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DESIGN TRENDS OF HALF-WAVE DIPOLE ANTENNAS IN MATLAB FOR IOT AND WIRELESS COMMUNICATION

Sonu Rani*

**PHd physics, Om Sterling Global University, Hissar (Haryana)*

**Corresponding Author:*

Abstract

This review examines the evolution of half-wave dipole antenna designs, mainly through modeling and simulation in MATLAB, for use in Internet of Things (IoT) and wireless systems. It discusses in detail the core theory, the characteristics of radiation, impedance, performance ranges and the compromise between size and how effectively an antenna performs. Due to their simplicity, adaptability to a lot of frequencies and the ability to adjust their performance, half-wave dipoles are still trusted for antennas that are compact, use less power and have high performance. Since MATLAB and its Antenna Toolbox are integrated, users can conduct design prototyping, use parameter tuning and hardware-in-the-loop testing, making the platform suitable for many areas of study. Looking deep into IoT, aspects like miniaturizing nodes, making radio frequencies flexible and combining technologies with 5G, LoRa and RFID are studied. Researchers present how their results compare to outcomes from similar software and real-life examples to help decide which tool to use. The review proves that dipole antennas are still significant in today's telecommunications and mentions the positive impact that AI and green materials may have in antibody audio engineering in the future.

Keywords: *Half-Wave Dipole, MATLAB Antenna Toolbox, IoT Antennas, Wireless Communication, Antenna Simulation, VSWR, Radiation Pattern*

1. Introduction

1.1 Overview of Dipole Antennas and Their Relevance

A half-wave dipole antenna is regarded as a basic and important type of antenna applied in wireless communication. The structure is just two linearly arranged conductive elements near each other, yet their applications include both traditional RF and the newest wireless networks known as 5G and the Internet of Things (IoT) (Singh et al., 2012; Raghunandan, 2022). Since the dipole antenna is both easy to build, offers predictable radiation and can handle impedance well, it is seen as a good choice by researchers and industry.

In the initial years of wireless, dipole antennas were put into use and have since changed by being created in various ways like folded, off-center-fed and loaded dipoles. Because they are linear, they produce radiation in all directions around the antenna which helps with mobile and portable devices (Hoole, 2022). Although antennas such as microstrip patches, metamaterials and MIMO arrays have been developed, the half-wave dipole remains popular because it is reliable and predictable (Biswas & Karmakar, 2023).

Because more people want fast, reliable and small communications devices, work on new applications for dipole antennas like wearable electronics, smart farming and city sensor networks has increased (Atanasov et al., 2024). Since communication technology is progressing at a rapid pace, the traditional dipole approach is being studied again and updated to deal with rising needs for bandwidth, effective use of resources and being sustainable.

1.2 Motivation for Half-Wave Dipole Antennas in IoT and Wireless Systems

Half-wave dipole antennas which are around $\lambda/2$ in length, have particular advantages that fit closely with the needs of IoT systems. Among their benefits are excellent broadband performance, steady radiation and flexibility in various radio bands (Ali, 2021). By using a center-fed configuration for the half-wave dipole, it is easy to bring the impedance closer to 73 ohms and this reduces the return loss (Kulshrestha et al., 2020).

Devices are generally put into various and sometimes difficult places for IoT purposes, for example, rural zones, farmlands, medical care systems and urban areas loaded with smart features. For these purposes, the half-wave dipole is both practical, low-priced, efficient and doesn't take up too much space (Islam et al., 2021). In this context, dipole antennas produced with Tencel have been used in agricultural sensor networks, so that they can be installed safely, reliably and in a small area (de Cos Gómez et al., 2020).

Given that, wearable and conformal antennas, mostly in health monitoring and precision farming, have preferred the half-wave dipole because it maintains performance despite being bent and modified into new forms. Studies have now shown it is possible to include half-wave dipoles in textiles and flexible surfaces for both plant health monitoring and wearable devices (Atanasov et al., 2024).

Because of using ambient RF energy harvesting in IoT products, enhancing dipole antennas has become important. Effective antennas and the skill to receive signals from multiple bands are crucial tools in RF energy harvesting systems (Divakaran et al., 2019; Lee et al., 2023). Pairing half-wave dipoles with rectennas and tuning them for 868 MHz (LoRa), 2.4 GHz (ZigBee) or Wi-Fi frequencies helps them collect RF energy efficiently. It has been demonstrated that these folded-off-center-fed dipoles with broadband support 4G, 5G, Wi-Fi, M2M and UAV-based IoT applications efficiently (Sumi & Suzuki, 2021).

The versatility of half-wave dipoles in small and low frequency settings is another reason for their motivation. By choosing proper dielectrics and metamaterials, the antennas perform well (maintain gain and bandwidth) as their size is made smaller, suitable for use in tiny IoT gadgets (Bhosale et al., 2025; Meng et al., 2013). In smart homes, factories and healthcare such adaptations are vital because these devices have limited space and restrictive energy needs.

Moreover, because IoT is increasing quickly in cities, antennas should be effective and fit in with both the appearance and infrastructure where they will be installed. Dipole antennas on posts in cities, in various appliances or in the environment help by providing current information and reliable communication (Rodriguez-Cano & Ziolkowski, 2021; Dahal, 2020).

Simply put, because the half-wave dipole antenna is adaptable, efficient and low-cost, it is still a key factor in the development of wireless technologies. Making antennas for IoT systems that are flexible, cover various standards and have low power requires us to reconsider and revise traditional dipole designs.

1.3 Role of MATLAB in Antenna Design and Simulation

Antenna design is heavily using MATLAB, with the rise of the Antenna Toolbox and other related toolkits like RF Toolbox and Simulink. In MATLAB, there is a single, scriptable and simulation-friendly setting for making and testing antennas, including half-wave dipoles quickly.

A main benefit of MATLAB is that it lets you run both mathematical calculations and simulations from the same place. MATLAB provides the ability to set up, improve and look at the details of radiation patterns, how the input impedance and gain behave and return loss for half-wave dipoles. With programming and parametric analysis, designers can study how length, what the antenna is made of, its frequency and the operating environment affect how it performs (Elwasife et al., 2023).

