

A NOVEL TWO-LAYER VERTICAL WIRE MEDIUM FOR ENHANCING MONOPOLE ANTENNA GAIN IN LoRaWAN-BASED IoT APPLICATIONS

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Abstract

This research proposed a novel approach to enhance the gain of a monopole antenna. The design integrated a wire medium metamaterial structure and a dielectric material with a quarter-wavelength monopole antenna to improve gain performance, while maintaining compact size and lightweight characteristics. The antenna was designed to operate at a frequency of 922.5 MHz for use in a long range wide area network (LoRa WAN). The proposed structure consisted of a quarter-wavelength monopole antenna surrounded by a two-layer vertical wire medium. A polyamide material, shaped into a cylindrical form, was used as a spacer between the two layers of the vertical wire medium. Simulation results demonstrated that the dielectric wire medium significantly enhanced the gain of the monopole antenna from 4.5 dBi to 12.3 dBi-an improvement of 7.8 dBi. The antenna also exhibited a symmetric radiation pattern with reduced side lobes. The proposed technique enhanced the performance of existing systems without necessitating additional power input. To validate the simulation results, a prototype antenna was fabricated and experimentally tested. The measured results demonstrated good agreement with the simulations in terms of reflection coefficient, VSWR, radiation pattern, and gain.

Keywords: High Gain; Internet of Things; Long Range Wide Area Network (LoRaWAN); Monopole Antenna; Wire Medium Structure

Introduction

Wireless communication technologies are continuously evolving, with the Internet of Things (IoT) now gaining widespread popularity. The emergence of the IoT has driven the development of various supporting technologies, including the production of low-power chips and devices,

allowing different objects to communicate over the internet. However, limitations still exist, particularly in terms of power consumption from batteries and low radio signal strength, which hinder communication range and efficiency. As a result, there has been a push to develop new technologies

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such as LoRa—a wireless protocol specifically designed for long-range, low-power communication. However, the design of antennas to enhance the performance of LoRa technology and extend its coverage over long distances presents a significant challenge. Antennas are essential components in wireless communication systems. They convert electrical energy into electromagnetic waves for transmission and vice versa for reception. Among various antenna types, the monopole antenna a type of wire antenna is widely used due to its compact size, lightweight structure, and ease of design, fabrication, and installation. Antennas used for LoRa technology have a gain of 8 dBi and a length of 55 cm. They exhibit a standing wave ratio (SWR) of less than 1.5 and support communication ranges of 1-3 km in general environments and 5-10 km in open areas.

Based on a review of existing literature and technical data, a monopole antenna was designed. The monopole antenna is classified as a type of wire antenna consisting of a single conductive wire that acts as a resonator for radiating electromagnetic waves. It is installed on a ground plane (Kudpik *et al.*, 2017). Due to the nature of the open-ended resonator, radiation occurs along the entire length of the conductive wire. The length of the wire, which is determined by the wavelength, is a key parameter in defining the characteristics of a monopole antenna (Weiner, 2003; Zivkovic *et al.*, 2012). The quarter-wavelength ($\lambda/4$) monopole antenna is one of the most commonly used types (Muhammad, 2016). The radiation characteristics of a $\lambda/4$ monopole differ from a dipole because it radiates only above the ground plane and not below it (Sarahani, 2008). As a result, the gain of a $\lambda/4$ monopole antenna depends on both the length of the conductive wire and the size of the ground plane. A larger ground plane results in higher antenna gain (Valentino, 2001). However, studies have shown that a large ground plane can lead to complexity in design and installation, while a small ground plane reduces the efficiency of the monopole antenna.

Artificially engineered metamaterials (Yang & Rahmat-Samii, 2008) are specifically designed and constructed to exhibit desired electromagnetic properties not commonly found in nature, primarily arising from the structure of the material rather than its composition. Metamaterials are composed of an arrangement of small (subwavelength) inhomogeneous components (Angkavisanpan, 2010; Chaimoon & Akkaraekthalin, 2011). The electromagnetic properties include electric permittivity (ϵ), magnetic permeability (μ), and refractive index (n). Metamaterials can be constructed by embedding various artificial materials into or onto a specified medium or its

surface. The designer has the freedom to select different parameters, such as the properties of the medium, the size, shape, and components to be embedded, as well as the density or arrangement of these inclusions, to achieve unique electromagnetic responses that cannot be obtained from conventional natural materials. Examples of such responses include negative magnetic permeability and a negative refractive index. For these reasons, this type of electromagnetic material is also referred to as a metamaterial (Wongkasem & Matra, 2009).

Studies have shown that a suitably designed metamaterial structure, matched to the wavefront shape emitted from an antenna, can function as a resonant circuit when placed in front of the antenna. This leads to an overall enhancement in antenna performance (Duangtang *et al.*, 2016; Kampeephath *et al.*, 2017). Subsequently, researchers proposed a hybrid metamaterial approach to improve antenna efficiency by employing a metallic holes structure (Beruete *et al.*, 2007a; Beruete *et al.*, 2007b) to enhance bandwidth and impedance matching, alongside a vertical wire medium structure (Simovski *et al.*, 2012; Kampeephath *et al.*, 2019). When the designed metamaterials were optimized in terms of parameters and spacing and arranged to surround the monopole antenna, the antenna gain was significantly improved compared to a conventional monopole antenna. This research presented a two-layer vertical wire intermediate structure positioned optimally to enhance the performance of a monopole antenna, serving as the primary antenna for LoRaWAN technology. This vertical wire intermediate structure functioned as a resonant circuit for the antenna. Simulation results from the software showed that the antenna exhibited improved impedance matching and higher gain, leading to enhanced overall performance without any structural modification or alteration. This design maintained a compact and lightweight form factor, making the antenna easy to install and operate. This technique enhanced the performance of existing systems without requiring additional power input.

