range (Karim et al., 2019). Because they are now used in more advanced antenna systems like phased arrays, multiband components and adaptive topologies, they show how important they are. For half-wave dipoles to work well in larger RF systems, it is necessary to model them accurately because they are very important.

For many years, antenna engineers made physical models and tested them regularly in specialized places such as test ranges and anechoic chambers (Xu & Huang, 2019). Even though this method taught a lot, it was often both pricey and slow. When computational methods were introduced, the emphasis in design shifted from hardware to simulation (Koziel & Ogurtsov, 2014). Now, engineers use digital modeling tools to predict antenna performance, find the best design and explore different options before making physical prototypes (Sarker et al., 2023). As a result, designers can now explore more options and finish the project much faster and at a lower cost.

MATLAB has gained popularity as a platform for antenna modeling in this changing environment because of its adaptable environment, which facilitates both theoretical study and real-world simulation (Makarov et al., 2021). High-fidelity modeling utilizing techniques like the Finite Element Method (FEM), Finite Integration Technique (FIT), and Method of Moments (MoM) is possible using commercial full-wave simulation programs like ANSYS HFSS, CST Microwave Studio, and FEKO, although they can be more difficult to use and modify (Kim & Canfiend, 2014). On the other hand, users may experiment with different numerical approaches and construct bespoke models using MATLAB's matrix-based structure. By incorporating built-in tools for designing, visualizing, and analyzing popular antenna types including dipoles, arrays, and patches, the Antenna Toolbox, which was first introduced in MATLAB, has significantly expanded its capabilities (Beswick , 2020).

MATLAB also helps in combining different fields, so it is suitable for using signal processing, machine learning and optimization with antenna modeling. Beamforming, adaptive antennas and cognitive radio systems are all areas where this skill is increasingly helpful (Jaiverdhan et al., 2024). The Optimization Toolbox, Simulink and Deep Learning Toolbox in MATLAB help improve antenna designs by using real-time data, user feedback or system requirements (Sun et al., 2024). The platform also allows users to use custom scripts and well-known electromagnetic solvers and it can interact with extra solvers and hardware (Tong & Lee, 2024).

Dipole modeling in MATLAB is used widely, but the literature on it is not well gathered. Much of the existing content consists of hypothetical articles, tutorials for specific tools or single case studies that do not give a clear overview of the different modeling methods. Sometimes, people make important decisions about mixing MATLAB with CST or HFSS or about using the Antenna Toolbox or writing their own MoM scripts, without careful thought or explanation (Sarkar, 2022). Consequently, there are differences in how models are built and it is hard to repeat the results found in different studies.

Also, clear and helpful instructions for modeling antennas in MATLAB are necessary (Ali et al., 2023). It can be hard for new users to set up the correct simulation parameters or check the results, mainly in academic settings or at the beginning of research. Since MATLAB is open-ended, users need more structure and clarity to ensure they can use it efficiently, unlike commercial programs with detailed documentation (Niazai et al., 2023). Also, since there are no common rules and methods, it is difficult for companies to join forces and develop best practices.

The purpose of this paper is to address these issues by providing a detailed and well-structured overview of MATLAB methods for modeling half-wave dipole antennas. It includes Antenna Toolbox features, unique methods for Momentum, ways to use MATLAB and external solvers together and advanced optimization techniques, combining different simulation methods. The use of wireless communication, biomedical engineering and education are studied, as well as the pros, cons and computing power of each method.

It also points out that there are practical choices to make between how accurate the model is, how much control users have, how complex the solver is and how fast the calculations are. It points out the usual difficulties that practitioners encounter and suggests possible solutions and future improvements. It is important to use standard benchmarking, validated models and community-managed repositories to increase the reliability and repeatability of antenna simulations using MATLAB. The review is intended to act as a reference and a guide for engineers, researchers and educators who work with antenna design and electromagnetic modeling in MATLAB.