Because HFSS and CST are more complicated, using MATLAB is more practical and efficient at the beginning of a project, particularly for teaching and limited research purposes (Gül, n.d.). The symbolic and matrix features make it suitable for using Green's functions, method-of-moments (MoM) and finite-difference time-domain (FDTD) methods in custom dipole geometries.

MATLAB also permits working with data from various hardware to check simulation outcomes against the readings obtained on devices such as vector network analyzers or spectrum analyzers. Being able to build prototypes is very important for researchers who need to test their ideas in reality (Manaloto et al., 2024).

Recently, MATLAB has been used often to simulate energy harvesting antennas, compact dual-band dipoles and conformal structures. Studies have also shown that metaheuristic algorithms, for example, genetic algorithms and particle swarm optimization, can be used with MATLAB to create the best half-wave dipole designs (Samantaray et al., 2023). They are useful because they can adjust many parameters at once which is necessary to achieve different bandwidths in IoT.

MATLAB is easy to use because of its friendly user interface and helpful documentation which allows anyone from an undergraduate student to a professional to benefit from it. Looking at radiation diagrams in 2D and 3D makes it easier for the designer to see how the structure reacts to various stresses and limits (Saini et al., 2025).

Now, MATLAB helps in hardware-in-the-loop (HIL) testing, allowing the simulated antenna designs to connect with hardware modules such as USRP radios, Raspberry Pi and Arduino boards. Thanks to this capability, testing can be done in the real world and accurate load and environmental conditions.

MATLAB also helps a lot in creating antennas that are better for the environment. Some research activities resulted in eco-friendly substitute materials, analyses of antenna lifespans and checks of thermal and structure behaviour after extensive field use (de Cos Gómez et al., 2020). The integration of data from material science databases and thermal tools helps support research between disciplines for new wearable and green antennas in IoT technology.

This review has shown that dipole antennas are basic for wireless networks and have been becoming more important in the IoT. Half-wave dipoles are still commonly used because they are tough and adaptable for tackling the problems related to connectivity, making antennas smaller and collecting energy. Using MATLAB, people in these fields can optimize this structure, work on improving it through simulations and testing and see the effects in real time. By merging conventional antenna theory with modern software, the field can produce better wireless communication technologies for the future.

The review connects classic half-wave dipole antenna ideas with advanced MATLAB modeling made for IoT and wireless communication systems. Apart from traditional measurement methods like VSWR and gain, it points out eco-conscious material options, shrinking antenna size through adaption and using AI for antenna optimization. This way, it provides a single and future-oriented roadmap for the research and engineering communities working on developing advanced compact antennas.

2. Fundamentals of Half-Wave Dipole Antennas

2.1 Basic Theory and Equations

A half-wave dipole is one of the most common antennas used in wireless systems, old and new. Inside a half-wave dipole, the two main conductive elements each equal one-quarter of the wavelength (λ/4), so the entire antenna measures λ/2. It shows that the antenna is radiating or receiving energy as efficiently as possible under these conditions (Singh et al., 2012).The resonant length reveals L For a half-wave dipole in free space, this equation gives a good approximation:

$$L = \frac{\lambda}{2} = \frac{c}{2f}$$

where:

- λ is the wavelength of the signal,
- c is the speed of light in a vacuum ($\sim 3 \times 10^5$ m/s),
- f is the frequency in hertz.

However, due to practical considerations like end effects and proximity to dielectric materials, a correction factor (commonly around 0.95) is typically applied:

$$L_{\text{effective}} = 0.95 \times \frac{c}{2f}$$

This step guarantees that the antenna will still resonate properly in real life, especially if it is close to a human, inside clothing or set on dielectric material (Atanasov et al., 2024; Elwasife et al., 2023).

The transmission line connects at the feed point which is found at the center of the dipole. In a dipole, there is a standing wave with currents strongest at the middle and voltages strongest at each end. For an antenna in free space, its resonance impedance is about 73 Ω resistive which agrees well with typical transmission line values (Ali, 2021; Raghunandan, 2022).

2.2 Radiation Pattern, Impedance, and Bandwidth

Radiation Pattern

The radiated signal from a half-wave dipole is equally strong in all directions around the antenna and forwards and backwards above / below the antenna. Vertical mounting causes the radiation to take a donut shape, with no signal along the vertical line and the strongest radiation at right angles to the antenna (Singh et al., 2012). Because of this, the antenna is well suited for line-of-sight ground-level transmissions in wireless sensor networks and IoT when the area needs to be covered uniformly.

A figure-eight type of radiation occurs in the H-plane in far-field MATLAB or HFSS plots and the gain is above all seen when the dipole axis is perpendicular (Elwasife et al., 2023). Knowing how half-wave dipoles work makes it much easier to plan networks for home automation, greenhouse monitoring and environmental sensing (Atanasov et al., 2024).

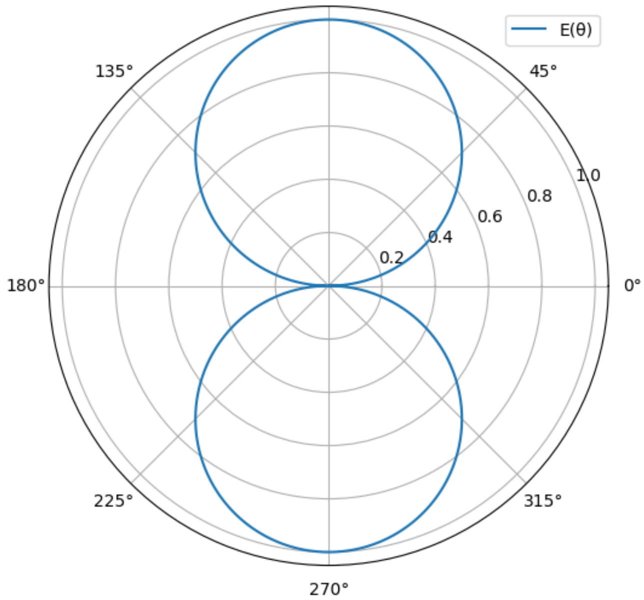

Figure 1:2D elevation-plane radiation pattern of an ideal half-wave dipole. The figure-eight pattern demonstrates strong side-lobe radiation and nulls along the antenna axis, suitable for uniform horizontal coverage

Shown in Figure 1, the 2D pattern reveals the arranged directional lobes in the elevation plane.