The Design of the Antenna

Figure 1, a quarter-wavelength ($\lambda/4$) monopole antenna was designed to operate at a frequency of 922.5 MHz, with a conductor diameter of 1 mm, mounted on a circular ground plane with a diameter equal to one wavelength. The simulation results, obtained using electromagnetic wave simulation software, provided the reflection coefficient (S_{11}) and the standing wave ratio

(SWR) of the antenna. The radiation patterns of the standard prototype $\lambda/4$ monopole antenna are illustrated in Figures 2, 3, and 4.

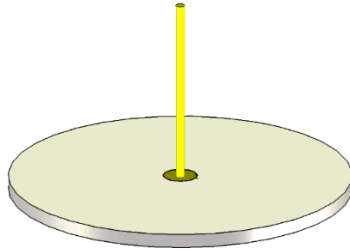


Figure 1.A quarter-wavelength ($\lambda/4$) monopole antenna

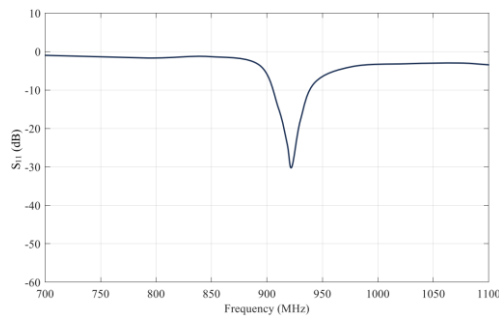


Figure 2. Reflection coefficient (S_{11}) of the initial $\lambda/4$ monopole antenna

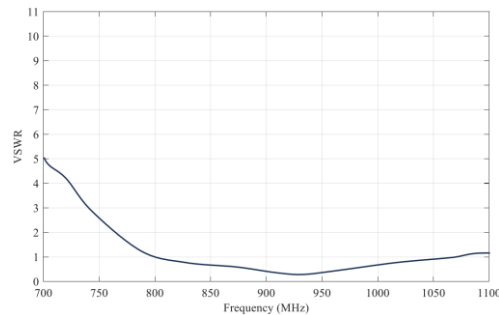
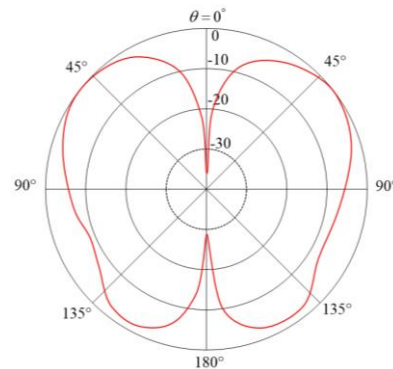


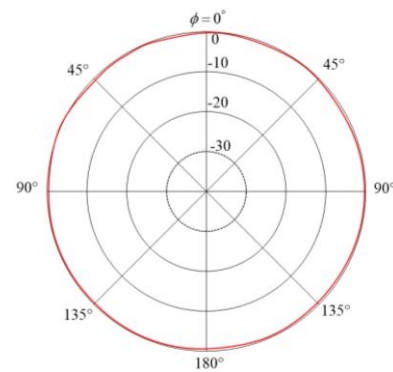
Figure 3. Standing wave ratio (SWR) of the $\lambda/4$ monopole antenna

Design of Wire Medium Structure

Design and Analysis of a Wire-Structured Medium to Achieve an Optimal Configuration and Enhance the Radiation Pattern Efficiency of a Monopole Antenna (Wongsan & Khamsalee, 2019). The wire-structured medium was designed to focus on creating a compact structural form. The design positioned the wire-structured medium alongside or as close as possible to the monopole antenna to develop a monopole antenna structure with a shape & closely resembling a standard-sized monopole antenna. A vertical wire medium structure was



(a)



(b)

Figure 4. Radiation pattern of the prototype quarter-wavelength ($\lambda/4$) monopole antenna

suitable for generating the wave pattern of a quarter-wavelength monopole antenna, which provided an omnidirectional radiation pattern. The wire medium structure, made of aluminum rods ($\epsilon_r = 8.4$, $\tan \delta = 0.002$), was arranged parallel to the monopole antenna. The dimensions of this structure were optimized and specified for best performance as follows (Duangtang *et al.*, 2016): a diameter ($d = 2r$) of 2.5 mm and a length (l_l) of 52 mm, corresponding to the length of the monopole antenna.