2. Methodology

This literature review employed a structured and technically grounded approach to identify, screen, and synthesize relevant studies on the simulation and analysis of half-wave dipole antennas using MATLAB. Given the widespread use of MATLAB in antenna modeling—ranging from in-built functions to custom-coded solvers and hybrid co-simulation workflows—the review methodology was designed to capture methodological variety, ensure content relevance, and allow for interpretive comparison across simulation strategies. This process focused on simulation configuration, modeling assumptions, output validation, and the functional use of MATLAB as either a primary or integrated platform in the modeling environment.

2.1 Type of Review

The diversity of modeling methodologies in the selected field was accommodated by a narrative review structure. Unlike meta-analytical or systematic frameworks which require a high degree of homogeneity across study designs and metrics, the narrative approach is more appropriate for reviewing literature that spans multiple simulation methods, tool architectures and levels of abstraction. In this case, the review includes studies that use MATLAB's Antenna Toolbox, user defined numerical modeling (Method of Moments (MoM)) and externally linked commercial software packages with MATLAB in their simulation or post processing chain. Also, narrative structure makes it possible to compare across theoretical accuracy, solver performance and application contexts.

2.2 Data Sources and Search Strategy

A multi-source search was conducted in leading scientific and engineering databases to retrieve relevant publications. IEEE Xplore, ScienceDirect, SpringerLink, and Scopus were used, as well as curated technical content available through MathWorks File Exchange. Material published between 2015 and 2025 was searched for in English-language journal articles, peer-reviewed conference papers, and validated technical documentation. Search terms were refined using Boolean logic, for example, "half wave dipole antenna," "MATLAB modeling," "Method of Moments," "Antenna Toolbox," and "dipole radiation analysis." This guaranteed a balanced retrieval of both the foundational work and the recent developments.

2.3 Inclusion and Exclusion Criteria

This study was limited to research that utilized MATLAB directly to simulate or analyze half-wave dipole antennas. This included studies that created unique numerical models using MATLAB code as well as studies that used MATLAB's built-in toolboxes with preset antenna models and solver configurations. Furthermore, as long as MATLAB was used extensively for tasks like creating geometry, adjusting parameters, or processing data, papers that integrated MATLAB with external electromagnetic modeling programs like CST Microwave Studio, HFSS, or NEC were accepted. Excluded from consideration were studies that were entirely theoretical and did not use MATLAB in any way, as well as those that were based only on experimental hardware testing or fabrication without any simulation component. Content from unauthorized or unverified sources, such blogs or online forums, non-English periodicals, and inaccessible items were also not included.

2.4 Screening and Selection Process

Duplicate records were eliminated following the initial search, and the remaining titles and abstracts were carefully examined to assess their applicability to the research. The full texts of the articles that met the first requirements were obtained. The evaluation looked at the description of input parameters, the solvers used and the analysis of results, with a main focus on how detailed the modeling was in each study. Studies that did not clearly explain the simulation environment or the MATLAB code used were not considered in the review. The studies were grouped by their main modeling techniques to help compare different approaches. By grouping the themes, it became possible to analyze the pros and cons of each strategy. Any papers that did not include simulation or MATLAB were not considered. Furthermore, articles published in languages other than English and sources that were not properly verified, such as blogs, forums, or unavailable materials were not taken into account.

2.5 Data Extraction and Thematic Synthesis

From each included study, essential information was extracted using a structured framework tailored to the review topic. This included the type of MATLAB implementation used, antenna geometry and electrical dimensions, solver configuration, and simulation metrics such as return loss, impedance, radiation pattern, and gain. Where applicable, the method of validation—either through analytical models, commercial solvers, or measurement data—was also noted. Four analytical themes were subsequently identified from the studies: hybrid MATLAB-based processes, optimization-focused modeling, custom-coded numerical simulations, and Antenna Toolbox modeling. A comparative assessment of simulation depth, computational effectiveness, and appropriateness for scholarly, commercial, or instructional purposes was facilitated by this theme synthesis.

3. Theoretical and Computational Frameworks

A strong understanding of theoretical ideas and computational techniques is required to effectively model and simulate half wave dipole antennas and validate the produced data. This part covers basic electromagnetic concepts that underpin dipole radiation, the primary analytical methods for estimating the fields produced by these antennas and a discussion of popular numerical simulation techniques that are typically implemented with MATLAB.