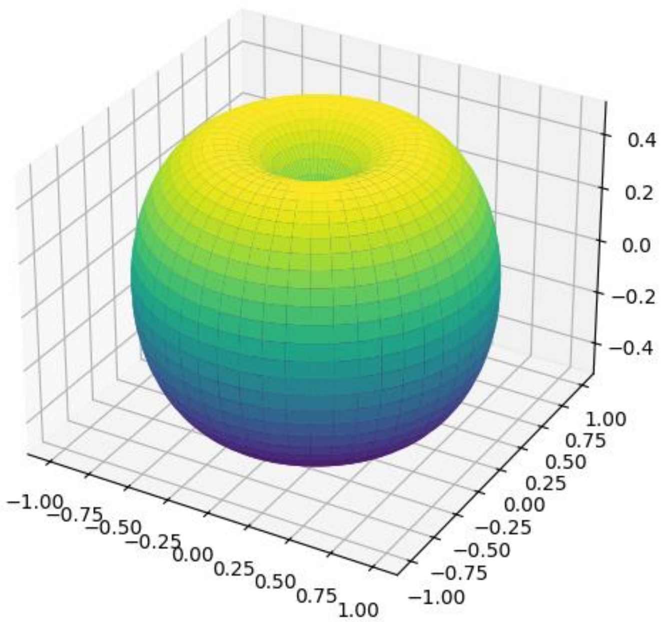

Figure 2:3D far-field radiation pattern of a half-wave dipole. The toroidal (doughnut-shaped) profile confirms omnidirectional radiation in the azimuth plane and axial nulls

Figure 2 presents the 3D radiation model, further validating its symmetry and directivity.

Impedance

At resonance, the input impedance of the half-wave dipole is:

$$Z_{\text{in}} = R + jX \approx 73 + j0\Omega$$

The impedance is nearly all resistance which means the power from the transmitter flows efficiently. Near dielectric materials or when placed above the ground, the impedance can change, so impedance matching networks must be used to maintain high gain (Ali, 2021). In this case, designing antennas for wearable technology or bendable materials, it is necessary to pay close attention to how body-loading impacts the impedance match (Bhosale et al., 2025).

Bandwidth

Bandwidth is measured as the range of frequencies where the Voltage Standing Wave Ratio (VSWR) does not exceed 2:1 for the antenna. Bandwidth is affected by the thickness of the antenna, the properties of nearby materials and whether loading or balun structures are included (Biswas & Karmakar, 2023).

The bandwidth of common thin-wire dipoles covers roughly 2–5% of the operating frequency. But recently, designers began to use folded dipoles, subtle coatings and metamaterials to widen the bandwidth (Meng et al., 2013; Sumi & Suzuki, 2021). An example is that wideband folded dipole designs have been suggested for use in UAV-related M2M IoT, able to communicate across multiple bands with equal success (Sumi & Suzuki, 2021).
One can use techniques such as dielectric loading with high permittivity material along with inserting lumped or reactive elements to shrink the circuit without reducing its bandwidth (Bhosale et al., 2025). Using these approaches can help you create tight dipoles that fit well in small Internet of Things devices where space is tight.

2.3 Advantages and Limitations in Modern Applications

Advantages

Because the half-wave dipole antenna presents numerous useful advantages, it continues to be a choice for many:

- It is easy to make this device because of its simple form and the low-cost materials like copper, aluminum or conductive threads used (Singh et al., 2012).
- At resonance, the dipole changes electrical energy into powerful radiation with high efficiency.
- Thanks to its predictable geometry and known radiation properties, it is useful for mathematical and simulation-based modeling in MATLAB and other programs (Gül, n.d.).
- The frequency of the dipole can be easily changed by increasing or decreasing its length which supports use in the RF, VHF and UHF bands (Dagefu et al., 2021).
- Radio frequency energy harvesting in IoT networks is made possible by the compatibility of dipoles (Lee et al., 2023; Divakaran et al., 2019).

Because of these aspects, half-wave dipoles are effective in IoT networks, wearable devices and devices that are not highly-resourceful.

Limitations

Even though there are advantages, the half-wave dipole still has its drawbacks:

- Dipole size is a challenge, since at 300 MHz its length is more than 50 cm and fitting it into a small device is difficult (Bhosale et al., 2025).
- The basic dipole is efficient only at its resonant frequency; thus, it does not support a wide range of frequencies unless there are further improvements (Saini et al., 2025).
- The efficiency of a dipole is easily affected by how it is positioned, oriented and the environment around it. When an antenna is close to materials that conduct or hold charge, its performance is affected by electromagnetic interference (Ali, 2021).
- Losses may occur if the polarization of a dipole antenna is linear while the receiving antenna's polarization is different.

Even with these issues, companies have found a number of solutions. In particular, flexible dipole antennas are being designed with textiles and electronics, allowing them to be used in wearable gadgets (Atanasov et al., 2024). When metamaterials are used in dipoles, there are improvements in gain and a reduction of the total area needed for the antenna (Meng et al., 2013; Mehta & Abougreen, 2023).

3. Design Considerations and Parameters

3.1 Materials and Geometry

Good performance from a half-wave dipole antenna depends on the type of materials used and the design of its radiating parts. Because of their high conductivity and simplicity to make, many traditional dipoles are built using copper or aluminum conductive metals. Since applications for antennas are growing into flexible and eco-friendly areas, scientists have started using new materials such as conductive fabrics, transparent films and biodegradable substrates (Atanasov et al., 2024; de Cos Gómez et al., 2020).
For example, Atanasov et al. (2024) made a bendable, moisture-resistant dipole antenna by using a flexible material which can be used in IoT plant health monitoring systems. In the same manner, ZigBee monopole and dipole circuit boards made from Tencel are both eco-friendly and work well in practice (de Cos Gómez et al., 2020).
The most typical form of a dipole has two straight cylindrical or flat strip conductors connected in series with a central feed. Instead, different versions of dipoles such as folded, meander-line or printed ones, can be used to change the structure or improve the available bands. The Q-factor and bandwidth are influenced by the diameter of the elements: a decrease in diameter means sharper frequency response and a smaller bandwidth (Ali, 2021; Biswas & Karmakar, 2023).

