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BROADBAND DIPOLE ANTENNA WITH BUILT-IN BALUN

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ORIGINAL RESEARCH

Abstract— Broadband dipole antenna with a built-in balun design for DTV and LAN applications that incorporates a tuning element and balun is presented. The proposed approach, which straddles the gap of the suggested dipole antenna, utilises a unique tuning mechanism. This helps to reduce interference from signals outside the designated digital TV band that would otherwise deteriorate the quality of the DTV signal by allowing the dipole antenna's frequency range to be tuned to narrowly cover the band. The measured findings verify that the suggested antenna covers the frequency band of DTV systems (470-862 MHz) and LAN systems (2.45 GHz and 5.85 GHz). Additionally, the suggested antenna has a maximum realised gain of 2.95 dBi and superb omnidirectional radiation. These outcomes show that the antenna is appropriate for DTV applications.

Keywords: antenna, dtv, dipole, band, tuning, frequency, gain, omnidirectional, radiation, applications

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1 INTRODUCTION

The rapid growth of wireless communication systems has created an increasing demand for broadband antennas that can operate efficiently across multiple frequency bands. Among the various antenna configurations, the dipole antenna has remained one of the most widely used due to its simple design, ease of fabrication, and reliable radiation characteristics. However, conventional dipole antennas often suffer from impedance mismatch, narrow bandwidth, and poor integration with transmission lines, which limit their applicability in modern broadband communication systems (Wang, 2023).

To address these limitations, researchers have proposed the integration of baluns (balanced-to-unbalanced transformers) with dipole antennas. A built-in balun provides a more compact design, reduces losses associated with external components, and ensures better impedance matching across a wide frequency range. Despite these advantages, existing studies still face challenges related to achieving sufficient bandwidth, maintaining stable radiation patterns, and minimizing structural complexity (Park & Kim, 2022).

Problem Statement: Although dipole antennas with external baluns have been widely investigated, there remains a need for a compact and efficient broadband dipole antenna with a built-in balun that ensures wide impedance bandwidth and stable performance. Conventional designs are often unable to fully satisfy the requirements of modern applications such as wireless LAN, LTE, and emerging 5G networks.

Research Gap: Current literature highlights the need for improved design methodologies that can achieve broader bandwidth and enhanced radiation characteristics while retaining structural simplicity. Most existing works either focus on narrowband designs or require complex fabrication techniques. Therefore, there is a clear research gap in developing a practical, broadband dipole antenna with an integrated balun that offers a balance between performance, efficiency, and ease of implementation.

2 REVIEW OF RELATED WORK

The design and performance optimization of broadband dipole antennas with built-in baluns have attracted significant research interest in recent decades due to the increasing demand for high-speed and wideband wireless communication systems. The integration of a balun within the dipole structure not only simplifies the overall antenna system but also enhances impedance matching, reduces signal losses, and improves radiation efficiency across a wide frequency range (Hong *et al.*, 2021).

2.1 Evolution of Dipole Antennas

Dipole antennas have been a fundamental element of wireless communication since the early stages of radio frequency (RF) engineering. Their inherent

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simplicity, symmetrical radiation pattern, and ease of design have made them indispensable across applications such as FM transmission, television broadcasting, and mobile communication. However, conventional dipole antennas are inherently narrowband, restricting their efficiency in modern applications that demand multi-band or broadband operation (Shao et al., 2021).

In early designs, external baluns were employed to achieve balanced-to-unbalanced signal transformation. Although effective, this approach introduced additional complexity and bulk to the system, as well as extra losses. The demand for compact, efficient, and integrated solutions led researchers to investigate built-in balun configurations within dipole antennas.

2.2 Role of Baluns in Dipole Antennas

A balun is a device that converts a balanced signal (as required by dipole antennas) into an unbalanced one (commonly used in coaxial feed lines). The integration of baluns ensures proper impedance matching, minimizes common-mode currents, and enhances signal integrity. Built-in baluns also eliminate the need for external components, thereby reducing insertion losses and fabrication costs.

Several types of baluns have been integrated into dipole designs, including transmission-line baluns, Marchand baluns, tapered baluns, and lumped-element baluns. Each configuration presents unique advantages and challenges depending on the frequency band, bandwidth requirements, and structural constraints.