The wire medium structure comprised multiple small wires arranged in parallel within horizontal planes. These were stacked in layers with uniform spacing between each layer, as illustrated in Figure 5. The design of the wire medium was conducted at the resonance frequency, specifically at the center frequency $f_0 = 922.5$ MHz. According to theoretical principles, the radii of the wires selected for the design were significantly smaller than the wavelength corresponding to the operating frequency ($r \ll \lambda$). Both the inter-wire spacing (b) and the inter-layer spacing (a) were smaller than the wavelength at the design frequency to ensure proper medium behavior. The wire-based metamaterial structure were represented by an

equivalent circuit model that induced resonance through the structure, as illustrated in Figure 6. The wire-based metamaterial exhibited t an effective permittivity approaching zero and the design process included calculations to determine the effective permittivity of the wire medium (ϵ_{WM}) (Belov *et al.*, 2003; Burghignoli *et al.*, 2008). This verification ensured that the designed structure possessed the metamaterial characteristic of near-zero effective permittivity, as expressed by Equation (1).

$$\epsilon_{WM} = \epsilon_0 \epsilon_{rh} \left(1 - \frac{k_p^2}{\epsilon_{rh} k_0^2 - k_y^2} \right) \quad (1)$$

where

ϵ_0 = the permittivity of free-space

ϵ_{rh} = the relative permittivity of the host medium

k_y = the wave number along the wire axes

k_0 = the free-space wave number

k_p = the plasma wave-number

$$k_p^2 = \frac{2\pi}{a^2 (\ln(a/2\pi r) + 0.5275)}$$

$$k_0^2 = \left(\frac{k}{\sqrt{\epsilon_h}} \right)^2$$

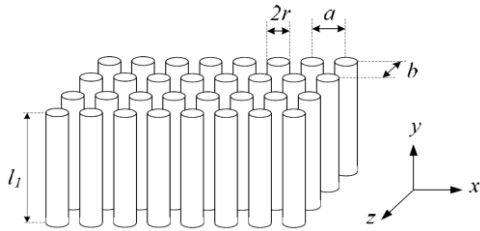


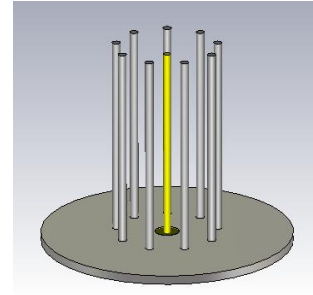
Figure 5. Basic structure of the wire medium



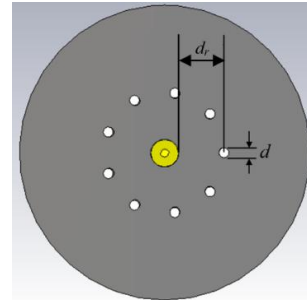
Figure 6. Resonance circuit generated by the wire medium structure

The radius d was 2.5 mm. The design involved arranging nine wire elements evenly around the monopole antenna to find the optimal wire radius r , as illustrated in Figure 7, to function as a resonance

circuit. In this study, d_r represented the distance between the monopole antenna and the wire structure, as well as the circular ground plane. When the distance d_r exceeded 35 mm, the antenna matching improved at higher frequency ranges. Conversely, for d_r less than 35 mm, the antenna exhibited better matching at lower frequencies. When the distance d_r was exactly 35 mm, optimal antenna matching occurred, resonating at a frequency of 922.5 MHz. The distance $d_r = 35$ mm was set as the optimal spacing, providing the best antenna gain performance. Figure 8 illustrates the comparison of the reflection coefficient values for optimal wire spacing in conjunction with the monopole antenna.



(a)



(b)

Figure 7. Wire medium with nine elements arranged around a monopole antenna

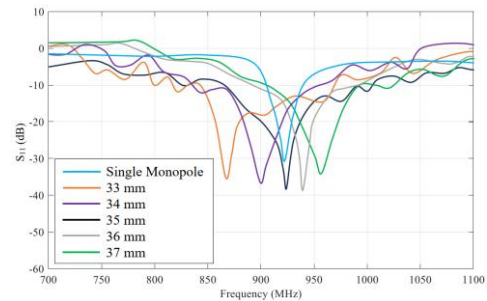


Figure 8. Comparison of reflection coefficients for various optimal distances of the wire structure integrated with the monopole antenna

To further enhance the antenna performance, simulations were conducted by increasing the number of layers in the wire-mesh intermediate structure, with a fixed spacing of 35 mm between each layer. Simulations were performed using CST software to determine the optimal number of layers. The results indicated that the antenna exhibited the best impedance matching when the intermediate wire-mesh structure consisted of two layers, resonating at a frequency of 922.5 MHz. Increasing the number of layers beyond two resulted in poorer matching performance. Therefore, a two-layer intermediate wire-mesh structure was selected with a spacing of 35 mm between layers. Figure 9 illustrates the comparison of the reflection coefficient for different numbers of wire-mesh layers integrated with the monopole antenna.