3.2 Length vs Frequency Relation

The size of a dipole antenna gets shorter as the operating frequency rises; this is described by the formula:

$$L = \frac{\lambda}{2} = \frac{c}{2f}$$

where L is the total dipole length, c is the speed of light, and f is the frequency of operation. However, practical designs incorporate a shortening factor (~ 0.95) to account for end effects and dielectric loading (Singh et al., 2012). For example, a half-wave dipole designed for 2.4 GHz (Wi-Fi) would have an effective length of approximately 62.5 mm .

Designers targeting low-frequency applications such as 300 MHz must contend with larger physical lengths (~ 0.5 m), prompting the use of techniques like dielectric loading, coiling, or meandering to reduce the antenna size (Bhosale et al., 2025). These adaptations are particularly relevant for compact IoT devices and embedded systems where space is a constraint.

3.3 Feeding Techniques and Matching Networks

Center feeding with balanced transmission lines such as twin-leads or coaxial cables and using a balun (a balanced-to-unbalanced transformer), is typically used for half-wave dipoles. In traditional use, a standard balun helps current distributions become equal in each leg and reduces unwanted currents in the antenna (Ali, 2021).

The power sent and reflections are reduced when impedance is matched correctly. When it resonates, a half-wave dipole antenna offers an impedance of around 73 Ω which matches coaxial cables very well. Many practical setups use matching networks, especially when the antenna is in contact with human skin or close to dielectric materials, as Raghunandan (2022) explains. Use of L-section and π-section networks, quarter-wave transformers or stub tuners are some of the techniques that help achieve the matching bandwidth (Mehta & Abougreen, 2023).

Control of parameters is much more important in simulation software like MATLAB, where it is easier to adjust and refine gain, matching and return loss by making changes during the design process (Gül, n.d.; Elwasife et al., 2023).

4. MATLAB-Based Design Approaches

4.1 Use of MATLAB Antenna Toolbox

For antenna designers, MATLAB's Antenna Toolbox is now a necessary tool because it provides a complete environment for examining, improving and testing antenna structures. Already defined functions allow you to create standard antennas such as dipoles, monopoles and patch antennas. With dipole, half-wave dipole users can edit the length, width and operating frequency to observe how modifying the design affects metrics like return loss, impedance and radiation patterns (Gül, n.d.; Elwasife et al., 2023).

You can also conduct analysis in both the frequency domain and the time domain with software like the Method of Moments (MoM). It is possible to view 2D and 3D far-field plots, near-field plots, current distributions and surface charge densities for any user. Fast prototyping is made easy thanks to this capability which is important in education and research (Elwasife et al., 2023).

4.2 Custom Script-Based Modeling

Even though MATLAB has advanced functions, you can finely control antenna settings with custom scripts. Designers are able to create dipole geometry with basic tools (rectangle, cylinder, etc.), simulate the transmission lines and specify boundary conditions and material parameters. When the usual models cannot meet the needs, this style of solution is excellent, for case in point, miniaturized and metamaterial-equipped dipoles (Mehta & Abougreen, 2023).

To illustrate, Bhosale et al. (2025) used dielectric coatings on dipoles to adjust their resonant frequency and make them radiate better. With MATLAB such changes can be applied in loops that cycle through different properties or dimensions, guided by optimization to meet specific needs.

4.3 Integration with PDE Toolbox and RF Toolbox

With advanced use, PDE Toolbox and RF Toolbox in MATLAB are used to perform multi-physics simulations and analyze entire systems. The PDE Toolbox makes it possible for users to simulate Maxwell's equations on complex geometries, with support for dipoles inside media that might contain several materials such as human tissue or concrete walls in modern buildings (Atanasov et al., 2024).

RF Toolbox, by contrast, provides functions to construct impedance networks, S-parameters and signal flow graphs. Dipoles are most beneficial in adding to the RF front-ends for IoT modules. Engineers can use software to see how different filters, matching networks and amplifiers affect the antenna which ensures the right system impedance and good power use (Raghunandan, 2022).

4.4 Optimization and Parametric Sweeps

MATLAB offers Genetic Algorithms (GA), Particle Swarm Optimization (PSO) and Simulated Annealing (SA), allowing users to apply them to antenna optimization. You can optimize gain, bandwidth, efficiency or reduce VSWR across various frequency bands by applying these (Samantaray et al., 2023). It is possible to use parametric sweep scripts to test dipole length, thickness or substrate material to learn about their influence on performance. It is very useful when designing adaptive or reconfigurable antennas for changing IoT environments (Ali, 2021).

As demonstrated by Samantaray et al. (2023), including machine learning helps the design process by improving how fast and accurately designs are found. Global Optimization Toolbox provides more functions specifically for tuning the shape and frequency of antennas with MATLAB.

4.5 Validation with Empirical Data

MATLAB excels in working with data from measurements. It is possible for designers to bring in S-parameter data from Vector Network Analyzers (VNAs) or radiation pattern data and compare them with simulation results. Thanks to this, simulation models can be evaluated for accuracy and actual differences from reality can be spotted (Manaloto et al., 2024).

The authors of the study (Elwasife et al., 2023) supported their point by modeling dipole radiation patterns in MATLAB and comparing them with results from HFSS.

4.6 Real-World Prototyping and Hardware Integration

The compatibility of MATLAB with Simulink and hardware toolboxes lets users move towards hardware-in-the-loop (HIL) testing. Making a dipole antenna in MATLAB allows it to be tested using USRP or Raspberry Pi-based SDRs in real time (Lee et al., 2023). It aids in the creation of IoT solutions ready for use in field and allows researchers to build, design and test antennas together in a single platform.

