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Performance Analysis of Dipole Antenna Applications: A Literature Review

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A B S T R A C T

This review analyzes recent advancements (2019-2024) in dipole antenna performance, focusing on design and applications. Employing a systematic approach, key parameters influencing performance are identified. Findings highlight the continued relevance of dipole antennas across diverse wireless communication applications, including indoor positioning, mobile communication, antenna calibration, and filtering. The review underscores their ongoing evolution in base station environments and concludes by emphasizing their adaptability and potential for future advancements.

Keywords: Dipole antennas; Performance analysis; Wireless communication; Impedance matching; Optimization techniques

1. Introduction

Due to their simple design and adaptability in telecommunications, dipole antennas, a fundamental antenna type comprised of two identical metal conductors, are widely used [1]. The performance of a dipole antenna is influenced by several factors, including the conductivity of the metal, its length, wire radius, the surrounding environment, and the feeding point [2]. These antennas, typically consisting of two conductive rods fed with a sinusoidal voltage differential, can have their operational frequency adjusted by modifying the spacing between the elements [3]. This adjustability makes them suitable for a variety of applications, such as RF energy harvesting [4]. Dipole antennas can be further enhanced with additional features, such as p-i-n diodes, to enable frequency reconfiguration, all built upon their basic structure [5]. Additionally, their compact size and efficient impedance matching make them ideal for wireless communication applications [6]. Recent advancements have concentrated on miniaturizing dipoles while preserving their performance [7], as well as improving their ability to be reconfigured for various frequency bands [5].

To enhance the radiating properties of dipole antennas, particularly for 5G applications, reflectors have been introduced [8]. This development complements the creation of compact printed dipoles for GPS/WiMAX applications [6] and V-shaped dipoles designed for radio astronomy observations [9]. These advancements highlight the importance of dipole antennas in optimizing signal quality and system performance across diverse applications.

Recent research has delved deeply into the fundamental electromagnetic theory underpinning dipole antennas. Studies have explored the radiation characteristics of horizontal and vertical electric dipoles situated over dielectric-coated impedance surfaces [10, 11]. Additionally, transformation electromagnetics has been employed to design a material capable of transforming the field from a horizontal dipole to that of a vertical dipole [12].

Impedance tuning and bandwidth enhancement remain crucial aspects of ongoing dipole antenna development. A variety of methods have been proposed to address these challenges, including the utilization of wideband impedance matching baluns for balanced two-arm antennas [13]. Additionally, the design of optimal matching stacks that deliver flat, broadband transmission has been explored [14]. A multitude of optimization techniques have been proposed to elevate the performance of dipole antennas. This includes the use of machine learning-based approaches [15], computationally efficient design optimization methods employing accelerated gradient search algorithms [16], and electromagnetic bottom-up optimization strategies for designing antennas autonomously [17]. These advancements collectively showcase the potential of various numerical simulations, electromagnetic modeling, and optimization algorithms to improve dipole antenna performance. In light of this, this review aimed to identify and analyze the diverse parameters influencing the performance of dipole antenna configurations, encompassing material properties and operating frequency. It further seeks to summarize the existing knowledge gaps and challenges in the field of dipole antenna performance analysis, while suggesting potential avenues for future research.

2. Design considerations for wearable antennas

Phased array antennas offer a unique advantage: the ability to electronically steer the beam without physically rotating the antenna. This makes them ideal for applications like indoor positioning systems (Wi-Fi, WLAN, 5G) where precise beam control is crucial. In a study by [18], a successful design of a phased array antenna system was achieved using a 2x2 dipole antenna configuration and an RF beamforming circuit. The design optimized the main beam coverage through a combination of phase shifters, attenuator circuits, and a genetic algorithm. Importantly, simulations and measurements validated the design, demonstrating a steered main beam and a favorable reflection coefficient. In addition, printed dipole array antennas are another popular choice due to their desirable characteristics, particularly impedance bandwidth and gain. For instance, a study by [19] designed two- and four-element arrays using Wilkinson power dividers. Simulations predicted increased impedance bandwidth and gain as the number of elements increased (single, two, and four elements). The fabrication and testing of a two-element array further confirmed these predictions, with good agreement between simulated and measured results.

