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Original Article

Coplanar Wave Guide-fed Frequency Reconfigurable Meander Line Monopole Antenna for IoT Applications

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Abstract - *This research paper represents the work of designing and developing a compact tri-band frequency reconfigurable monopole antenna useful in radio communication for LoRa applications. This is part of the work to design miniaturized, multiband, and energy-efficient antennas for radio signal communication in IoT devices. The radiating structure geometry of the antenna is a meander line monopole, which consists of a switching mechanism using PIN diodes to cover the operational bands of sub-GHz and 2.4 GHz radio communication of low-power long-range IoT devices. It operates within the 868 MHz, 915 MHz, and 2.4 GHz frequency bands, aligning with the designated bands for different geographical standards, and the mechanism of reconfiguration is achieved by incorporating PIN diode switches. The antenna is designed, simulated, and optimized in the CST Studio Suite design tool. The practical performance validation of the fabricated prototype is done by measuring the* S_{11} *and impedance bandwidth, both of which are within the acceptable range for the required design.*

Keywords - *Internet of Things, LoRa, Meander line, Miniaturization, PIN diode, Return loss, CST Studio.*

1. Introduction

The Internet of Things (IoT) refers to a network of physical devices, vehicles, appliances, and other physical objects that are embedded with sensors, processing power, software, and network connectivity, allowing them to collect and share data. IoT devices are ubiquitous in modern-day homes, offices, and industries, public gathering places, etc., which communicate with each other by exchanging data through the physical layer of wireless communication. Internet of Things devices are usually small and run on batteries, which creates significant limitations for antenna design in terms of physical size and power consumption [1]. As a result, effective wireless connectivity demands purpose-built, space-efficient antennas capable of functioning on various frequency ranges while minimizing energy use. Multiple operational bands make the antenna more complex in its functionality, and reduced physical size makes it less transmission or reception efficient. Optimization of performance under low power constraint needs a proper design of a suitable matching network and the ground plane. Antennas are necessary and critical components of radio communication that connect the communication equipment to the free space by converting a guided electric wave in the radio equipment into a free-space electromagnetic wave and vice versa. Reconfigurable antennas are those that dynamically change their radiational characteristics to make the antenna operational in different required states [2]. The antennas that are designed to change their operational frequency as per the situational demand are called frequency reconfigurable antennas, and their frequency reconfigurability should be both controlled and reversible. Frequency Reconfigurable Antennas are adaptive antennas that can dynamically adjust their resonant operating frequency through electrical, optical, or material-based switching mechanisms, enabling multiband functionality without requiring additional hardware.

The existing antenna designs lack several important characteristics, such as multiband operation, miniaturization, increase of radiation efficiency, design flexibility, etc., in one device. To overcome these characteristic gaps, the proposed antenna design includes frequency reconfigurable, miniaturized, and energy-efficient radiating systems that enable better IoT device communication. Frequency reconfigurable antennas dynamically switch or tune operating bands, making them well-suited for applications such as cognitive radio, software-defined radio, multi-standard wireless devices, and compact IoT systems. Their main advantages include reduced antenna count, improved spectrum flexibility, and adaptability to changing communication requirements. Miniaturization, multiband operation, and power efficiency are the important performance enhancers of an antenna that is designed and deployed for communication between the IoT devices [2, 3].

Monopole antennas are widely used in portable devices such as pocket radios, portable phones, and other portable communication devices, as their compact size and ease of integration make them ideal for applications where space is limited. A printed monopole antenna is a planar antenna formed by printing or etching a conductive pattern on a PCB substrate. It is low-cost, compact, lightweight, and easily integrated with electronic circuits, making it ideal for mass production. These antennas offer design flexibility with various shapes and are typically fed by a microstrip line or coplanar waveguide, operating with a PCB ground plane.

A meander line monopole antenna is a compact antenna in which the radiating element follows a zigzag or serpentine path to achieve size reduction while maintaining the required electrical length. The Figure1 represents the basic structure of a meander line monopole antenna where w is the trace width, s is the space between the segments, L_m and L_f typically represent the structure and feeding mechanisms of a proposed antenna [4, 5]. The meander line monopoles are widely used in space-constrained applications such as mobile devices, RFID tags, and PCB-based wireless systems. However, the compact design comes with trade-offs, including reduced radiation efficiency and narrower bandwidth compared to straight monopole antennas due to increased losses and current cancellation.