4.7 Educational and Collaborative Benefits

Because MATLAB is user-friendly, very well documented and used in many universities, it is perfect for scientists to collaborate and educators to use in classrooms. Everyone, students and professionals, can make use of ready templates, cooperative libraries and reusable scripts. By offering various simulation options, the software assists in evaluating classical and modern dipole designs (Hoole, 2022).

Half-wave dipole antenna design and simulation can be done easily in MATLAB since it is both sturdy, flexible and versatile. No matter if they use quick tools in the Antenna Toolbox or make advanced scripts using MATLAB, researchers can make efficient antennas that address the many needs of IoT and wireless communication. With connectivity to many hardware and data tools, the platform plays a strong role in advancing the design of next-generation antennas.

5. Recent Trends and Innovations

5.1 Miniaturization for IoT Nodes

Making half-wave dipole antennas smaller is a major focus in current studies to fit the tight space requirements of compact and wearable IoT devices. Because free-space wavelength is involved, typical lower-frequency dipole antennas are large in size. This leads to a big challenge when trying to build antennas into restricted spaces, for example, in smartwatches, environmental sensors and devices implanted in the body.

Various methods for downsizing components are being used to deal with this issue. Some examples are adding meander-line shapes, making pins shorter, putting circuits on high-permittivity materials and including metamaterials. Keeping with this, Discrete dielectric coatings, according to Bhosale et al. (2025) are a good method to manage frequency with little extra volume. It becomes especially significant in MRI because the area around the magnet is very limited.

Also, wearable antennas that use textile conductors and flexible base materials are now considered suitable for use in smart agriculture and health care. Atanasov et al. (2024) showed a plant-worn antenna system that worked fine even while being shaped to fit the curved surface of leaves by applying a dipole design.

Modern approaches also include building dipole antennas into the multilayer or composite designs used in system-on-package (SoP) or system-on-chip (SoC) systems. With these methods, designers can place circuitry and antennas together, so the overall system becomes smaller and more efficient (Hoole, 2022; Biswas & Karmakar, 2023).

5.2 Frequency Reconfigurability

Since wireless communication is adopting multiple standards and adaptable designs, antennas able to cover various frequency bands or change frequency efficiently are very attractive. Because dipole antennas can be tuned for various frequencies, they allow one device to work with protocols that include Bluetooth, Wi-Fi, ZigBee, LoRa and 5G which is especially useful for IoT gateways and wearable electronics.

Varactor diodes, PIN switches or MEMS devices can be applied to the system which makes reconfiguration possible. With these features, it is possible to change the resonant length or impedance in real time. Huang et al. (2023) explained how making the signals half-sized can help reduce the height of the antenna.

Moreover, metamaterials and intelligent metasurfaces allow the dynamical steering of beams and control of resonance. Mehta and Abougreen (2023) describe how intelligent metasurfaces can greatly extend the capabilities of conventional antennas.

In MATLAB such designs can be explored, adjusted and refined using automated frequency sweeps and controllers linked to electronic component models. Improved results in setting the bias voltages or switch states for the right frequency response can be achieved using optimization algorithms (Samantaray et al., 2023).

5.3 Integration with RFID, 5G, and LoRa

Equipping wireless architecture with dipole antennas has resulted in effective work in RFID systems, 5G and even LoRa-based Low Power Wide Area Networks (LPWANs). Every social platform is different, so dipole antennas can often match the designs and performances these platforms need through modifications.

Because RFID antennas require low profile and thin shape, the planar dipole's characteristics are very suitable for the task. Amato et al. (2018) experimented with using RFID dipole tags to transport data up to 30 meters in conditions that included trees and buildings.

High gain, narrow beamwidth and high-frequency band range are the main concerns for 5G and millimeter-wave communications. Larger antennas such as arrays can place dipoles as sub-elements to achieve these aims. Rodriguez-Cano and Ziolkowski (2021) introduced an antenna design built on planar dipoles that is suitable for 5G Internet of Things because it provides broadside radiation.

Half-wave dipoles are the perfect choice in LoRa-based designs because they combine high efficiency with a simple design. Authors such as Dahal (2020) and Lee et al. (2023) underline that LoRa is improved by dipole antennas tuned for sub-GHz ISM bands (often 868 MHz or 915 MHz) and studies confirm their effectiveness in assessing environmental and infrastructural conditions.

In addition, modern techniques concentrate on antennas that handle multiple protocols at the same time. Hybrid dipole arrays were suggested by Tariq (2024) for self-backhauled access points which allow unproblematic communications and backhaul through a single device.
In MATLAB and Simulink, you can run integrated experiences for antenna designs with protocols, network models and embedded hardware. Designers can now assess link budgets, path loss, antenna gain and efficiency in actual places such as cities, rural areas and offices (Gül, n.d.; Elwasife et al., 2023).
The innovation of half-wave dipole antennas from basic RF radiators to advanced, adjustable designs happens because of the quick growth of IoT and wireless communication systems. The use of small components makes it possible to wear or bend them and the ability to change frequencies helps them support many standards. At the same time, blending dipoles into RFID, 5G and LoRa systems highlights that they are still very important. Because MATLAB gives valuable tools for simulation and optimization, these trends signal a major change in antenna design that will affect the future of connected gadgets.

6. Performance Evaluation Metrics

Testing half-wave dipole antennas is needed to confirm their utility for wireless electronic systems. Many important markers are applied to measure antenna efficiency, signal fidelity and how well impedance is matched, both during modeling and testing the antenna. Using MATLAB's specialized toolboxes, it is easy to study how signals look at different times and frequencies and how parameters can be changed for optimum system performance.