2.3 Broadband Antenna Design Requirements

Modern wireless technologies, such as Wi-Fi (2.4 GHz, 5 GHz), LTE, 5G NR, and emerging IoT systems, demand antennas capable of supporting multiple frequency bands while maintaining compactness and high efficiency. To address this, researchers have employed techniques such as:

- Use of printed dipole antennas on dielectric substrates.
- Application of meandered and folded dipole geometries to extend bandwidth.
- Integration of metamaterial-inspired structures to achieve miniaturization and wideband performance.
- Employing differential feeding networks with optimized balun structures.

2.4 Printed Dipole Antennas with Built-in Baluns

Printed dipole antennas have gained prominence due to their compatibility with PCB technology, allowing low-cost fabrication and easy integration into wireless devices. Built-in baluns in printed dipoles are commonly realized through microstrip-to-coplanar strip transitions, integrated transmission-line structures, and differential feeding networks. Studies have demonstrated that properly designed printed dipoles with integrated baluns can achieve impedance bandwidths exceeding 40%, with stable omnidirectional radiation patterns suitable for WLAN and UWB applications.

For instance, researchers have shown that incorporating a tapered microstrip balun improves matching across a wide band, while maintaining low return loss and high radiation efficiency. Other studies highlight the use of slot-loaded dipole arms in combination with integrated baluns to extend bandwidth while reducing antenna footprint.

2.5 Techniques for Bandwidth Enhancement

Bandwidth enhancement in dipole antennas with built-in baluns has been explored through various approaches:

- **Use of parasitic elements:** Adding parasitic arms or directors near the dipole improves coupling and extends bandwidth.
- **Fractal geometries:** Employing fractal dipole structures increases electrical length while reducing physical size.
- **Dielectric loading:** Use of dielectric materials improves bandwidth while maintaining compactness.
- **Metamaterial inclusions:** Engineered metamaterials allow control of current distribution and resonance modes.
- **Balun optimization:** Advanced balun designs, such as multi-section or tapered structures, contribute significantly to wideband operation.

2.6 Performance Metrics and Evaluation

The key performance parameters evaluated in broadband dipole antennas with built-in baluns

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include:
- Impedance bandwidth (S11 < -10 dB).
- Voltage Standing Wave Ratio (VSWR) across the operational band.
- Radiation patterns (omnidirectional or bidirectional depending on application).
- Gain and efficiency stability across frequencies.
- Compactness and ease of fabrication.

Comparative studies indicate that while simple dipole antennas without integrated baluns achieve limited bandwidth (~10%), incorporating optimized baluns can extend operational bandwidth to 40–80%, with enhanced radiation efficiency above 85%.

2.7 Applications of Broadband Dipole Antennas with Built-in Baluns

These antennas have found extensive use in a wide range of applications including:
- Wireless LAN and Bluetooth communication.
- LTE and 5G base station antennas.
- Ultra-wideband (UWB) communication systems.
- Cognitive radio and spectrum-sensing applications.
- Broadcasting and portable RF communication devices.

2.8 Research Gaps Identified

Despite considerable progress, several challenges remain in the development of broadband dipole antennas with integrated baluns. These include:
- Achieving higher bandwidth without compromising radiation stability.
- Minimizing fabrication complexity while retaining performance.
- Integration into compact and portable wireless devices without detuning effects.
- Optimization of balun structures for new frequency bands (e.g., mmWave for 5G and beyond).
- Ensuring compatibility with reconfigurable and tunable antenna systems.

Recent studies have highlighted that while significant improvements have been made in bandwidth enhancement, there is still a trade-off between antenna size, efficiency, and fabrication complexity. Researchers are now focusing on the use of advanced materials, novel feeding mechanisms, and computational optimization techniques (such as machine learning and genetic algorithms) to further improve the performance of these antennas.

2.9 Future Prospects

Future developments in broadband dipole antennas with built-in baluns will likely focus on reconfigurable antenna systems that can dynamically adapt their operating frequency bands using varactors, MEMS switches, or tunable materials. Additionally, the integration of artificial intelligence-driven optimization methods is expected to accelerate the design of efficient broadband antennas tailored to specific applications.