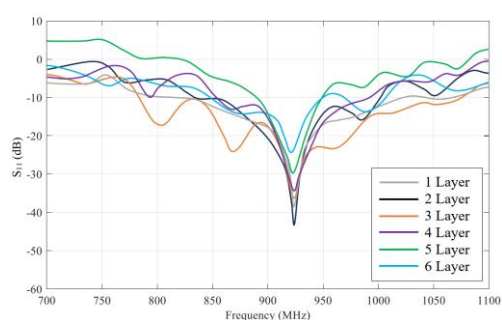


Figure 9. Comparison of reflection coefficients for different numbers of wire structure layers integrated with the monopole antenna

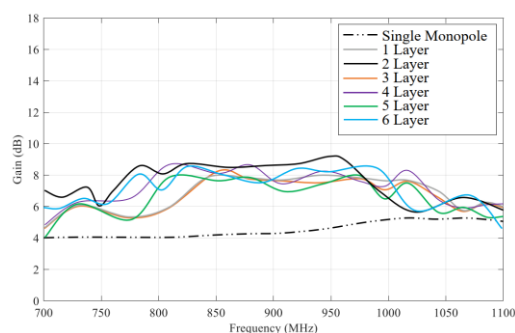


Figure 10. Comparison of antenna gain for each number of wire structure layers integrated with the monopole antenna

The simulation results suggested that a two-layer wire medium provided the best antenna matching, corresponding to a resonance frequency of 922.5 MHz. This performance was superior compared to configurations with a greater number of layers. The spacing between each layer of the two-wire-layer configuration was 35 mm. However, this interlayer spacing was large and hindered practical applications. To enhance usability and

improve the gain potential, the design was integrated with a monopole antenna, as illustrated in Figure 10. According to research (Duangtang *et al.*, 2016), found that a dielectric material reduced the spacing between wire layers when introduced between them. Therefore, the researchers designed the antenna with a carefully selected dielectric material to optimize performance.

Investigation of the Dielectric Material Types Placed Between a Two-Layer Vertical Wire Medium Structure in Conjunction with a Monopole Antenna

A wire-based medium structure was designed to enhance the radiation pattern efficiency of a monopole antenna. The objective of the design was to develop a compact wire medium structure positioned adjacent to or at the shortest possible distance from the monopole antenna. This approach ensured that the enhanced antenna structure retained a form factor comparable to a standard monopole antenna. The proposed technique can be applied to existing monopole antennas to improve their radiation performance. An evaluation of the optimal positioning of the two-layer vertical wire medium structure found that the reflection coefficient at the resonant frequency corresponding to the center frequency of the monopole antenna met the design specifications. However, the gain was not significantly high, with the spacing between the wires too large, leading to difficulties in practical implementation and reduction the cost-effectiveness of the construction.

The aim of the study was to enhance the antenna gain and reduce the distance between the first and second layers of the wire-based metamaterial structure. To achieve this, various dielectric materials were analyzed, as referenced in (Wongsan & Khamsalee, 2019; Kampeephat & Kamphikul, 2021). The analysis was conducted using CST simulation software. The selected dielectric materials were inserted between the wire layers, as illustrated in Figure 11. Six dielectric materials were considered for evaluation as air ($\epsilon_r = 1$), polyamide ($\epsilon_r = 3.5$), FR4 ($\epsilon_r = 4.5$), wood ($\epsilon_r = 2.03$), acrylic sheet ($\epsilon_r = 3.34$), and aluminum ($\epsilon_r = 8.5$). The types of dielectric material for the design were selected based on criteria such as ease of availability, lightweight properties, low cost, and suitability for antenna design applications. The dielectric materials considered were all commonly used in antenna fabrication due to their desirable characteristics. The dielectric materials were placed between the two layers of wire structures integrated

with a monopole antenna. Simulation and analysis were conducted using the CST Studio Suite software. The results showed that each of the six types of dielectric materials evaluated exhibited a return loss at the designed antenna's resonance frequency of 922.5 MHz, as illustrated in Figure 12. The polyamide dielectric yielded the best reflection coefficient at the resonance frequency when compared with the other six types of dielectric materials, while the dielectrics made of air, polyamide, and aluminum exhibited similar bandwidths. By contrast, dielectrics such as FR4, acrylic, and wood showed narrower bandwidths, attributed to the inherent properties of these materials. When integrated with the monopole antenna and the two-layer vertical wire medium structure, the electromagnetic wave propagation characteristics were significantly influenced by the dielectric material, and certain dielectrics resulted in higher reflection due to their interaction with the vertical wire medium. In this study, polyamide was selected as the interlayer dielectric material between the two wire layers, in conjunction with the monopole antenna, owing to its superior performance characteristics.

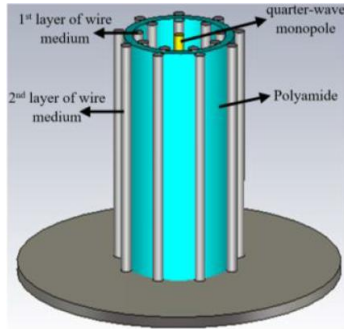


Figure 11. Dielectric type classification for performance evaluation

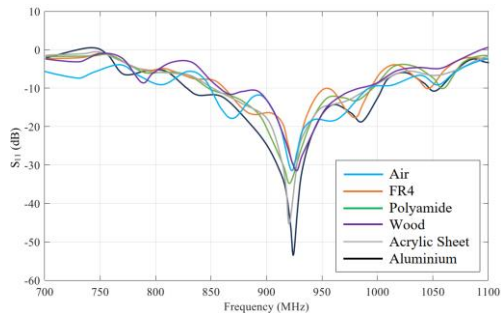


Figure 12. Comparison of S_{11} reflection coefficients for different dielectric types inserted between the two layers of wire structure integrated with the monopole antenna

According to the study in (Kampeephath *et al.*, 2019), investigated a quarter-wavelength monopole antenna surrounded by a vertical wire medium structure. The proposed model demonstrated a maximum gain of 8.65 dBi. In our study, the design process of the first layer of vertical wire medium was introduced and optimized for appropriate positioning. To further enhance the antenna performance, a second layer of wire medium structure was added. To reduce the spacing between the two wire medium layers, a polyamide dielectric material was inserted between them. This configuration was integrated with the monopole antenna to increase its overall gain.