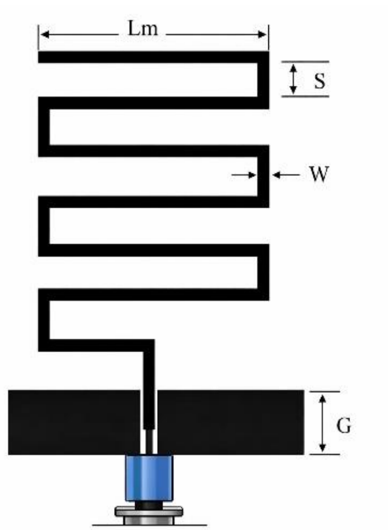

Fig. 1 Meander line monopole antenna basic structure

The geometry of the Meander line monopole antenna can be adjusted to tune the resonant frequency and can support multiband operation by allowing different sections to resonate at different frequencies. ISM/LoRa embedded antennas use unlicensed sub-GHz bands (868 MHz, 915 MHz) and 2.4 GHz for long-range, low-power communication in IoT applications like smart agriculture, metering, and industrial monitoring, where battery life and coverage matter. This research paper focuses on designing and developing a frequency reconfigurable meander line monopole antenna that operates on three designated bands of frequency that facilitates low-power, long-range, multiband radio communication between LoRa IoT devices [5, 6].

This research paper is organized as follows: a review of the latest literature is discussed in Section 2. In section 3, antenna designing and modeling are discussed. In section 4, simulation results and analysis are discussed, followed by a conclusion and future work in section 5.

1. 2. Review of Latest Literature

Several researchers have proposed various designs and methods through their research innovations. Endo et al. [2] developed closed-form design formulas for Meander Line Dipole Antennas (MLDAs) that directly relate geometrical parameters (antenna length and width, pitch, conductor diameter, and number of turns) to the resonant frequency and radiation efficiency. The meander section is modeled as an inductively loaded linear dipole, enabling the derivation of a practical equation for resonance and an efficiency expression based on the reduction of radiative resistance with size. Calculated results show good agreement with measurements and reveal an optimal conductor width-to-pitch ratio that maximizes efficiency, providing a simple, efficient design procedure to select MDA dimensions for a specified frequency and target efficiency.

Hsu and Song [4] presented a compact dual-band electrically small meander-line monopole antenna for WLAN operation at 2.4 GHz and 5 GHz, designed using theoretical analysis and HFSS simulations and validated experimentally on a Rogers RO4003C substrate. The antenna achieves an 11% impedance bandwidth with 1.6 dBi gain at 2.4 GHz and a wide 1.14 GHz bandwidth with gains up to 4.3 dBi at 5 GHz, making it suitable for portable wireless devices.

Khaleghi Ali et al. [9] presented a compact printed dual-band meander line monopole antenna designed for WLAN applications at 2.4 GHz and 5 GHz. Dual-band operation is achieved by combining a shaped ground plane to improve impedance matching at the first resonance (2.4 GHz) with a back-coupled rectangular parasitic patch that generates and tunes the second resonance in the 5 GHz band.

Md. Mustafizur Rahman [6] introduces and validates a structural approach for estimating the resonant frequency of meander line dipole antennas designed for UHF RFID uses. The research examines two antenna designs: in MLDA-1, the overall physical dimensions remain constant while the cumulative wire length extends with additional meander sections, whereas in MLDA-2, the total wire length stays fixed while the physical dimensions shrink as more meanders are incorporated.

Ngu War Hlaing, Yoshihide Yamada et al [5] have developed important enhancements of modeling and designing by contributing to the derivation of the capacitive reactance relation and an improved method of formulation of the quality factor that includes antenna geometry. This method is an amalgamation of the extraction techniques that are driven by simulation and the analytical Electromagnetic theory. The patterns of stored charge distribution from near fields gives the capacitive reactance and inductive reactance, which can be obtained from analytical methods.