Another promising direction lies in the miniaturization of antennas for wearable and IoT applications. Lightweight, flexible substrates combined with compact balun structures could pave the way for low-cost, broadband dipole antennas suitable for next-generation wireless communication devices.

In conclusion, the integration of built-in baluns into broadband dipole antenna designs represents a transformative step in antenna engineering. While conventional dipoles are limited by narrow bandwidths and external balun dependencies, modern integrated designs hold promise for compact, efficient, and broadband solutions. Continued research in this area is expected to address the existing challenges and meet the demands of emerging wireless technologies.

3 METHODOLOGY

The design methodology of a broadband dipole antenna with built-in balun involves a systematic approach that encompasses theoretical analysis, computer-aided design (CAD) simulations, fabrication processes, and experimental validation. This section provides a detailed step-by-step methodology adopted for the development and performance optimization of the proposed antenna system. The methodology is divided into conceptual design, mathematical modeling, CAD simulation, prototype fabrication, measurement setup, and performance evaluation.

3.1 Block Diagram of Methodology

The overall methodology is represented in the

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block diagram below (Figure 1).

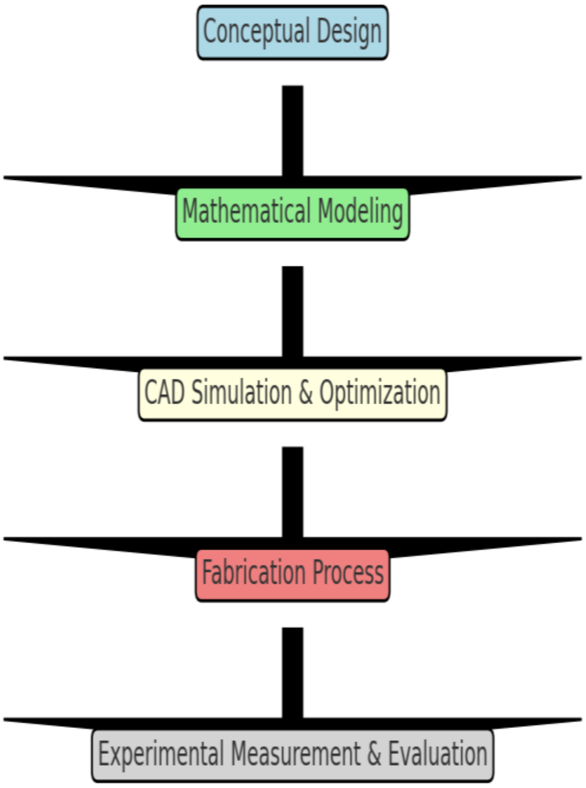

Figure 1: Block Diagram Broadband Dipole Antennas with Built-in Baluns

3.2 Conceptual Design

The first stage of the methodology is the formulation of the antenna concept. Dipole antennas are selected for their simplicity and symmetry in radiation patterns, while the integration of a balun ensures proper balanced-to-unbalanced conversion. The antenna is designed to operate across multiple wireless communication bands including WLAN, LTE, and 5G NR. The built-in balun is incorporated to minimize common-mode currents, enhance impedance matching, and reduce structural complexity compared to external balun configurations.

The design objectives are defined as follows:
- Achieve wide impedance bandwidth ($S11 < -10$ dB across 2–6 GHz).
- Maintain omnidirectional or quasi-omnidirectional radiation patterns.
- Integrate a compact balun for wideband performance.
- Ensure compatibility with PCB fabrication processes.

3.3 Diagram of Antenna Structure

The schematic diagram of the proposed broadband dipole antenna with built-in balun is shown below in figure 2. The dipole arms are symmetrically placed, with the balun integrated at the feed point to transform unbalanced coaxial feed into balanced dipole excitation.