3.1 Fundamentals of Half-Wave Dipole Antennas

A half wave dipole antenna which is a resonant structure, is almost half the wavelength of the frequency it is supposed to send or receive. It is typically a center fed conductive element that distributes current sinusoidally along its length with the least current at the ends and the most at the center. An ideal situation would be a thin, free space dipole with an input impedance of about 73 ohms resistive and about 42.5 ohms reactive. However, real world variables such as substrate type, adjacent objects and conductor thickness can cause variations in this impedance. The radiation pattern of the antenna is similar to a doughnut, with the highest radiation coming from directions that are perpendicular to the axis of the dipole. The bandwidth and efficiency of the antenna may be impacted by changes to its construction or the surroundings. Simulation programs like as MATLAB or CST Microwave Studio are frequently used to study these issues.

3.2 Analytical Modeling of Radiation

The use of Maxwell's equations under thin-wire boundary conditions is usually the first step in analytical approaches for antenna modeling. As a result, integral equations—most notably Hallén's and Pocklington's equations—that characterize the current distribution along a radiating wire are used to formulate electric and magnetic fields. In classical circumstances, these models provide closed-form estimate of impedance characteristics and far-field components (Silva Valdecasa et al., 2017). However, purely analytical approaches are inadequate in real-world situations when complexity is introduced by the surroundings, geometry, or material change. For increased fidelity and flexibility, semi-analytical methods and discretized solutions are used here (Rumpf, 2022).

3.3 Introduction to Numerical Techniques

In antenna modeling, the Method of Moments (MoM) is a commonly used numerical method for resolving boundary value issues. The continuous issue is converted into a set of linear algebraic equations, the structure is discretized into segments, and current is approximated using basis functions. The development of antenna solvers, including MATLAB versions, has relied heavily on MoM, which is particularly useful in thin-wire applications (Makarov et al., 2021). Input impedance, VSWR, gain, and 2D/3D radiation patterns may be precisely simulated using both scripted and GUI-driven interfaces provided by MATLAB's matrix computing capabilities and its dedicated Antenna Toolbox.

Expansion of MoM implementations to support coupling phenomena, optimization-driven design, and non-resonant structures has been shown by research into MATLAB-based custom solver settings (Beswick, 2020). MATLAB is also often used to control or set up other simulation tools such as CST or HFSS, so that users can combine its automation and scripting with the graphical user interfaces of those tools (Patidar et al., 2024). This method is useful in array design because it makes it easier to control the size and spacing of objects which helps repeat the design faster and more accurately.

The progress in antenna design has led to studies on low-profile antennas that perform well such as reconfigurable and metasurface-enhanced antennas. Before validating with full-wave simulation, MATLAB modeling is often the initial step in these systems. It has been shown that using metasurfaces behind dipole structures can enhance both the directivity and the bandwidth (Alkurt & Karaaslan, 2019). MATLAB is also important for large-array analysis because it has effective solvers and localized methods that reduce the workload without affecting the results (Conradie, 2024). Because modern communication systems require more bandwidth and fast switching, it is now more important to include high-speed circuit components and detector models in antenna simulation. In these cases, MATLAB is commonly used to analyze electromagnetic fields which forms the foundation for further checks and improvements in photonic or radio frequency simulations.

4. MATLAB-Based Modeling Approaches

To simulate and analyze halfwave dipole antennas correctly, you need strong electromagnetic modeling tools. MATLAB is based on matrices and has dedicated toolboxes, it can handle both high and low level methods in antenna simulation (Raj et al., 2015). This section discusses four main ways to model in MATLAB: using the Antenna Toolbox, implementing Method of Moments (MoM) on your own, combining MATLAB with external electromagnetic solvers and performing parametric optimization studies. Every approach finds a balance between how much users can control, how fast it works and how many applications it supports.