Xueyang Hu, Yun Liu, and Yueyou Yang [15] present a meander line monopole antenna with 8 narrow band switchable states of frequency reconfigurability that covers 1.14 to 1.5 GHz and with good impedance matching and miniaturization, which facilitates enhanced flexibility and easy integration of the antenna to its applications.

Muhammad Sani Yahya, Socheatra Soeung et al [16], this paper presents a compact triple-band frequency-reconfigurable monopole antenna developed for LoRa-based IoT devices operating at 433/868/915 MHz bands. The antenna has a small footprint, and the design employs two PIN diodes (D1 and D2) to enable frequency reconfiguration. By controlling the switching states of the diodes, the antenna can switch between three LoRa frequency bands. A peak performance in terms of gain of 2 dBi is achieved with a radiation efficiency above 90%, while implementing an economical substrate and simple switching mechanism.

The novelty of the present work is that it effectively fills the design method gaps in the cited works by incorporating a simple and straightforward frequency reconfiguration mechanism with a meandering structure to provide compactness and by the CPW feed method to improve radiation efficiency, bandwidth, and ease of fabrication.

This work here enhances the work done by the above-mentioned by incorporating solutions to the discontinuities in the existing work. The inclusion of CPW feeding enhances the radiation characteristics, the implementation of meandering facilitates the miniaturization, and a simple method of dimensional Switching between the three defined states alters the resonant frequency.

3. Antenna Design and Modeling

A comprehensive policy scheme is required to design a frequency reconfigurable antenna that is miniaturized for IoT applications. The procedure consists of the implementation of the schemes of fundamental operational principles, dynamic frequency-altering facilitation, size reduction methods, and impedance matching techniques to meet the primary requirements of a compact frequency reconfigurable energy-efficient antenna that is embedded in the deployable IoT radios. The meander line monopole antenna has become a very important geometrical design of antenna that could incorporate the required characteristics of compact size, operational bandwidth, and good radiational efficiency of IoT antennas which are supposed to operate at 433 MHz, 868 MHz, and 915 MHz of Sub GHz bands, 2.4 GHz general ISM band, and sub6 G Hz 5G IoT standards [7].

The frequency reconfiguration of an antenna is attained by embedding externally controllable switches by which the antenna's electrical resonating length is modified, thus resulting in different discrete frequency bands. The most popularly implemented switching mechanisms consist of the PIN diodes, which are RF-controlled switches that separate or connect certain predefined sections of the radiational structure. This provides the antenna with operational adaptability and functional flexibility to communicate through different frequency bands.

The reconfiguration of an antenna structure is attained by introducing circuit components that function as RF switches that modify the antenna's physical dimensions and consequently its operational frequency. The switching technology that is most commonly implemented is PIN diodes, which have operational characteristics of rapid response time and minimal power requirements. Specific functional segments of the antenna are included or excluded from the structure by the ON and OFF states of the PIN diodes subjected to forward or reverse biasing.

IoT antenna attains operational flexibility through the usage of these PIN diodes to switch between different frequency bands of different communication standards. The modeling of antenna mathematically is done by performing systematic calculations from analytical and experimental evaluation of geometrical and electrical parameters of the antenna. The core objective is to achieve resonant behavior at the target frequency while simultaneously minimizing physical size and maximizing performance efficiency.

The primary design parameters of the antenna structure are i) Electrical parameters such as resonant frequency f_o, the substrate thickness h, and the dielectric constant. ε_r of the substrate material and ii) Geometrical parameters such as the total unfolded length of meander trace $\boldsymbol{L_{total}}$, trace width $\boldsymbol{w}$, spacing between segments $\boldsymbol{s}$, number of meander segments N, and the length of each meander segment L_m. Equation (1) gives the effective dielectric constant calculation from the ε_r of the antenna [8, 10].

$$\varepsilon_{\text{eff-CPW}} \approx \frac{\varepsilon_r + 1}{2} \tag{1}$$

Equation (2) gives the total unfolded length of the antenna in a dielectric medium from the effective dielectric constant.