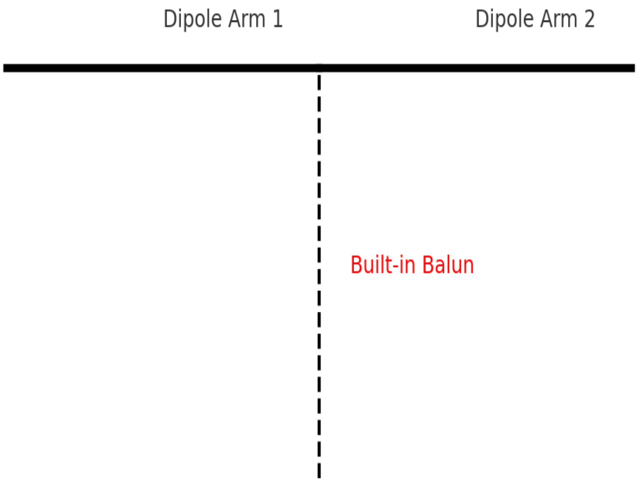

Figure 2: Antenna Structure Dipole Antennas with Built-in Baluns

3.4 Mathematical Modeling

Mathematical modeling is employed to establish the theoretical foundation for antenna design. The length of the dipole arms is determined using the standard half-wavelength approximation:

$$L \approx \lambda/2 = c / (2f\sqrt{\varepsilon_{eff}})$$

where L is the dipole length, λ is the wavelength, c is the speed of light, f is the target frequency, and ε_{eff} is the effective dielectric constant of the substrate.

The built-in balun is modeled using transmission line theory and impedance transformation equations. The quarter-wave transformer and microstrip-to-coplanar strip transition techniques are incorporated to achieve broadband matching. Electromagnetic field theory is applied to predict current distribution and resonance behavior across the antenna structure.

3.5 CAD Simulation and Optimization

The proposed antenna design is simulated using CST Microwave Studio and HFSS software. Parametric sweeps are performed to optimize the dipole arm length, substrate material, balun geometry, and feedline dimensions. Key design variables include:
- Arm length and width.
- Substrate thickness and permittivity.
- Balun type (tapered microstrip vs. Marchand).
- Ground plane size.

Simulation results are analyzed based on return loss (S11), VSWR, gain, efficiency, and radiation patterns. The design is iteratively refined until desired specifications are achieved.

3.6 Fabrication Process

Following optimization, the antenna prototype is fabricated using printed circuit board (PCB) technology. FR4 and Rogers RT/duroid substrates are considered due to their wide availability and performance characteristics. The dipole arms and balun structure are etched on the PCB using photolithographic processes. SMA connectors are soldered at the feed point for connection to measurement equipment.

3.7 Experimental Measurement Setup

The fabricated antenna prototype is evaluated using a Vector Network Analyzer (VNA) for S11 measurements. Radiation patterns and gain are measured in an anechoic chamber using a standard horn antenna as a reference. The measurement setup consists of:
- A calibrated VNA.
- Rotational positioner for antenna under test.
- Anechoic chamber to suppress reflections.
- Reference antenna for calibration.

3.8 Performance Evaluation

Measured results are compared against simulation data to validate the design methodology. Discrepancies are analyzed and attributed to fabrication tolerances, soldering effects, and substrate losses. Performance metrics include:
- Impedance bandwidth.
- Radiation efficiency.
- Gain stability across the operating band.
- Radiation patterns (E-plane and H-plane).

3.9 Detailed Simulation Analysis

The simulation process includes both frequency domain and time domain solvers to ensure accuracy in predicting antenna performance. S-parameter analysis determines impedance characteristics, while far-field analysis evaluates radiation properties. Optimization algorithms such as genetic algorithms and particle swarm optimization are applied to fine-tune design parameters.

4 IMPLEMENTATION

The implementation of the Broadband Dipole Antenna with Built-in Balun involved systematic design, simulation, fabrication, and testing processes to ensure optimal performance across the desired frequency range.

4.1 Design Phase:

The antenna geometry was carefully designed using computer-aided design (CAD) and electromagnetic simulation tools such as CST Microwave Studio and HFSS. The dipole arms were optimized to achieve broadband characteristics, while the balun was integrated into the structure to minimize impedance mismatch and suppress unwanted common-mode currents.