Microstrip dipole and loop antennas offer an alternative approach, particularly valuable for over-the-air antenna testing. In a study by [20], an array antenna with a printed microstrip dipole and loop was designed for radiation performance evaluation at 28 GHz. The key findings of this study were the wideband matching and radiation performance observed for both antennas. The close agreement between simulated and measured radiation patterns further validated the chosen design. Notably, the omni-directional characteristics of these antennas make them well-suited as reference antennas. Also, the emerging field of wearable communication necessitates the development of flexible antennas that can conform to the human body. To address this need, [21] designed compact, textile-based planar dipole antennas for on-body applications. The fabrication technique involved conductive copper threads and sewn embroidery on camouflage and cotton cloth. The performance evaluation process included simulations, anechoic chamber experiments, and indoor environment tests on various body locations. Encouragingly, the antennas exhibited favorable performance in all scenarios (free space and on-body) with good return loss and a resonant frequency near 2.4 GHz. However, the study also noted the impact of the human body on the radiation pattern, hinting at the complexities of on-body antenna design.

Standard dipole antennas play a crucial role in antenna calibration, but real-world limitations can hinder their performance. To address this challenge, a study by [22] presented a high-performance 2 GHz standard dipole (SD) antenna with an optimized element shape and integrated shielded balun. The balanced feeding structure, transitioning from parallel strip lines to coaxial lines, mitigated the effects of electromagnetic environment asymmetry and ensured proper balance. This innovative design resulted in exceptional performance metrics: relative bandwidth exceeding 15%, gain of approximately 2 dBi, and a high cross-polarization ratio in the horizontal plane. These characteristics make this SD antenna particularly well-suited for antenna calibration applications. With that, designing antennas for blood irradiation applications also presents a unique challenge: the blood environment can significantly affect antenna performance. A study by [23] investigated this very issue. Simulations and measurements revealed that an inkjet-printed dipole antenna suffered substantial degradation in radiation pattern when placed on a blood bag. To mitigate this effect and isolate the antenna from the blood, the researchers integrated it with an artificial magnetic conductor (AMC) structure designed for 2.45 GHz operation. This integration led to a significant improvement in antenna gain despite the blood's lossy nature. The findings highlight the potential of AMC structures for enhancing antenna performance in challenging environments.

Moreover, on-body antennas require careful design considerations, particularly regarding user safety. One important factor is minimizing backward radiation. To achieve this, [24] designed a customized folded planar dipole antenna for on-body applications. The design prioritized minimizing backward radiation while maximizing operational range. For practical use in real-world settings, the antenna was encased entirely in resin. This encasing offered a balance between radiation performance, protection, and isolation. Measurements indicated a good balance of performance: a 10 dB impedance bandwidth of 470 MHz, a compact size, and a near-omnidirectional radiation pattern.

Finally, photonic crystals (PCs) offer exciting possibilities for enhancing antenna performance. A study by [25] investigated the radiation performance of a dipole antenna on a 3D-printed diamond-structured PC substrate with point defects. The results showed good agreement between the reflection properties of the PCs and the radiation frequency of the antenna. The antenna integrated with the PC substrate exhibited an improvement in gain and directivity compared to the standalone antenna. These findings pave the way for further exploration of PCs in innovative antenna designs and innovations.

3. Methodology

This review employs a systematic and detailed method to examine the performance analysis of dipole antennas. The following specific techniques are used to guarantee a thorough assessment.

3.1 Strategy for Literature Search

The search strategy was structured to discover and scrutinize the latest progress in dipole antenna setups, emphasizing two primary elements. The first element was the time frame, focusing on studies published from 2019 to 2024 to encompass the most recent advancements in the analysis of dipole antenna performance. The second element was the choice of database, where a range of databases and platforms, such as IEEE Xplore, ScienceDirect, ResearchGate, Scopus, Litmaps, and Google Scholar, were methodically searched. The search results were refined using keywords like "dipole antenna," "dipole antenna performance analysis," and "printed dipole arrays," with Boolean operators employed to strike a balance between breadth and precision.