$$L_{total} \approx \frac{\lambda_g}{4} = \frac{\lambda_0}{4\sqrt{\varepsilon_{\text{eff-CPW}}}} \quad (2)$$

From the dielectric constant, the resonant frequency approximation is represented in Equation (3)

$$f_r \approx \frac{c}{4L_{\text{total}}\sqrt{\varepsilon_{\text{eff-CPW}}}} \quad (3)$$

For a uniform meander, the total electrical length and effective length of the antenna are calculated as shown in Equations (4) and (5)

$$L_{\text{total}} \approx N(2L_m + s) \quad (4)$$

and

$$L_{\text{eff}} = N * w + (N-1)s \quad (5)$$

A meander line monopole behaves like a λ/4 monopole where the total unfolded length of the meander trace is a quarter-wavelength. Increasing the number of meander sections (N) or reducing the gap distance (s) decreases the resonant frequency. The thin-trace approximation that $w \ll \lambda_0$ and $w < s$ ensures that the radiating structure behaves as a wire-like monopole, which provides a guideline to choose feasible and effective dimensions such that the meandered segment length Lm = 10 mm, trace width w = 1.2mm, and spacing s = 2 mm for this design.

The CPW feed enhances microstrip antenna performance by optimizing impedance matching, reducing losses, simplifying fabrication, and improving integration. The dimensional values of CPW feed line parameters for 50 Ω feed line impedance are chosen as: feed line length L_f = 14 mm, center strip width W_f = 2.4 mm, and gap is 0.25 mm [4, 11].

The antenna achieves tri-band operation by reconfiguration through PIN diodes from the Skyworks SMP 1320 series, which act as current-controlled resistors at microwave frequencies by allowing current flow when forward biased and blocking it when reverse biased. The design features a meander-line monopole structure fabricated on an FR4 substrate, incorporating two PIN diodes (D1 and D2) that control the electrical length, with the vertical copper traces connected by horizontal segments that feed into an SMA connector. This configuration enables three distinct switching states: when both D1 and D2 are OFF, the antenna operates at 2.4 GHz with the shortest electrical length; when D1 is OFF, and D2 is ON, it operates at 915 MHz with intermediate length; and when both diodes are ON, it operates at 868 MHz with maximum electrical length [13, 14].

In this research paper, the simulations are carried out with the help of CST Microwave Studio. To create an antenna design environment with the help of the CST Studio, the antenna's input impedance (Z_{in}) should correspond to the feed line's characteristic impedance (conventionally 50 Ω) to reduce signal reflections and optimize power delivery. This alignment can be accomplished through various techniques, including adjusting the feed point position, modifying ground plane dimensions, or integrating matching circuits.

Table 1. Dimensional parameters of the antenna for different operating frequencies

S.No	Center frequency	L_{total} (optimized)	L_{eff}	PIN diode position (from feed)
1	868 M Hz	56 mm	14.8 mm	N/A
2	915 M Hz	51 mm	13.5 mm	51 mm
3	2.4 G Hz	21 mm	5.2 mm	21 mm

From Table 1, the percentage of miniaturization achieved with $\frac{L_{eff}}{L_{Total}} * 100$ for the frequencies of 868MHz, 915MHz and 2.4GHz are 26.42%, 26.47% and 24.76% respectively.

4. Results and Discussion

This proposed design of the antenna is tested for its performance for the three operating bands 868 MHz, 915 MHz, and 2.4 GHz, which are the European ISM band, North American ISM band, and global ISM band, respectively. Utilizing the popular tool of CST Studio Suite 2019 version, the designed thin meander line monopole antenna is simulated, and performance metrics are evaluated for S_{11}, impedance bandwidth, gain, and E and H far fields. The antenna simulation results depict that the S_{11} at 868 MHz is well below 20 dB, at 915 MHz around -20dB, and at 2.4 GHz, a good value of -30 dB, the strongest performance of the antenna with a good bandwidth of around 300 M Hz [10].