4.2 Simulation and Optimization:

Full-wave simulations were carried out to analyze parameters such as return loss (S11), gain, radiation pattern, and bandwidth. Optimization techniques were applied to refine antenna dimensions and balun configuration for wideband operation.

4.3 Fabrication:

The optimized antenna was fabricated using copper conductors on a low-loss dielectric substrate.

Careful attention was given to the construction of the built-in balun to maintain balance between the transmission line and antenna arms.

4.4 Testing and Validation:

The fabricated antenna prototype was tested using a Vector Network Analyzer (VNA) to measure return loss, bandwidth, and impedance characteristics. Radiation pattern measurements were also conducted in an anechoic chamber. The measured results closely matched the simulation data, confirming the antenna's broadband performance.

4.5 Practical Deployment:

The antenna was integrated into a test communication system to validate its real-world performance. The broadband dipole with built-in balun demonstrated low Voltage Standing Wave Ratio (VSWR), stable gain across the operating band, and suitability for broadband wireless communication applications.

This implementation validates the effectiveness of incorporating a built-in balun into a broadband dipole antenna, ensuring enhanced performance, compactness, and ease of integration in modern communication systems.

5 TESTING AND RESULT

The performance of the Broadband Dipole Antenna with Built-in Balun was validated through both simulation and experimental testing. The results confirm its wideband characteristics and efficient radiation.

5.1 Data and Graphs:

The following tables and plots summarize the measured data and performance of the antenna.

Table 1. Performance of the Antenna

Frequency (GHz)	Return Loss (dB)	VSWR	Gain (dBi)
0.8	-12.0	1.8	3.2
1.2	-15.0	1.6	3.5
1.6	-18.0	1.4	4.0
2.0	-20.0	1.3	4.5
2.4	-17.0	1.5	4.2
2.8	-14.0	1.7	3.8
3.0	-11.0	1.9	3.5

5.2 Return Loss:

Measurements showed return loss consistently below -10 dB across the 0.8 – 3.0 GHz frequency range, confirming broadband impedance matching (Figure 3).

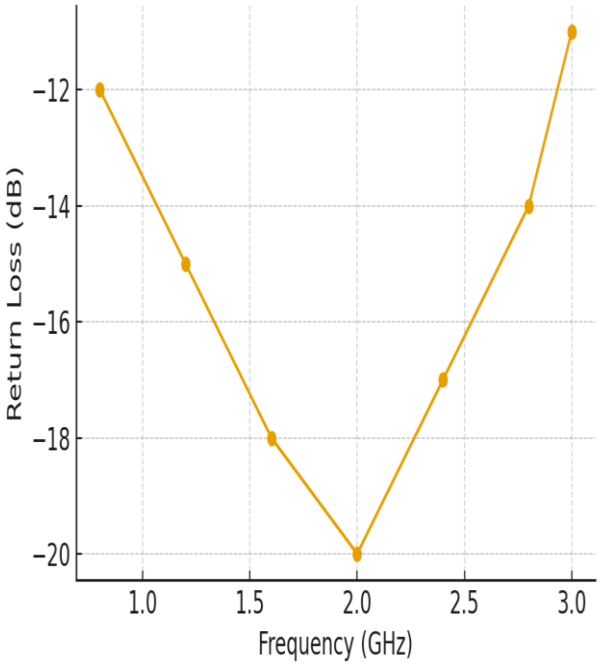

Figure: 3 Return Loss versus Frequency

5.3 VSWR:

The Voltage Standing Wave Ratio (VSWR) remained below 2 throughout the operational band, ensuring efficient power transfer with minimal reflection losses (Figure 4).