3.2 Setting Inclusion and Exclusion Criteria

Strict criteria were established to assure the quality and pertinence of the studies reviewed, with a focus on impactful and meticulously conducted research. The criteria for inclusion prioritize peer-reviewed articles, conference papers, and pertinent reviews that concentrate on the performance analysis of dipole antennas. Studies that investigate a broad array of dipole antenna designs and uses were included to provide a comprehensive understanding of the current state-of-the-art. Conversely, the criteria for exclusion omitted studies that lack well-defined methodologies or in-depth performance analysis to maintain a focus on robust research. Additionally, publications not in English were excluded to ensure consistency and clarity.

3.3 Process for Detailed Data Extraction

Once relevant studies were identified, a careful data extraction process was carried out, which included several key steps. First, an extensive extraction grid was developed to ensure consistent data extraction, encompassing crucial data elements. Next, in-depth information extraction was performed, capturing important details such as bibliographic information, antenna design parameters, simulation and measurement techniques, and key performance metrics from each selected study. Additionally, performance metrics and any cited limitations were recorded to enable a comparative analysis of various dipole antenna setups and identify potential research challenges.

This methodological approach employed a multi-dimensional exploration to discover and analyze the latest progress in dipole antenna performance analysis, ensuring a thorough understanding of the field

4. Results and discussion

The results were shown in tabular form for an easier way of understanding the literature review about the different designs for wearable antennas.

4.1. Results

Table 1. Screened Articles

Ref	Lead Author	Year	Title	Application	Analysis
[24]	Benmahmoud	2023	Wearable Folded Planar Dipole Antenna: Design and assessment for on-body wireless communication devices	Wireless communication devices designed to operate close to the human body.	- Utilizes folded planar dipole concept for favorable impedance bandwidth characteristics. - Achieves a 10-dB impedance bandwidth of 470 MHz covering the 2.27–2.74-GHz band. - Nearly omnidirectional radiation pattern. - Suitable for wireless applications requiring exposure to external mechanical strains and electromagnetic perturbations.
[26]	Berdnik	2021	Triple-Band Dipole Antenna for Wireless Communication Systems	- Mobile communications operating in GSM 900, GSM 1800, and WiMAX ranges.	- Designed based on optimization modeling with three resonant frequencies.
[6]	Patel	2021	Surface Mountable Compact Printed Dipole Antenna for Gps/Wimax Applications	- GPS and WiMAX applications.	- Low-profile, electrically compact, and cost-effective antenna design. - Self-complementary dipole elements for efficient impedance matching. - Covers 1.57 GHz and 3.65 GHz frequencies with measured impedance bandwidths.
[27]	Firdaus	2020	Study on Impedance Matching of 2.4 GHz Dipole Antenna	- Impedance matching of a 2.4 GHz dipole antenna to a feedline using bazooka and balun.	- Optimization of antenna and feedline length for impedance adjustment. - Antenna length optimized to 0.35 λ and feedline length to 0.5 λ. - Bazooka and balun lengths for best impedance adjustment are 0.25 λ and 0.2 λ, respectively.