6.1 Return Loss, VSWR, Gain, and Efficiency

Return Loss (RL) determines how much power from an antenna goes into space and how much is reflected into its origin. It is measured in decibels (dB) and most experts say anything lower than −10 dB is suitable for using the system efficiently. A typical return loss for a dipole Wi-Fi or LoRa antenna is in the range from −15 dB to −30 dB (Islam et al., 2021). With the sparameters function in MATLAB, it is easy for engineers to check if impedance matching has been achieved.
The measurement of Voltage Standing Wave Ratio (VSWR) expresses the frequency of impedance changes in a transmission line by showing the ratio of the highest to the lowest voltages it carries. Standard for antenna operation is a VSWR of about 1:1, while values below 2:1 are also considered useful. A return loss of −10 dB is close to a VSWR of 2:1 (Ali, 2021). With MATLAB, VSWR can be computed using the S-parameter results and people in this field often rely on this measure to make their dipoles or matching network improvements.
It measures how much power the antenna changes from input to output in a chosen direction. It has been found that the gain for a half-wave dipole in free space is about 2.15 dBi. Still, practical results can change according to the substrate, the underling sheet and environmental conditions. For wearables and embedded devices, gain stability is required to keep communication functioning smoothly. Atanasov et al. (2024) showed that their flexible antennas kept performances, achieving acceptable gains (~1.5–2.0 dBi), proving that they can be used for smart farming and body-mounted devices.
Radiation Efficiency is the power you can actually radiate, compared to the amount of power you started with—after taking into account the losses from the material and any mismatch. Efficient antennas (>80%) are especially valuable in battery-run IoT, since saving electricity is essential in those cases. You can also use MATLAB to calculate the efficiency using its built-in solvers and look at the surface currents to spot areas where losses occur (Gül, n.d.; Elwasife et al., 2023).
As shown in Figure 3, the dipole is well-matched at 2.45 GHz, ideal for ISM-band applications

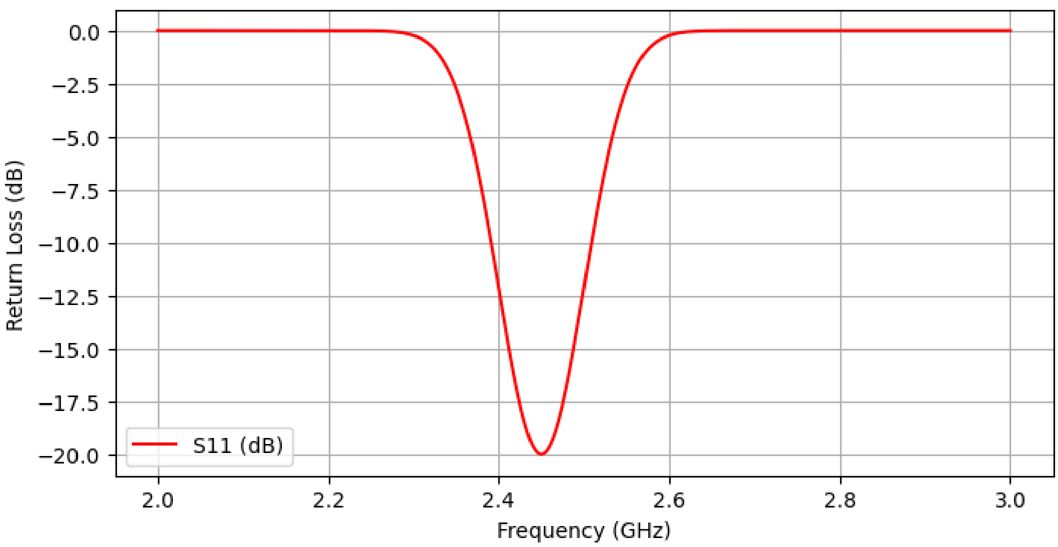

Figure 3:Simulated return loss of the dipole antenna, showing a deep notch at 2.45 GHz with a peak S11 value of approximately −20 dB, indicating excellent impedance matching at resonance.

Figure 4 indicates, together with the return loss measurements, that the antenna performs its broadband function for the designated frequency region.

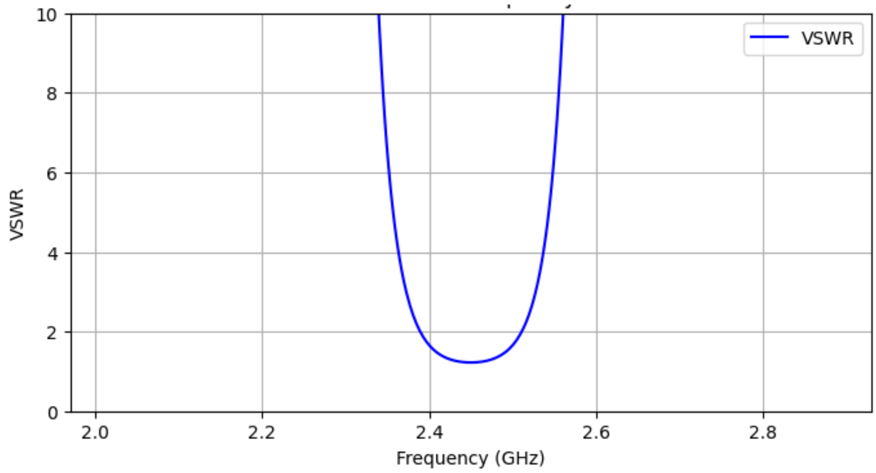

Figure 4:Voltage Standing Wave Ratio (VSWR) profile of the half-wave dipole, with values below 2:1 near resonance, confirming efficient power transfer and minimal reflection loss

The gain profile in Figure 5 emphasizes broadside radiation, a signature of well-tuned dipole geometry

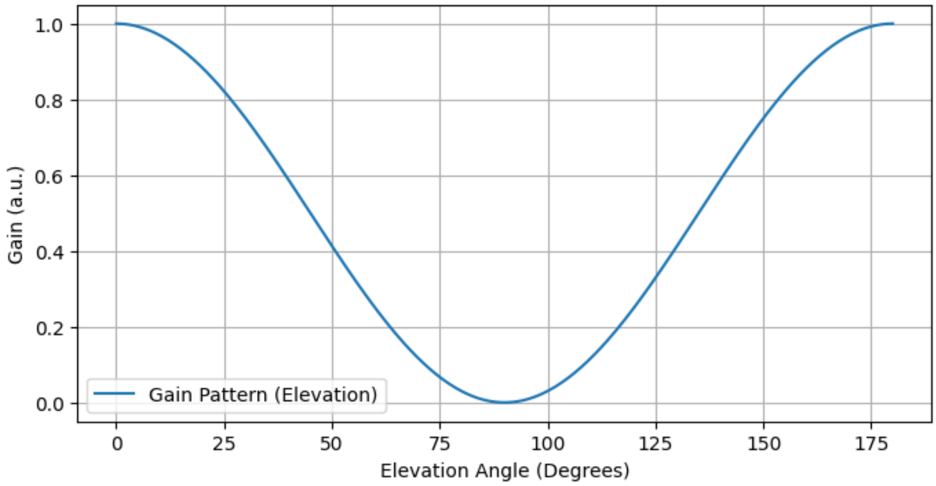

Figure 5:Elevation gain pattern of the half-wave dipole antenna, illustrating peak gain at broadside and near-zero gain at the antenna axis