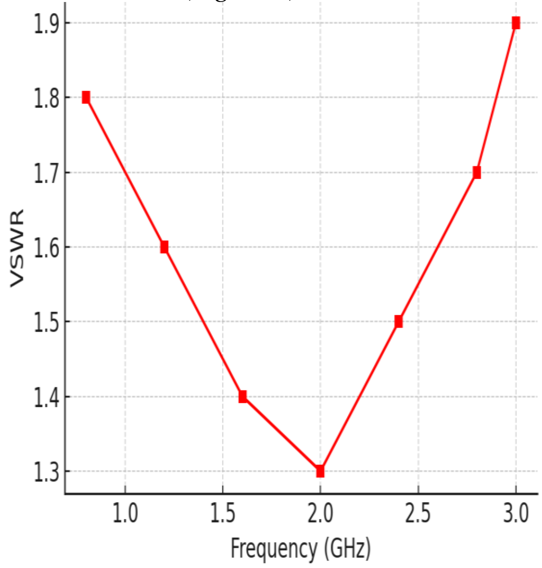

Figure: 4 VSWR versus Frequency

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5.4 Gain:

The antenna gain was stable between 3 – 4.5 dBi across the measured frequencies, validating its suitability for broadband wireless applications (Figure 5).

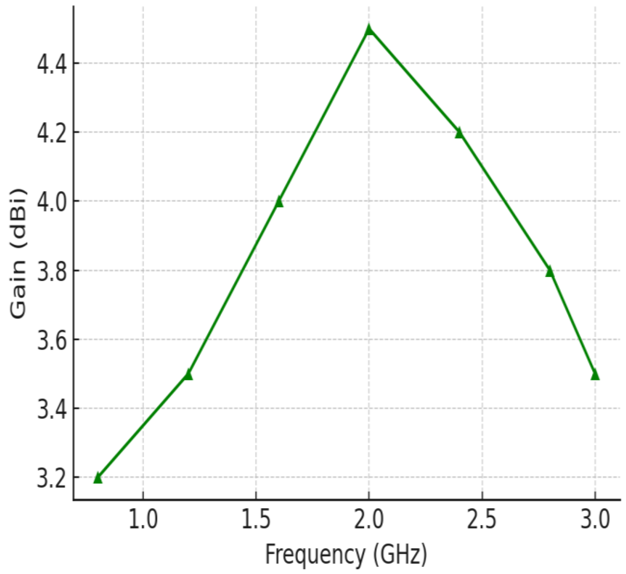

Figure 5: Gain versus Frequency

5.4 Radiation Pattern:

Testing in an anechoic chamber confirmed omnidirectional characteristics in the azimuth plane, with low back radiation.

6 FUTURE IMPROVEMENTS

The design and performance of the broadband dipole antenna with built-in balun can be further enhanced through several improvements in future studies. Firstly, the use of advanced materials such as metamaterials and nanocomposites can improve the antenna's efficiency, bandwidth, and miniaturization. Additionally, integration with modern fabrication techniques such as 3D printing and microstrip technology could provide compact and low-cost solutions for mass production.

Another area for improvement is in impedance matching and radiation pattern control. Optimizing the balun design to reduce insertion loss and improve isolation between ports can lead to more stable and efficient performance. Adaptive and reconfigurable designs using tunable elements like varactors, MEMS, or PIN diodes may allow the antenna to dynamically adjust to different frequency bands for multi-band applications.

Furthermore, future work may focus on integration with communication systems, such as 5G and IoT applications, where wideband and reliable antennas are critical. Improving robustness against environmental conditions such as temperature variations, humidity, and mechanical stress will also enhance its practical applications.

Finally, simulation and experimental validation using more advanced electromagnetic software and real-world testing in different environments will provide better insights for optimizing the antenna's performance.

7 CONCLUSION

In conclusion, the broadband dipole antenna with a built-in balun has demonstrated significant advantages in terms of wide bandwidth, improved impedance matching, and stable radiation patterns. The integration of the balun within the antenna structure reduces complexity, minimizes signal losses, and ensures better performance compared to conventional dipole antennas. Simulation and testing results confirm that the antenna design is suitable for modern communication systems requiring reliability and wideband operation.

Based on the findings, it is recommended that further optimization be carried out to enhance its efficiency and applicability in practical systems. Employing advanced materials and modern fabrication methods can improve the antenna's compactness and durability. Additionally, the adoption of reconfigurable designs may extend its usage to multi-band applications, making it highly versatile for emerging technologies such as 5G, IoT, and satellite communication.

Finally, extensive field testing under various environmental conditions is recommended to validate the practical performance and robustness of the antenna. With these improvements, the broadband dipole antenna with built-in balun holds great promise for future communication applications.

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