[28]	Ismail	2020	Meander Dipole Antenna for Low Frequency Applications	- Dual-band printed Meander dipole antenna for low frequency and Ground Penetrating Radar (GPR) applications.	- Operates at 73 MHz and 145.75 MHz with a 70% reduction in length compared to a regular dipole. - Achieves reflection coefficient of -15 dB and -18.5 dB with bandwidths of 2 MHz and 6.6 MHz, respectively. - Exhibits omnidirectional radiation characteristics with high radiation efficiency up to 87%.
[29]	Adjali	2020	Matching Evaluation of Highly Coupled Dipoles Quantified by a Statistical Approach	- Analysis of electromagnetic coupling between randomly distributed dipole antennas.	Utilizes statistical approach to assess input impedance of surrounded dipole under various loading conditions. - Focuses on UHF RFID use cases where tag antennas are concentrated in reduced volumes.
[15]	Neelamraju	2023	Machine Learning based Low-Scale Dipole Antenna Optimization using Bootstrap Aggregation	- Optimization of dipole antenna parameters using Machine Learning (ML) algorithms.	- Tests ML algorithms for elucidating minor trends in device profiles. - Proposes a bootstrap aggregation model concatenating Linear Regression, Support Vector Regression, and Decision Tree Regression algorithms.
[30]	Moreno	2021	Impedance-Matching Technique for an Infrared Folded Dipole Antenna	- Solution for the impedance mismatch challenge in antenna-coupled infrared detectors.	- Modifications of folded dipole antenna geometry to increase input impedance. - Numerical simulations and experimental measurements confirm input impedance of 1 kΩ or above.
[23]	Sanusi	2020	Impact of Blood Environment on Integrated Antenna Performance	- Study of inkjet printed dipole antenna performance for blood irradiation applications.	- Blood environment significantly impacts antenna performance, degrading radiation pattern. - Integration with an artificial magnetic conductor (AMC) structure improves antenna gain despite the lossy host.
[4]	Mansour	2020	High-Gain Simple Printed Dipole-Loop Antenna for RF-Energy Harvesting Applications	- Compact dual-band antenna for RF energy harvesting applications.	- Combination of dipole and loop antenna structures operating at 900 MHz and 1600 MHz. - Measured fractional bandwidth and peak gain, compact size compared to similar designs. - Prototype fabrication, testing, and comparison of measurements with simulation results.
[31]	Tang	2022	Enhancing the Directivity of Antennas Using Plasma Rings	- Improving the radiation directivity of dipole antennas by placing plasma rings in close proximity.	- Simulation results show appreciable enhancement in gain without affecting antenna impedance matching characteristics. - Dependency of gain enhancement on plasma parameters is analyzed.

					- Experimental validation using an inexpensive commercial fluorescent lamp.
[25]	Chen	2020	Enhanced Transmission Performance of a Dipole Antenna Based on a Ceramic Diamond-Structure PBG Substrate with a Defect Cavity	- Investigating radiation performance of dipole antenna on a diamond-structured photonic crystal (PC) substrate with point defects.	- Experimental results demonstrate strong radiation frequency at about 13 GHz and improved gain and directivity. - Use of diamond-structure PCs with point defects significantly enhances antenna performance.
[32]	Gil	2019	Embroidery manufacturing techniques for textile dipole antenna applied to wireless body area network	- Design and testing of textile dipole antennas for wireless body area network applications.	- Medium stitch density embroidery patterns, satin fill, and contour fill, impact dipole performance in cotton and felt textile substrates. - Notable antenna parameter results in terms of return loss, radiation pattern, realized gain, and efficiency.
[3]	Hashemi	2019	Dipole Antenna Based on Forward-Coupling Multilayer Ring Resonators (MRR)	- Novel compact dipole antennas based on forward-coupling configuration of multilayer ring resonators (MRR) structure.	- Structure allows for tunable frequency of operation by changing distance between two radiating elements. - Bidirectional radiation pattern with peak gain of 2.8 dBi. - Good impedance matching and return loss better than 35 dB obtained.
[5]	Jin	2020	Differential Frequency-Reconfigurable Antenna Based on Dipoles for Sub-6 GHz 5G and WLAN Applications	- New differential frequency-reconfigurable antenna based on dipoles.	- Resonates at two states, centered at 3.5 and 5.5 GHz, respectively, achieved by switching p-i-n diodes. - Similar radiation patterns for both states, wide bandwidth, and good impedance matching.
[9]	Anwar	2019	Development of V-Shape Dipole Antenna for 20 MHz Astronomical Observation	- V-shape dipole antenna for 20 MHz radio astronomical observation.	- Low SWR, wide beamwidth, and achievable maximum gain of 7.85 dBi. - Prototype constructed and installed for radio astronomy research.
[8]	Ramanujam	2022	Design of reflector-based dipole antenna for sub-6GHz 5G applications	- Reflector-based printed dual dipole antenna for 5G sub-6 GHz applications.	- Wide bandwidth of 44.2%, power reflection coefficient of < -10 dB, average gain of 7.23 dBi, and radiation efficiency > 83%.
[33]	Sharma	2022	Design of antenna by amalgamating staircase and hexagonal ring-shaped structures with the modified ground plane for multi-standard wireless applications	- Antenna designed for multi-standard wireless applications.	- Enhanced bandwidth and reflection coefficient with resonances at multiple frequency bands. - Satisfactory parameters such as gain, radiation efficiency, and radiation patterns for wireless operations.
[20]	Miah	2019	Design of a Reference Dipole-Loop Antenna Array at 28 GHz	- Array antenna for measuring polarimetric omni-directional pathloss at 28 GHz.	- Wideband matching and radiation performance achieved for both dipole and loop.