Figure 13 illustrates the proposed antenna model, consisting of a monopole antenna and two layers of vertical wire medium structures separated by a thin polyamide tube with a thickness of 3 mm, as shown in Figure 14. The simulation results revealed a maximum gain of 12.3 dBi with the following dimensions: $d_l = 10$ mm, $d_p = 3$ mm, and $d_w = 2.5$ mm.

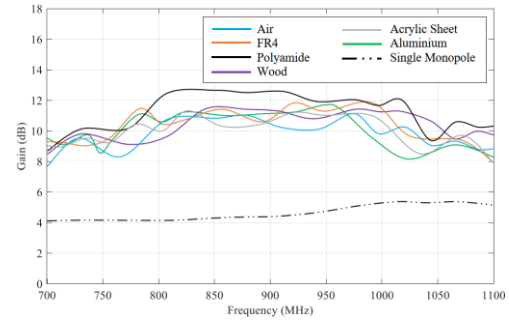


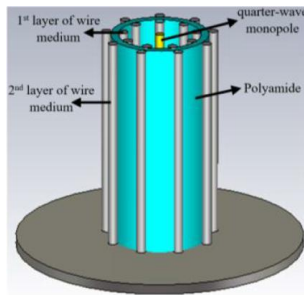
Figure 13. Comparison of antenna gain for various dielectric types inserted between the two layers of wire structure integrated with the monopole antenna

As shown in Figure 1, the antenna design involved several related parameters including:

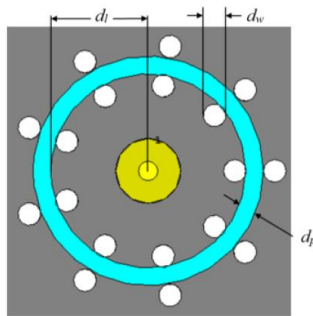
- d_l is the distance from the center of the monopole to the inner edge of the polyamide dielectric tube,
- d_p is the thickness of the polyamide dielectric tube, and
- d_w is the diameter of the dual-layer wire medium structure.

Figure 14 illustrates the simulated model of the proposed antenna prototype. The simulation was conducted using CST software to evaluate and compare the antenna's performance. Figure 15 presents the comparison of the reflection coefficients (S_{11}) among the prototype monopole

antenna, the monopole antenna integrated with a vertical conducting wire structure, and the proposed antenna. The results indicated that the proposed antenna achieved the best impedance matching, with a reflection coefficient of -52.5 dB. Figure 16 shows the comparison of the radiation patterns of the prototype monopole antenna, the monopole antenna integrated with a vertical conducting wire structure, and the proposed antenna. The proposed antenna exhibited a narrower half-power beamwidth (HPBW), resulting in higher gain. Figure 17 shows that the proposed antenna achieved a maximum gain of 12.3 dBi, representing an improvement of 7.8 dBi compared to the prototype monopole antenna, with a comparison of frequency range (MHz) and antenna gains of the three configurations, including the proposed antenna, summarized in Table 1.



(a)



(b)

Figure 14. The proposed antenna model

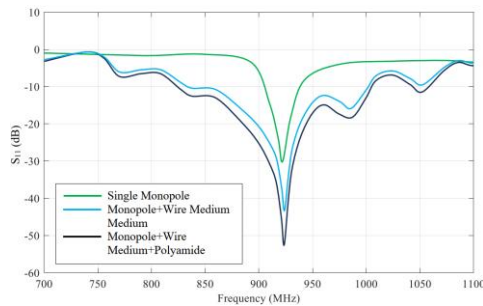
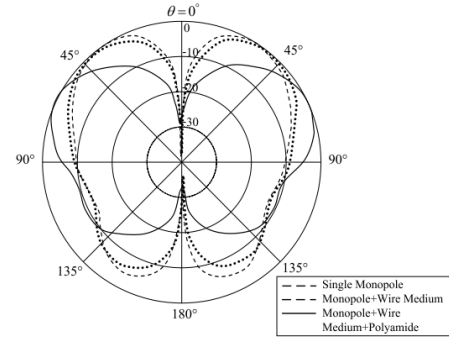
Figure 15. Comparison of the reflection coefficient (S_{11}) of the monopole antenna integrated with the vertical wire medium structure

Figure 16. Comparison of the radiation patterns of the monopole antenna integrated with the vertical wire medium structure

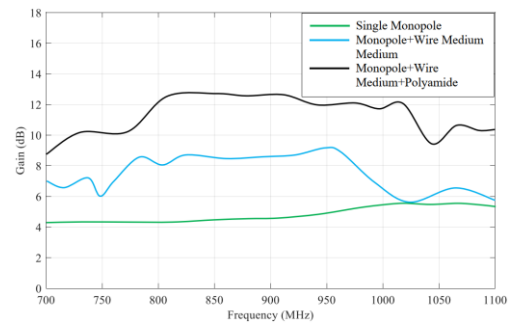


Figure 17. Gain of the proposed prototype of the monopole antenna integrated with the two-layer vertical wire medium structure.