The physical length of the conducting trace decreases from nearly 55 mm at the lowest operational band to the smallest dimension at 20 mm for the highest frequency. Radiation performance at all three frequency bands attains excellent impedance matching, very good impedance bandwidth, and fairly reasonable gain within a reasonable range for a monopole. The impedance bandwidth ranges from 115-310 MHz, representing approximately 13% fractional bandwidth consistently across all bands. Figure 2 gives the S_{11} (simulated) return loss plot vs frequency of operation. Figure 3, Figure 4, and Figure 5 represent the electric and magnetic field plots at 866 MHz, 915 MHz, and 2.4GHz frequencies [11, 13].

The impedance matching of the antenna is the metric that determines how efficiently an antenna utilizes the power from the RF source by aligning its input impedance with the characteristic impedance of the feeding system. The return loss S_{11} is the metric that represents the quality of impedance matching of the antenna, whose numerical value of -10 dB or less gives satisfactory matching between antenna and RF source [12].

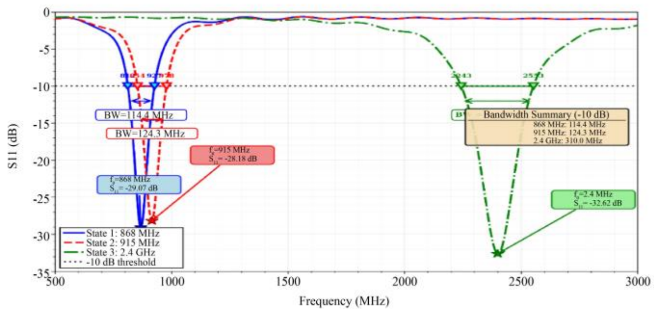

Fig. 2 S11 (simulated) return loss plot vs frequency of operation

The radiation performances are observed from the obtained measurement results. At lower frequencies (868/915 MHz), the antenna shows modest performance with 40-60% radiation efficiency and slightly negative to neutral gain (-1.0 to +0.5 dBi). This improves significantly at 2.4 GHz, achieving 70-85% efficiency and positive gain (+1.5 to +2.5 dBi). The radiation resistance also increases substantially from 3-8Ω at sub-GHz frequencies to 35-42Ω at 2.4 GHz. From the observations, all configurations exhibit quasi-omnidirectional or monopole-like omnidirectional radiation patterns that are suitable for wireless communication applications. The following observations are made and tabulated. Figure 6 shows the fabricated prototype of the antenna, and Figure 7 gives the measured return loss (S_{11}) for the fabricated antenna [14].