4.1 Modeling Using MATLAB's Antenna Toolbox

MATLAB's Antenna Toolbox provides an easy and object oriented way to define and study different antennas, including the canonical half wave dipole. A dipole object can be created using the dipole function, its frequency parameters can be set and its input impedance can be seen over a sweep using impedance or returnLoss. Customization of parameters such as length, width and feed offset is allowed by object properties which can be used in educational as well as industrial scenarios (Balanis, 2016).

High level functions like pattern and patternAzimuth make it easy to plot radiation pattern in 2D and 3D, across user defined frequency range. Integration with MATLAB's visualization tools can enhance plotting features, allowing radiation lobes to be exported, pattern behavior to be animated across frequency bands and publication ready figures to be generated. The EHfields function also provides near and far field analysis which provides electric and magnetic field distributions in Cartesian and spherical domains (Mailloux, 2017).

The toolbox has a strong feature of automation. for-loops or functional programming paradigms (e.g. arrayfun) can be used to execute batch simulations. Users can script simulations that sweep over different dimensions, frequencies or material properties efficiently. Additionally, toolbox integrates with MATLAB's App Designer and Simulink for GUI based or dynamic control of antenna parameters (Capek et al., 2018).

4.2 Custom Numerical Modeling (MoM in MATLAB)

The Method of Moments (MoM) can be implemented from first principles in MATLAB for those users who want more control or educational insights. Using this method, the Electric Field Integral Equation (EFIE) for the dipole structure is developed. Piecewise sinusoids or pulses are used as basis functions to model the current distribution in each segment of the antenna (Kunze et al., 2023).

The main idea is to calculate the impedance matrix Z which shows how segments are coupled, using the right Green's function. The voltage at the feed point is called V and the linear system ZI = V is solved to determine the currents in each

segment. Because MATLAB supports complex numbers and linear solvers, it is a good choice for implementing the MoM method (Alyammahi, 2023).
With custom implementation, you can see all the details of the solver which is useful for checking commercial tools, teaching or research that needs changes not available in GUI platforms. You can change the number of segments, the distance between observations and the type of quadrature to check how the results converge or how accurate they are. Users can also add dielectric layers, reactive loading or environmental effects to the implementation (Capek et al., 2018).

4.3 Hybrid Approaches (MATLAB + External EM Solvers)
MATLAB has a lot of capability for standalone simulations, hybrid approaches that connect MATLAB to full wave electromagnetic solvers like CST Microwave Studio, ANSYS HFSS or NEC provide better modeling fidelity and real world applicability. Parameter sets are generally controlled using MATLAB which is also used to generate model scripts or read simulation outputs for post processing and visualization (Giannetti, 2023).
MATLAB COM automation or scripting interfaces allow users to define geometry, materials and simulation parameters in CST or HFSS. Users can run hundreds of simulations with different antenna lengths, substrate types or boundary conditions using high level engine for parameter sweeps in MATLAB. MATLAB can import S-parameters, field distributions or far field data after simulations are finished for comparative or optimization based analysis (Capek et al., 2018).
This hybrid integration is very useful in antenna array, multiband or reconfigurable geometry applications in particular. For example, MATLAB can be used to optimize the inter element spacing in a dipole array and the underlying EM solution is handled by CST. Parameter sweeps in MATLAB can be used to find optimal frequency configurations for multiband designs which are then refined in full wave solvers for fabrication level precision. These workflows bridge the gap between academic modeling and industrial prototyping.