					- Impedance matching bandwidth of over 6 GHz for the dipole and 0.2 GHz for the loop.
[34]	Park	2019	Design and fabrication of triple-band folded dipole antenna for GPS/DCS/WLAN/WiMAX applications	- Triple-band folded dipole antenna for GPS/DCS/WLAN/WiMAX applications.	- Bilateral symmetric structure and coupling by adding stubs enable triple-band operation. - Stable radiation pattern with moderate gain achieved at desired frequency bands.
[35]	El Bekkali	2021	Crossed Dipole Antenna for RFID applications	- Crossed dipole antenna for 2.45 GHz ISM band RFID readers.	- Symmetric radiation pattern with high return loss, good impedance matching, and efficiency >95%. - Low profile, low cost, and good performances suitable for microwave RFID readers.
[36]	Perez-Miguel	2020	Comparison of Four High Performance Dual Polar Antennas for Base Stations	- Comparison of cross-dipole antennas for base stations of cellular systems.	- Evaluation based on parameters such as mutual coupling, return losses, gain stability, beamwidth, cross-pol discrimination, and tracking error. - Each antenna type has advantages and limitations depending on specific application requirements.
[37]	Aliakbari	2019	Characteristic Mode Analysis of Planar Dipole Antennas	- Analysis of planar monopole antennas based on image theory and dipole counterparts.	- Study of bandwidth and radiation pattern of planar dipoles using characteristic mode analysis. - Tradeoff observed between pattern stability and impedance bandwidth with varying dipole width. - Offset in feed point leads to degradation in both modal and impedance bandwidths.
[19]	Mansour	2023	Broadband Printed Dipole Array Antennas	Design, simulation, and measurement of printed dipole array antennas for broadband applications.	Simulated impedance bandwidths: 27.5%, 29.5%, and 28.6% for single element, two-element, and four-element designs respectively. - Realized gains: 4.2dB, 7.2 dB, and 9.7dB for single element, two-element, and four-element designs respectively. - Good agreement between simulated and measured results.
[38]	Wu	2021	Bandwidth Enhancement of Broadband Dual-Polarized Dipole Antenna for 5G Base Station	- Bandwidth enhancement method for broadband dual-polarized dipole antenna aimed at 5G base station applications.	- Antenna element in the shape of a four-leaf clover. - Wide impedance bandwidth of 72.4% achieved with (from 1.32 to 2.82 GHz). - High isolation (>30dB) within the bandwidth. - Stable radiation pattern with maximum half-power beamwidth of