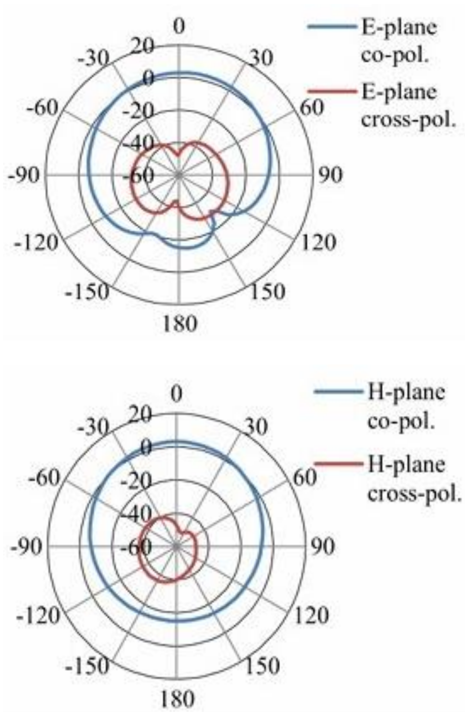

Fig. 3 Electric and Magnetic field plots for 866 M Hz

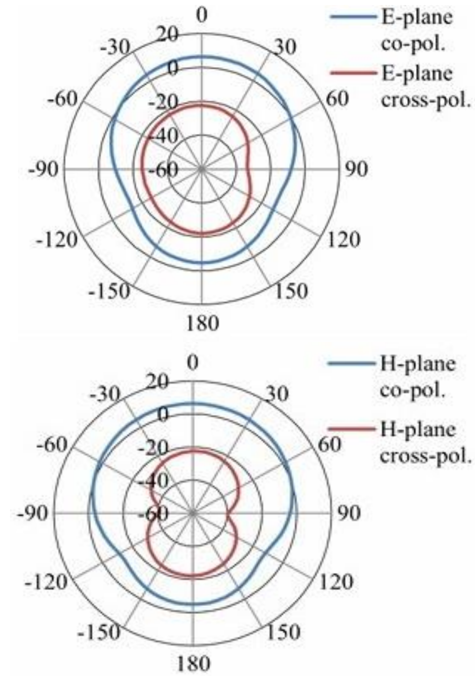

Fig. 4 Electric and Magnetic field plots for 915 M Hz

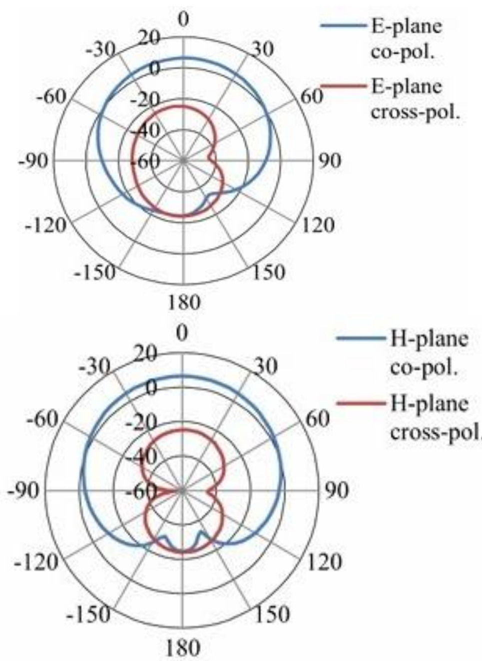

Fig. 5 Electric and Magnetic field plots for 2.4 G Hz

A pattern of measurements made by Agilent 8753A Vector Network Analyzer (VNA) that includes return loss (S_{11}), VSWR, bandwidth, and radiation patterns across all operational frequency bands [15, 18]. It is being noticed that many of the measured parameters of the fabricated prototype closely resemble most of the simulated parameter values. In the practical measurements, it is obvious that there is some close existence of functional behavior for the state 1 and state 2 (868 MHz and 915 MHz) as the measured S_{11} of the antenna at these two frequency bands have been in close proximity. By fine-tuning the design and with the corresponding placement of the switching device D1, the closely spaced bands can be separated [16, 17].

The fabricated prototype has a compact PCB footprint of 36 mm x 19 mm, exhibits a good return loss at the three desired resonant frequencies, and provides a reasonable gain for an omnidirectional antenna. A considerable amount of miniaturization is achieved by the meandering geometry, while the efficient multiband operation is achieved by reconfiguration, which also eliminates the need for complex matching networks.