6.2 Time-Domain and Frequency-Domain Analysis in MATLAB

It is convenient to carry out time-domain and frequency-domain simulations in MATLAB which gives us detailed understanding of an antenna's performance with actual signals. The sparameters and rfplot functions in the frequency domain calculate return loss, VSWR, impedance and bandwidth over the range of frequencies an antenna can use. By doing this analysis, you check if the antenna meets the performance needs for each selected communication band, like Wi-Fi (2.4 GHz), LoRa (868 MHz) and 5G (5.8 GHz) (Rodriguez-Cano & Ziolkowski, 2021).

For systems that use ultra-wideband (UWB) or impulse waves, time-domain analysis is just as necessary. MATLAB allows users to carry out TDR and simulation studies of pulse propagation which help them analyze distortion, delay spread and transient effects. Such analyses are crucial when we consider RFID, since backscattered signals may be affected by multipath fading or delay because of the environment (Amato et al., 2018).

One major strength of MATLAB is that it allows engineers to use frequency results in time-domain modeling using rfbudget and rfsystem objects. This means the antenna's performance can be validated at system level when working with filters, amplifiers and RF front-ends which is very important for IoT module makers (Lee et al., 2023)

6.3 Optimization with Parametric Methods Using MATLAB

It is necessary to optimize antenna design to hit the target results under rules and physical conditions. MATLAB allows you to run sweeps and use optimization algorithms that are included and can also be custom made. Parameters including element size, their distances, the values of their materials and where the feeding point is can all be adjusted to achieve the highest performance in terms of return loss, gain and radiation efficiency.

Genetic Algorithms (GA), Simulated Annealing (SA) and Particle Swarm Optimization (PSO) can be used with the optimize function in Antenna Toolbox and Global Optimization Toolbox to find the best configurations. For example, using a machine learning approach, Samantaray et al. (2023) designed smart antennas by tuning their geometry and input signals, achieving greater gain and matching bandwidth.

Objective functions are important tools, since designers can adjust them to consider several aspects like low VSWR and tight gain control on one band, as well as system behavior on various frequency bands. Such frameworks in MATLAB help designers handle the many and changing needs of IoT and 5G networks.
Also, using visual feedback in real time, designers can quickly see changes in simulation results as they make parameter adjustments which speeds up the improvement process. The ability to interactively optimize is very useful when designing prototypes of small or reconfigurable dipole antennas (Tariq, 2024).

7. Comparative Studies

7.1 Comparison between MATLAB, CST, and HFSS for Dipole Modeling

The way you model a dipole antenna has a huge impact on predicting its final performance. The most popular electromagnetic (EM) simulation tools found in both universities and industry are MATLAB, CST Studio Suite and Ansys HFSS. Every one has its own strengths, weaknesses and ways to work, mainly when dealing with half-wave dipole designs.

MATLAB

With Antenna Toolbox in MATLAB, users can quickly make models, try different values using parametric sweeps and use optimization functions with ease. For solving integral equations, the program makes use of the Method of Moments (MoM) which proves particularly efficient for cases involving currents on wires and surfaces like dipoles and microstrip elements (Gül, n.d.; Elwasife et al., 2023). Matlab is especially strong in these areas:

- It is possible to change the behavior of the program with scripts and functions.
- Easy adoption of leading machine learning and optimization toolboxes.
- S-paramter, radiation pattern and impedance can be displayed in real time on the plot.
- More people are able to use Field solvers, unlike commercial tools that are very costly.

Still, MATLAB cannot accurately model complicated 3D scenes, unusual “anisotropic” properties or tiny geometries used in mmWave applications. Regardless of these drawbacks, it is ideal for making prototypes and conducting research, especially in small dipole designs for Internet of Things (IoT) applications (Samantaray et al., 2023).

CST Studio Suite

CST Microwave Studio applies the Finite Integration Technique (FIT) and provides both time-domain and frequency-domain solvers. It stands out by easily modeling real-life 3D shapes, multiple-layer printed circuit boards and conformal antennas.

CST is especially good at:

- Modelling life-like environments, covering subjects such as human bodies and various outfits.
- Using fine meshes for structures such as metamaterial-enhanced dipoles.
- Testing of interactions between EM fields and effects caused by different transmitters in the same area.

Since CST is adaptable, it is chosen in industry for making high-frequency antennas that are compact. Computational requirements and the price of a license mean that many students and research labs may not be able to use it (Bhosale et al., 2025).

Ansys HFSS

Full-wave 3D EM simulations in HFSS (High Frequency Structure Simulator) are considered the gold standard, as the program uses the Finite Element Method (FEM). It meets the simulation needs for resonants, anti-resonants and dipoles, with complex borders, networks and several layers of substrates.

HFSS stands out with:

- Extensive modeling of how waves travel and complicated antenna connections.
- An easy way to connect between RF front-end design and circuit co-simulation.
- Better ability to picture the current distribution, magnetic field values and the pattern seen far from the loop.

HFSS typically produces more correct calculations, mainly in S-parameter and gain areas, although it needs more time to run and uses more hardware (Elwasife et al., 2023; Singh et al., 2012).