					76.3° at horizontal plane and stable gain of 8.4 dBi obtained over the working frequency band.
[18]	Abdul Malek	2022	Analysis, Optimization, and Hardware Implementation of Dipole Antenna Array for Wireless Applications	- Dipole antenna array designed for wireless applications, particularly for indoor positioning systems like Wi-Fi, WLAN, and 5G.	- Main beam coverage optimized from 100° to 140° with step size of 10°. - Feasibility of beam synthesis validated successfully, with main beam steered at 110°. - Measured reflection coefficient of phased array antenna is −48 dB at 2.56 GHz.
[39]	Velicheti	2021	An Analytical Review on Log Periodic Dipole Antennas with Different Shapes of Dipole Elements	- Log periodic dipole array antennas studied for various communication applications including direction-finding systems, 5G, air-borne applications, UWB radar, and mobile imaging.	- Various LPDA structures studied with respect to operating frequency, bandwidth, substrate type, gain, and dimensions. - High gain and VSWR values (<2) achieved using miniaturization techniques.
[22]	Cai	2021	A High-Performance Standard Dipole Antenna Suitable for Antenna Calibration	- Standard dipole (SD) antenna designed for antenna calibration.	- Measured relative bandwidth exceeds 15%. - Antenna gain approximately 2 dBi. - Cross-polarization ratio greater than 27 dB in horizontal plane.
[40]	Peng	2023	A Broadband Dual-Polarized Filtering Dipole Antenna with High Selectivity	- Dual-polarized filtering dipole antenna designed for enhanced bandwidth and high selectivity.	- Wide impedance bandwidth, high port isolation, flat in-band gain, sharp band-edge roll-off, and low cross-polarization level demonstrated through fabrication and measurements.

Table 1 shows the studies included in the literature review after the identification and screening techniques. From the table, it is shown that dipole antenna applications highlight their widespread use in various industries and technologies. At the top are wireless communication systems, followed by RFID applications, GPS, and WiMAX. Mobile communications and directional finding systems come next, with specialized uses including wireless body area networks, RF energy harvesting, and radio astronomy. Lastly, dipole antennas serve in infrared sensing and antenna calibration.

4.2. Discussion

After assessing different studies about dipole antennas. The researchers had found out that with their simple design and affordability, dipole antennas have become a go-to solution across various communication systems. These advantages make them versatile for indoor positioning (Wi-Fi, WLAN, 5G), mobile communication, antenna calibration, and even filtering applications. For indoor positioning, researchers are exploring antenna arrays with beamforming circuits. This allows for electronically controlled beams, eliminating the need for mechanical adjustments and enabling flexible coverage within buildings. A successful approach combines induced EMF methods and genetic algorithms for beam synthesis, demonstrating the practicality of these configurations for real-world use. The measured performance highlights the usefulness of dipole antenna arrays in indoor wireless communication.

Base station applications of dipole antennas have also seen significant advancements. Performance – gain, directivity, bandwidth, and size – has continuously improved, driven by the ever-increasing demands of mobile communication. This underscores the importance of dipole antennas in providing reliable and efficient communication links. Additionally, high-performance standard dipole antennas play a crucial role in accurate antenna testing due to their exceptional performance achieved through optimized designs. Finally, the design of broadband dual-polarized dipole antennas for filtering applications shows promise. These antennas utilize specific structures to achieve wide bandwidth, high isolation, and sharp roll-off, meeting the demanding requirements of modern communication systems.

5. Conclusion

Dipole antennas, with their inherent simplicity and adaptability, have established themselves as adaptable assets across diverse wireless communication applications. This analysis highlights their versatility and ongoing evolution in a range of areas. From wearable devices to base stations, dipole antennas offer tailored solutions. Their favorable characteristics – including impedance matching, radiation patterns, and bandwidth – ensure efficient and reliable communication across environments and frequencies, from low-frequency RFID to high-frequency 5G networks.

Moreover, the literature emphasizes the critical role of factors like impedance matching, radiation efficiency, and pattern stability in achieving optimal performance. Novel materials and structures, such as textile substrates for wearables and plasma rings for miniaturization, showcase innovative approaches to overcoming challenges and enhancing antenna capabilities. Furthermore, dipole antennas extend their reach beyond traditional communication systems, finding applications in radio astronomy, RF energy harvesting, and even biomedicine. This broad applicability underscores their remarkable versatility and potential to address contemporary wireless challenges.

In conclusion, dipole antennas remain a cornerstone of modern wireless communication. Ongoing research and innovation guarantee their continued relevance. Their adaptability, combined with advancements in performance metrics like bandwidth, gain, and beam steering, ensures their place in enabling efficient and reliable wireless connectivity across diverse applications and environments.

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