Table 1. Simulation results

Antenna	Gain (dBi)	Frequency Range (MHz)
A single monopole	4.5	9.11 - 9.38
A monopole with wire medium structure	8.6	8.35 - 10.0
A monopole with wire medium structure and polyamide (proposed antenna)	12.3	8.25 - 10.63

Antenna Fabrication and Performance Evaluation

A monopole antenna integrated with a two-layer vertical wire medium structure was designed based on the simulation results, with a polyamide material used as the interlayer dielectric, following the structural design presented in the previous section. The antenna was fabricated according to the dimensions shown in Figure 14, using material parameters consistent with those used in the CST simulation software. An SMA 50 Ω connector (SMA female PCB straight) was soldered to the fabricated monopole antenna. The fully assembled monopole antenna prototype is shown in Figure 18.

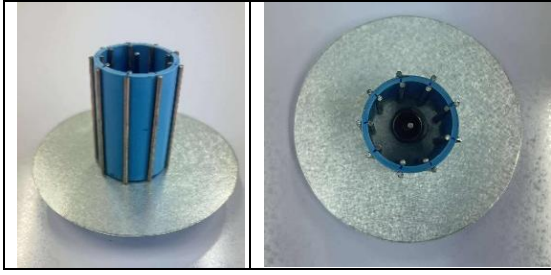


Figure 18. The monopole antenna integrated with the two-layer vertical wire medium structure

A critical parameter for evaluating impedance matching is the reflection coefficient (S_{11}) measured from the monopole antenna integrated with a two-layer vertical wire medium structure. In antenna engineering applications, an acceptable S_{11} value is equal to or less than -10 dB, corresponding to a voltage standing wave ratio (VSWR) of 2.0 or lower. According to standard practice, the -10 dB point is considered the threshold for acceptable return loss. The measurements were performed using a Vector Network Analyzer model MS46524B, with the results compared with those from electromagnetic simulations. As shown in

Figure 19, the measured reflection coefficient exhibited a bandwidth ranging from 825.5 MHz to 1,006.3 MHz, corresponding to 19.74%. By comparison, the simulated results showed a bandwidth from 800 MHz to 1,020.43 MHz, or 19.83%. These results demonstrated a high level of agreement between the measured and simulated data. A comparison was made with the VSWR of the printed circuit dipole antenna across the measured bandwidth of 825.5 MHz to 1,006.3 MHz. The measured VSWR remained below 2.0 throughout this range, as illustrated in Figure 20.

Similarly, the input impedance measurement of the proposed monopole antenna integrated with the two-layer vertical wire medium structure in the operational frequency range of 900 MHz to 950 MHz showed an input impedance of $49.166 + j10.749 \Omega$ at 922.5 MHz, as illustrated in Figure 21. The proposed monopole antenna exhibited superior performance compared to the conventional monopole design, offering a broader bandwidth that covered the entire operational frequency range and achieved improved impedance matching across the band.

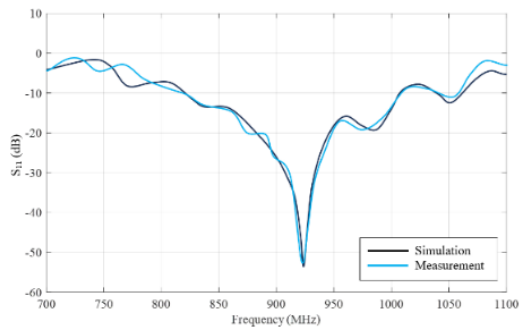


Figure 19. Simulated and measured results of the reflection coefficient

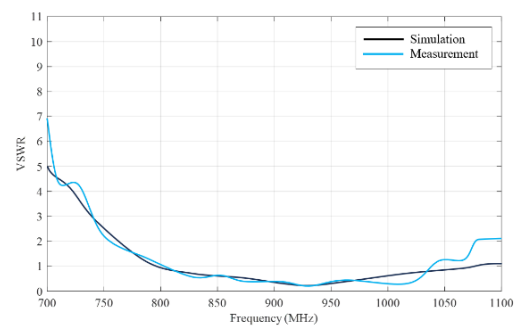


Figure 20. Simulated and measured voltage standing wave ratio (VSWR) of the monopole antenna integrated with the two-layer vertical wire medium structure.