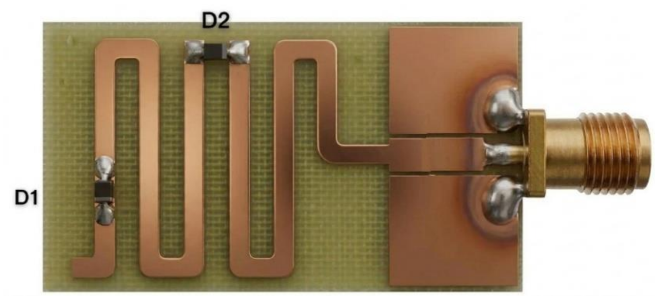

Fig. 6 Fabricated prototype of the antenna

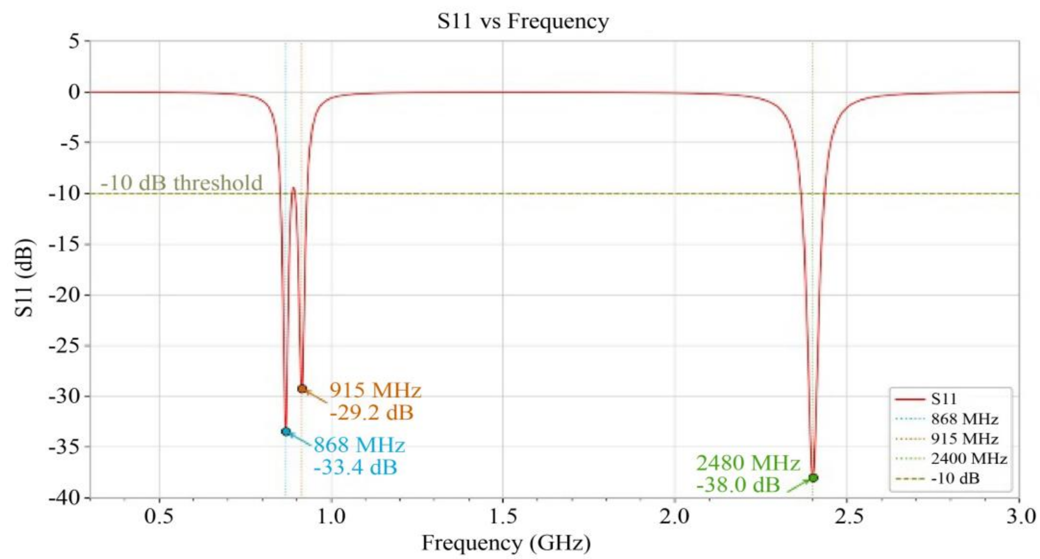

Fig. 7 Measured return loss (S11)

Table. 2 Performance analysis of the antenna at its 3 states generated by frequency reconfiguring

S. No	Parameter	Simulation results			Measured results		
		State 1	State 2	State 3	State 1	State 2	State 3
1	Operating frequency	868 MHz	915 MHz	2.4 GHz	868 MHz	915 MHz	2.4 GHz
2	Return loss (S_{11}) in dB	-29.07	-28.18	-32.62	-33.4	-29.2	-38
3	Bandwidth in MHz	114.4	124.3	310.0	50	40	140
4	Fractional Bandwidth	13.2%	13.6%	12.9%	5.8%	4.4%	5.8%
5	Impedance matching	Very good	Comparable to state 1	Outstanding	Very good	Reasonably good	excellent
6	State of PIN diodes	D1 ON and D2 ON	D1 OFF and D2 ON	D1 OFF and D2 OFF	D1 ON and D2 ON	D1 OFF and D2 ON	D1 OFF and D2 OFF

The state-of-the-art designs mainly include the PIN diode, varactor diode, or RF MEMS for frequency reconfigurability, and miniaturization is achieved by implementing high permittivity substrate, meandering, or slot loading techniques. In the proposed design of this paper, the CPW feeding, which results in good matching of antenna with the source, the meandering, which provides simple and effective miniaturization, and the PIN diode switching for frequency reconfigurability make this design unique in terms of ease, economy, and effectiveness for the operation in the designated bands of IoT devices.

Table 3. Comparative analysis summary of design mechanisms

Feature	Hu et al.[15]	Muhammad Yahya et al.[16]	Khaleghi[9]	Proposed design
Reconfiguration	3-bit Active (8 states)	Active Switching (3 bands)	Tunable Parasitic Patch	Active Switching (3 bands)
Switching Component	3 PIN Diodes	2 PIN Diodes	N/A (Passive)	2 PIN diodes
Miniaturization	Triple-folded meander	Spiral meander	Double Meander line	Simple Meandering
Feeding mechanism	Strip line feed	Strip line feed	Probe feeding	CPW feeding

5. Conclusion and Future Work

The thin meander line monopole antenna provides a compact solution for multiband IoT applications, successfully balancing size constraints with performance. While efficiency at sub-GHz frequencies is limited by inherent physics and substrate losses, the design delivers notably strong performance at 2.4 GHz. The simulation results and fabricated prototype metrics have a close comparison. The designed antenna is well-suited for IoT and short-range wireless embedded systems where compactness is desired, multiband operation is required, and energy efficiency is critical. The future work of this research may be to make the design more radiation efficient in terms of gain enhancement and to extend the design of the antenna to incorporate a fourth operational band, either at 433 MHz or at 1800 MHz.

Conflicts of Interest

"The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper."

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Corresponding author pursuing Ph.D, and he is doing research work with the help of his supervisors, and he is responsible for publications.

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