4.4 Parametric and Optimization-Based Studies
The rich optimization and modeling toolsets available in MATLAB such as the Optimization Toolbox, Global Optimization Toolbox and Simulink, allow for extensive parametric and algorithm driven antenna studies. Users can define cost functions in terms of parameters like return loss, gain or beamwidth and use algorithms like gradient descent, genetic algorithms or particle swarm optimization to minimize or maximize performance metrics (Alyammahi, 2023).
Structural variables such as dipole length, gap spacing, height above ground and substrate permittivity can be swept. These sweeps help determine sensitivity, operating bandwidth and optimal configurations. Antenna characteristics can be optimized for single or multi objective goals using functions such as fmincon, ga or surrogateopt. Flexibility in choosing the modeling backend (Antenna Toolbox or custom MoM solvers) is ensured (Kunze et al., 2023).
Simulink also provides real time design feedback, in addition to conventional optimization, by visualizing dynamic control of antenna parameters against system level performance. In adaptive or cognitive radio systems where antenna parameters change in response to the communication environment, this is especially useful.
While optimization greatly improves design precision, tradeoffs are made in terms of simulation time and solution fidelity. Coarse parameter sweeps are quick to run and give quick insights, but fine grained optimization often requires more computational resources. However, MATLAB is a very effective platform for modern antenna design and analysis due to its ability to combine analytical rigor with algorithmic flexibility (Alyammahi, 2023).

5. Comparative Analysis of Modeling Techniques
To fully understand the behavior of half wave dipole antenna, multiple modeling strategies should be used and their accuracy, computational efficiency, flexibility and suitability for various applications should be critically evaluated. In this section, MATLAB based techniques such as Antenna Toolbox, custom Method of Moments (MoM) implementations and hybrid solver integrations are compared with analytical benchmarks and industry standard electromagnetic (EM) simulation tools (Eshkabilov, 2022).

5.1 MATLAB vs Analytical Benchmarks
Under idealized conditions, MATLAB's simulation results for half wave dipole antennas, especially when using Antenna Toolbox or MoM based custom scripts, usually match closely with the results obtained from closed form analytical expressions. Such comparisons can be made on the basis of benchmark metrics such as input return loss (S11), input impedance, resonance frequency and radiation pattern symmetry (Makarov et al., 2021).

For example, the return loss computed by the Antenna Toolbox usually shows a sharp dip at the resonant frequency, as expected from the $\lambda/2$ dipole model. Impedance plots also show values converging to the well known analytical value of 73 ohms in free space for thin, center fed dipoles. But as the model complexity increases (e.g., with dielectric substrates, finite ground planes or curved geometries), small deviations begin to appear in both impedance and field distribution. As frequency increases or as the antenna is scaled down to electrically small sizes, these deviations grow and assumptions in analytical theory start to break down (Tong & Li, 2024).

Analytical solutions are useful as a basis of checks, but they often ignore complex boundary interactions, material dispersions and feeding structures. This gap is bridged by MATLAB's full wave solvers which simulate more realistic conditions at a slightly higher computational overhead (Bartone, 2023).

5.2 MATLAB vs Commercial Tools

MATLAB is compared against industry grade commercial solvers such as CST Microwave Studio (Finite Integration Technique), ANSYS HFSS (Finite Element Method) and NEC (legacy MoM solver) and it is shown that MATLAB has both strengths and weaknesses depending on the simulation task and user goals (Giannetti, 2025).

From a run time and solver efficiency point of view, MATLAB's Antenna Toolbox is well suited for rapid prototyping and educational exploration. It automatically generates its mesh optimized for speed rather than ultra fine resolution. However, CST and HFSS provide fine control over mesh density which is necessary for high precision in fields near edges or discontinuities which is essential for high frequency or multi resonant antenna designs.

For single element structures such as half wave dipoles, solver accuracy is generally comparable. However, for complex 3D geometries, non linear materials or multi port configurations, commercial tools are more robust and accurate in convergence. In addition, CST and HFSS have extensive built in libraries for connectors, materials and pre validated components which are less extensive in MATLAB (Raz et al., 2023).

Another point of distinction is visual quality and post processing tools. Dynamic 3D visualization, far field plot animations, SAR evaluations and parameterized sweep dashboards are supported by commercial solvers. Most of these capabilities are provided by MATLAB, though often requiring scripting which reduces ease of use for nonprogrammers.

However, when used with these commercial platforms, MATLAB really shines. It can be used, for example, as a scripting engine for batch parameter sweeps in CST or as a post processing platform to analyze HFSS output files using custom metrics. The hybrid use case presented here shows that MATLAB is not a replacement, but rather an augmentative tool for commercial solvers (Vasquez-Plaza et al., 2022).