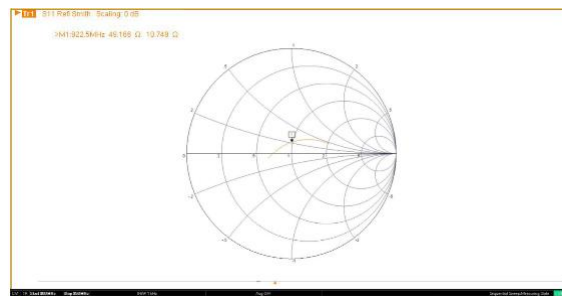


Figure 21. Measured input impedance of the monopole antenna integrated with the two-layer vertical wire medium structure

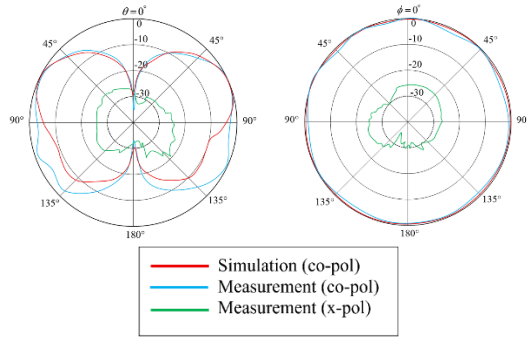


Figure 22. Measured radiation patterns in the xz- and yz-planes at operating frequency 922.5 MHz for the monopole antenna integrated with the two-layer vertical wire medium structure

The measurement was conducted in the far-field region. The minimum far-field distance (R) was calculated using the equation $R \geq 2D^2/\lambda$, where D represents the largest dimension of the antenna and λ is the wavelength corresponding to the operating frequency. Based on this calculation, the minimum far-field distance was determined to be greater than 0.04 meters. For this measurement setup, the distance was set to 0.04 meters. A monopole antenna was employed as the transmitting antenna at each operating frequency. The receiving antenna consisted of a vertically stacked dual-wire structure, also based on a monopole configuration. This receiving structure was rotated around its axis in each plane to receive signals transmitted from the transmitting antenna. The measurements were carried out over a full azimuthal range from 0° to 360° , and the co-polarized radiation patterns were measured in both the electric field plane (E-plane; xz-plane) and the magnetic field plane (H-plane; yz-plane). A comparison was conducted between the measured results and the simulation outcomes of the antenna to evaluate the effect of frequency on the radiation pattern. The monopole antenna integrated with the fabricated two-layer vertical wire medium structure exhibited an omnidirectional radiation pattern in the E-plane (electric field plane) within a single plane. The half-power beamwidths (HPBW) obtained from both simulation and measurement were 55.1 and 54.8, respectively, at a frequency of 922.5 MHz. In the H-plane (magnetic field plane), the antenna demonstrated an omnidirectional radiation pattern, which closely corresponded with the simulation results obtained using commercial electromagnetic simulation software, as illustrated in Figure 22. The gain measurement of the monopole antenna integrated with a two-layer vertical wire medium structure was conducted by constructing a half-wavelength dipole antenna at

each operating frequency to serve as the transmitting antenna. The monopole antenna, combined with the two-layer vertical wire medium structure, functioned as the receiving antenna. The received signal was then used to calculate the antenna gain based on the Friis transmission equation (Kampeeapat *et al.*, 2017), expressed in decibels (dBi), as shown in equation (2).

$$Pr = Pt - 2Loss_{2Con@t} - Loss_{Line@t} + G_{0t} - 20 \log \left(\frac{4\pi R}{\lambda} \right) + G_{0r} - 2Loss_{2Con@r} - Loss_{Line@r} \quad (2)$$

where the ratio Pr/Pt represents the proportion of received power at the receiving antenna to the transmitted power supplied to the transmitting antenna. R denotes the distance between the transmitting and receiving antennas, G_{0t} and G_{0r} are the gain values of the transmitting and receiving antennas, respectively, λ is the wavelength corresponding to each test frequency. $2Loss_{2con@t}$ and $2Loss_{2con@r}$ represent the losses from two sets of SMA connectors on both the transmitting and receiving sides, and $Loss_{line@t}$ and $Loss_{line@r}$ correspond to the losses from the transmission lines of the transmitting and receiving sections, respectively. After conducting measurements across all operating frequencies following the specified procedure, the measured gain values were used to calculate and plot a graph for comparison with the simulation results, as shown in Figure 23.

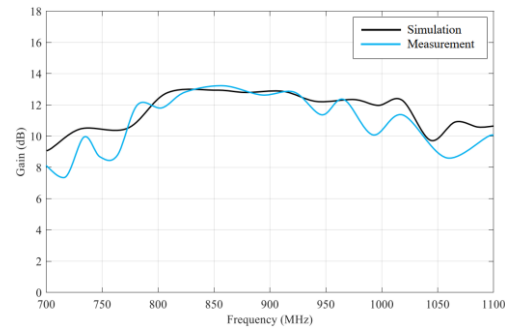


Figure 23. Gain of the monopole antenna integrated with the two-layer vertical wire medium structure

Figure 23 compares the results obtained from measurements with those from simulations using software for the gain of a monopole antenna combined with a two-layer vertical wire medium structure, incorporating a polyamide dielectric placed between the two wire layers. The simulation results indicated a gain of 12.3 dBi at an operating frequency of 922.5 MHz, while the measured gain was 12.17 dBi. For antenna performance testing,

measurements were conducted in an anechoic chamber using specialized frequency equipment. The tests were performed in a high-frequency laboratory to ensure accurate and reliable results. The monopole antenna combined with a two-layer vertical wire intermediate structure and a polyamide dielectric exhibited a gain increase of 7.97 dBi compared to the original monopole antenna, and a gain improvement of 3.68 dBi compared to the monopole antenna with only the two-layer vertical wire intermediate structure, as shown in Table 2. The design and fabrication of the monopole antenna with the two-layer vertical wire intermediate structure, followed by the measurement of various antenna parameters in the laboratory, showed good agreement between the simulation and experimental results. The test results demonstrated the applicability of the technology for long-range, low-power communication, thereby enhancing the efficiency of LoRa technology and the system covered remote areas.