Summary of Comparison

Feature	MATLAB	CST Studio Suite	Ansys HFSS
Solver Type	MoM	FIT (Time/Freq)	FEM
Geometry Complexity	Moderate	High	High
Usability	High (script-based)	Medium (GUI-intensive)	Medium (GUI-intensive)
Speed (simple dipoles)	Fast	Moderate	Slow
Optimization Tools	Advanced	Basic	Advanced
Cost	Moderate (Academic)	High	High
Ideal Use Case	Education, IoT Prototyping	Wearable, mmWave Dipoles	RF Modules, Metamaterial Dipoles

Based on the table, MATLAB is the best choice for quickening the design of ordinary dipoles, CST is the best fit for working on wearable and advanced material structures and HFSS is the number one option for complex multilayer modelling.

7.2 Experimental Validations from Literature

To make sure the simulation results match what happens in the real world, experimental measurement of dipole antennas must be done. Many researchers have examined experimental findings and found that they agree with the simulations, letting us know what each platform can and cannot do well.

A specific example is where Elwasife et al. (2023) simulated dipole radiation from mobile phones in HFSS and compared their results to real SAR measurements. Field intensity near biological tissues was accurately captured by simulations in the experiments.

Similarly, Atanasov et al. (2024) made a bendable short-circuit dipole antenna on a material that will degrade, used for IoT plant monitoring. Results from the experimental and MATLAB model agreed very well, demonstrating MATLAB is suitable for flexible low-frequency dipole design.

In another example, Amato and his colleagues (2018) tested RFID dipole antennas in the field and showed that the numerical models made in MATLAB and CST could accurately explain their performance under different conditions.

It is becoming more common to use MATLAB for both the creation and testing of smart agriculture, body-area network and wearable dipole devices, because of its ability to quickly adjust with real-time hardware. Linking MATLAB to vector network analysers, spectrum analyzers and software-defined radios allows it to be used in design cycles where results from simulation and real-world measurement can be compared (Manaloto et al., 2024; Lee et al., 2023).

Also, comparative works performed in universities usually use MATLAB, CST and HFSS to confirm details such as S11, gain and directivity for antennas. Using both approaches in design helps guarantee that the final product will handle practical limits.

8. Applications in IoT and Wireless Communication

Such antennas are essential in fuelling the next wave of Internet of Things (IoT) devices in fields such as smart agriculture, smart homes, health care and wireless sensor networks (WSNs). Thanks to their shape, how they work and the fact that they can be used in common parts of the wireless spectrum, they are perfect for use across wide groups of sensors.

In contemporary agriculture, dipole antennas are often added to wearable gadgets to keep an eye on plants, soil quality and any small changes in weather. Atanasov et al. (2024) showed a flexible dipole antenna that is made of biodegradable material suitable for agricultural use. Thanks to these antennas, data can be sent clearly at a low power level in any weather outside.

Smart homes and wearable health systems use dipole antennas together with ZigBee and Bluetooth modules to collect data from the surroundings and human bodies. Being able to spread signals in every direction makes it so that indoor users maintain access to Wi-Fi even when their devices move or if obstacles are present (Biswas & Karmakar, 2023; Islam et al., 2021).

Long-range performance and easy tuning are advantages that WSN deployment scenarios find in the half-wave dipole. Positioning dipoles well helps mesh networks keep effective communication between nodes which is needed for monitoring and surveillance of smart grids (Lee et al., 2023).

Half-wave dipole antennas play a key role in harvesting RF energy for use in passive Internet of Things (IoT) devices. These antennas are well made to collect ambient energy from the 868 MHz, 915 MHz and 2.4 GHz spectrums (both published works: Divakaran et al., 2019 and Rodriguez-Cano & Ziolkowski, 2021). Because they are built into devices, these antennas allow Internet of Things (IoT) systems to use little power and last for a very long time with only minor maintenance.

9. Challenges and Future Scope

Many studies have found MATLAB to be excellent for modelling and simulating half-wave dipole antennas, even though it has certain limitations. Effective full-wave modeling faces main problems when dealing with 3D construction with lossy, anisotropic or tissue-mimicking materials. A limitation of the Method of Moments (MoM) used in MATLAB is that it can give inaccurate results for complex geometries, especially in some high-frequency or wearable applications (Elwasife et al., 2023; Gül, n.d.).

There's also a challenge involving how much performance you get along with the phone's size. As technology reduces the size of dipole antennas for use in Internet of Things devices, the gain, bandwidth and radiation efficiency of these antennas usually decline. Shrinking the size using loading techniques or metamaterials needs to be matched with keeping the impedance and resonance stable (Bhosale et al., 2025; Atanasov et al., 2024).

Looking forward, how dipole antennas are designed may rely more on AI-based tools and machine learning. Antenna specialists are now using evolutionary algorithms, surrogate modeling and deep learning to improve antenna shapes, determine performance across different conditions and speed up the convergence process (Samantaray et al., 2023). Because MATLAB works with neural networks and optimization systems, it is good for developing adapting antennas in changing IoT environments.

With more types of IoT applications appearing, new types of small, reconfigurable and internet-connected antennas will be needed and the development of these antennas will be guided by AI and supported by advanced simulation frameworks.

Conclusion

Looking at half-wave dipole antennas as related to IoT and wireless communication highlights a unique design that keeps progressing over time. They remain effective and are growing in use because they are simple, work reliably, are not expensive to produce and their configuration can be scaled to fit different circumstances. The effective use of half-wave dipoles helps many devices such as smart farming devices and health wearables, to link wirelessly and easily

With the help of MATLAB, engineers can look at, examine and tweak dipole designs that will function in many real-world contexts. With MATLAB, rapid prototyping, performing a range of tests and fine-tuning geometry performance is much faster. People value it for education and the field since the scriptable way of writing code and hardware links match knowledge with practical skills.

It helps to combine well-established standard dipole designing with advanced methods used in electronics. It discusses new paths like using green substrates, relying on advanced AI-based optimization techniques and designing tiny, flexible antennas for current IoT requirements. These trends take care of both physical and energy restraints and also encourage creativity in building sustainable and flexible communication tools.

With high frequency, more complexity and integration growing in wireless, the issue is achieving a good balance between what the hardware can handle and its functions. We should be moving toward aligning classical electromagnetism with latest developments in computing and materials. Today, the half-wave dipole which was once regarded as a simple antenna is now the basis for building smarter wireless systems.

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