5.3 Summary Matrix of Trade-Offs

To facilitate selection among the three major MATLAB-based modeling strategies, the following summary matrix categorizes their strengths and limitations (Table 1).

Table 1: The three major MATLAB-based modeling strategies

Approach	Strengths	Limitations
Antenna Toolbox	Easy setup, fast results, GUI-based	Black-box solver, limited customization
Custom MoM	Full mathematical control, transparency	High implementation effort, time-consuming
Hybrid	Accurate, scalable, industrially viable	Requires external tools and synchronization

Each modeling route aligns with distinct user objectives. For academic purposes where understanding the physics and math is central, custom MoM scripts are invaluable. For engineers prototyping designs, the Antenna Toolbox offers speed and interactivity. In contrast, hybrid methods are ideal for industrial research and product development where precision and scalability matter most.

Ultimately, the trade-off lies in balancing ease-of-use, transparency, scalability, and integration flexibility. MATLAB's modeling ecosystem accommodates all levels—from foundational learners to advanced researchers—making it a powerful platform when appropriately contextualized within a broader EM toolchain.

6. Applications and Case Studies

MATLAB is very versatile in modeling half wave dipole antennas and this versatility is not limited to academic simulation and is used in a number of real world applications from wireless prototyping to biomedical engineering and education. This section discusses three main areas (wireless/RF system design, biomedical antenna research and educational applications) where MATLAB modeling is very useful.

6.1 Wireless and RF Prototyping

Half wave dipole antennas are the basic building blocks in 5G, MIMO and IoT architectures. MATLAB streamlines the ability to model dipole arrays with varying inter element spacing, excitation phases and feeding configuration to evaluate beamforming capabilities, gain optimization and coverage performance (Pant & Malviya, 2023). One key application is directional transmission and adaptive beam steering which is achieved in 5G base station prototyping using phased dipole arrays. MATLAB's Antenna Toolbox and Phased Array System Toolbox can be used to simulate radiation patterns under different modulation schemes and user scenarios. RF engineers can perform parametric analysis prior to hardware fabrication (Fowdur et al., 2024) with these features.

An example is the design of a dipole array for the WLAN 2.4 GHz band. The frequency sweep can be applied and return loss, mutual coupling and radiation directionality can be assessed for a 1×4 or 2×2 dipole configuration. Theoretical spacing rules (e.g. $\lambda/2$) can be validated using built in functions such as designArray, while sensitivity analysis can be used to assess environmental effects on RF performance (Lappalainen et al., 2022). This digital prototyping in consumer electronics and communication systems reduces iterative costs and shortens development timelines (Hamrouni et al., 2022).

6.2 Biomedical and Wearable Antennas

Dipole antennas are also being used in biomedical telemetry and wearable devices. Researchers can use MATLAB with tissue equivalent phantom models (Elias et al., 2021) to test how body worn dipole antennas function in realistic human conditions. Researchers can import multilayer human tissue models such as skin, fat and muscle to study electromagnetic interactions at ISM bands (for example, 2.45 GHz). MATLAB allows users to set the dielectric constants and conductivity for each layer so that impedance matching and field confinement can be studied accurately. Dipoles designed to lower Specific Absorption Rate (SAR) and improve signal penetration are appropriate for use in health monitoring wearables and implantable systems (Qureshi et al., 2023). In addition, co simulation supports the use of external tools, for example CST for phantom geometry and MATLAB for field analysis, bandwidth study and optimization. The reason MATLAB is important for designing ECG patches, glucose sensors and biomedical telemetry nodes is that it allows for quick and noninvasive design iterations (Zhang, 2022).

6.3 Educational and Research Uses

MATLAB is a key tool in electromagnetic education and research because of its easy-to-use scripting and modular toolbox design. Many undergraduate and postgraduate courses require students to do dipole antenna modeling and MATLAB is often used to link the theory they learn with practical simulations (Dávila et al., 2023).