Table 2. Comparison between measured and simulated results of the antenna performance

Antenna	Gain (dBi)		Frequency range (MHz)	
	Sim.	Meas.	Sim.	Meas.
A single monopole	4.5	4.2	911.2 - 938.3	914.2 - 940.6
A monopole with wire medium structure	8.6	8.49	835.14 - 1000.0	840 - 1000
A monopole with wire medium structure and polyamide (proposed antenna)	12.3	12.17	825.5 - 1006.3	800 - 1020.43

Sim. = Simulation and Meas. = Measurement

The theory and principles related to path loss refer to the attenuation of a signal caused by natural phenomena, which occurs as the distance between the transmitter and receiver increases. Environments are generally categorized into three types: urban, suburban, and rural. The urban environment is characterized by high population density and a high concentration of buildings, whereas the suburban environment has a moderate level of population density and building concentration compared to urban areas. By contrast, rural environments exhibit low population density and sparse housing. These scenarios are illustrated in Figure 24 (Rappaport *et al.*, 2017).

In this study, the proposed antenna was intended for deployment in suburban or rural areas to support communication. The communication link between the transmitting and receiving antennas

was considered under a Line-of-Sight (LOS) condition.

Urban Environment (Urban) (Sangsuwan & Poochaya, 2020, 2021).

The urban environment represents areas with high population density, where the distance between the transmitting and receiving antennas is relatively short, ranging from 0.04 m to 5 m. Communication between the antennas is considered under a Line-of-Sight (LOS) condition.

$$PL = 32.4 + 21\log_{10}(d) + 20\log_{10}(f) \quad (3)$$

The graph in Figure 25 illustrates the relationship between path loss and distance in an urban environment, where the antenna separation ranges from 0.04-5 m. This corresponds to the LOS model described in Equation (3). For example, at a distance of 0.04 m, the graph shows that the path loss is 56.54 dB.



Figure 24. Environments

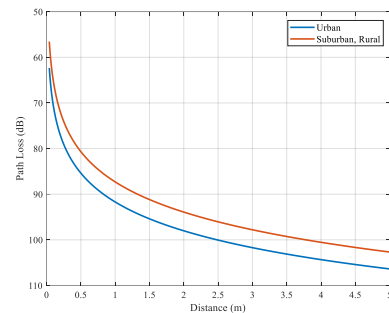


Figure 25. Graph illustrating the relationship between path loss and distance in urban, suburban and rural environments at a frequency of 922.5 MHz

Suburban Environment (Suburban)

The suburban environment represents areas located outside the central city, with a lower population density compared to urban areas. In this case, the distance between the transmitting and receiving antennas is larger, ranging from 0.04 m to 5 m. The communication between the antennas is considered under a Line-of-Sight (LOS) condition. (Sangsuwan & Poochaya, 2020, 2021).

$$PL = 28 + 22 \log_{10}(d) + 20 \log_{10}(f) \quad (4)$$

As illustrated in Figure 25, the graph shows the relationship between path loss and distance in a suburban environment, where the antenna separation ranges from 0.04-5 m. This corresponds to the LOS model described in Equation (4). For example, at a distance of 0.04 m, the graph indicates that the path loss is 62.34 dB.

Rural Environment (Rural) (Sangsuwan & Poochaya, 2020, 2021)

The rural environment represents areas with very low or no vehicle density. In this scenario, the distance between the transmitting and receiving antennas is large, ranging from 0.04 m to 5 m. The communication between the antennas is considered under a Line-of-Sight (LOS) condition.

$$PL = 28 + 22 \log_{10}(d) + 20 \log_{10}(f) \quad (5)$$

As shown in Figure 25, the graph illustrates the relationship between path loss and distance in a rural environment, where the antenna separation ranges from 0.04-5 m. This corresponds to the LOS model described in Equation (5). For example, at a distance of 0.04 m, the graph indicates that the path loss is 62.34 dB,

where:

- PL is the path loss (in decibels)
- d is the distance between the antennas (in meters)
- f is the frequency (in megahertz).

Conclusions

This study presented a novel approach to improving the performance of a quarter-wavelength ($\lambda/4$) monopole antenna by employing a two-layer vertical wire metamaterial structure with polyamide tubes serving as interlayer spacers. The use of polyamide enabled a reduction in the height of the two-layer vertical wire metamaterial structure, resulting in a more compact configuration. The vertical wire metamaterial functioned as a resonant

circuit for the antenna. Simulation results demonstrated improved impedance matching and a significant enhancement in antenna gain, increasing from 4.5 dBi to 12.3 dBi, representing an improvement of 7.8 dBi. The radiation pattern of the proposed antenna exhibited symmetry with reduced side lobes, thereby enhancing the overall radiation efficiency. Importantly, these improvements were achieved without modifying the original antenna structure. Our proposed design yielded a compact, lightweight antenna that was easy to install and deploy. The technique enhanced the performance of existing systems without requiring additional power input, making it particularly suitable for applications in Internet of Things (IoT) communication technologies.

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