For instance, students could build a center fed dipole and use MoM to find the current distribution, then compare the results with those from FEM-based solvers (HFSS) or FIT-based solvers (CST). By doing this, we can see more clearly how the numerical methods and solvers differ in their convergence and advantages (Zhang et al., 2022). MATLAB also allows you to see how the E/H field moves and animate radiation lobes which makes it easier to understand the concepts in class. MATLAB is also commonly used in antenna research for fast prototyping, studying parameters and comparing performance. Because of its scripting, researchers can perform many simulations and optimization loops which is crucial for studies that need to be repeated, analyzed and illustrated in journals.

7. Current Limitations and Emerging Directions

MATLAB has a powerful suite of tools for antenna modeling, there remain challenges and limitations that limit its applicability to complex real world scenarios. A major problem is that simplified models in the Antenna Toolbox have limited near field accuracy which can cause problems when electromagnetic interactions are important at small distances, e.g., in biomedical or compact antenna applications. Furthermore, MATLAB does not have a native time domain solver which forces users to perform frequency domain analysis and prevents them from simulating transient phenomena or wideband systems without the use of external software. A second concern is the high level of solver abstraction, particularly in GUI based tools which reduces transparency and the user's ability to modify low level mathematical parameters which is a major drawback for research intensive tasks that require fine grained control. Furthermore, MATLAB antenna modeling ecosystem does not have standardized benchmarking datasets which makes it hard to verify custom models across use cases or compare results across platforms, thus impeding reproducibility and collaborative development. Additionally, the simulation of complex material behaviors (e.g., lossy, dispersive or anisotropic media) is currently limited within MATLAB's framework and often requires hybrid workflows with commercial solvers for accurate modeling in high frequency or metamaterial contexts. There are many opportunities to expand MATLAB's antenna design capabilities looking ahead. Artificial intelligence, especially deep learning, is integrated to revolutionize antenna optimization workflows by providing intelligent parameter tuning, pattern recognition and design suggestion mechanisms which can be leveraged from MATLAB's existing machine learning toolboxes. Another frontier is digital twin technology, where MATLAB can enable real time modeling and feedback loops for adaptive and reconfigurable antennas with cloud based data streams and embedded sensors. The enhanced interoperability with software defined radios (SDRs) could make MATLAB both a simulation and deployment environment, bridging the physical prototype with virtual design tools and reducing time to market for communication systems. Additionally, open source libraries and academic repositories would be developed and curated to encourage community driven innovation where researchers can share, review and benchmark antenna designs. Finally, the Toolbox could be extended to support advanced computational electromagnetics (CEM) such as hybrid MoM-FEM approaches, broadband solvers and multiphysics integration which would significantly enhance MATLAB's competitiveness and versatility in industrial and academic research.

8. Conclusion

MATLAB has become a cornerstone in the modeling and analysis of half wave dipole antennas, providing a rich set of tools for both basic learning and advanced electromagnetic research. It is a key link between theory and practice, offering a flexible framework in which simulations can be quickly created, analyzed and visualized. Four main MATLAB methodologies have been reviewed: the user friendly Antenna Toolbox, the mathematically transparent Method of Moments (MoM) implementations, hybrid workflows using commercial solvers and advanced optimization based techniques using Simulink and Genetic Algorithms toolboxes. There are technical trade offs for each approach. Antenna Toolbox is very accessible and fast but it abstracts a lot of the solver detail. Full control and educational value is provided by custom MoM, but at the price of increased implementation complexity. High fidelity and industrial relevance are guaranteed by hybrid modeling, but at the expense of integration overhead. On the other hand, optimization techniques offer robust performance tuning at the cost of computational efficiency. These differences highlight the need to match the modeling strategy to the particular application requirements such as wireless prototyping, biomedical sensing or academic instruction. The community would benefit from shared benchmarking datasets, standardized validation protocols and cross platform result comparison tools to strengthen MATLAB's role in antenna engineering. These developments would not only increase model credibility and reproducibility, but also increase the collaborative advancement of the field. Looking forward, MATLAB is poised to help advance antenna systems by integrating more with AI, real time hardware and open source initiatives.

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