

Design, simulation, and experimental validation of a multiband cable antenna for IoT applications

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Abstract—The paper presents the design, numerical modeling, and experimental validation of a low-cost multiband cable antenna intended for Internet of Things (IoT) applications. The proposed antenna is based on a modified coaxial cable structure that acts as a radiator, enabling operation in multiple frequency bands, including the 868 MHz and 2.4 GHz ISM bands. The antenna design was developed in the CST Studio Suite environment and subsequently validated experimentally using a vector network analyzer (VNA). To assess fabrication repeatability, the frequency characteristics of four identical antenna prototypes were measured. The measured S_{11} reflection coefficient demonstrated stable multiband operation consistent with the simulation results. The proposed solution represents an attractive alternative to conventional external antennas in IoT systems.

Keywords—cable antenna; Internet of Things (IoT); multiband antennas; S-parameter measurements; electromagnetic simulation; CST Studio Suite

I. INTRODUCTION

THE rapid growth of Internet of Things (IoT) systems in recent years has led to a significant increase in the number of devices communicating wirelessly in a variety of operating environments. As the scale of these deployments expands, there is a marked increase in the demands placed on radio components, particularly antennas, which are a key element of the transmission path. In practical IoT applications, such as telemetry systems, critical infrastructure monitoring, industrial systems (IIoT), and devices installed in environments with high humidity, dust, or aggressive environmental factors, antennas must operate in enclosures with a high degree of protection (IP67, IP68). This necessitates the use of design solutions that simultaneously ensure high mechanical reliability and stability of electromagnetic (EM) parameters [1, 2].

Under such conditions, conventional integrated antennas, such as printed circuit board (PCB) antennas or chip antennas, often result in a significant deterioration of IoT system performance. This is primarily due to the influence of the device's enclosure, which in many cases acts as a barrier to the propagation of electromagnetic waves. Additionally, the presence of dielectric materials with uncontrolled electrical parameters leads to a shift in the antenna's resonance frequency

(detuning). As a result, the IoT system experiences a deterioration in impedance matching, an increase in the reflection coefficient, and a decrease in radiation efficiency. Adverse propagation conditions resulting from the location of devices (e.g., underground installations, metal enclosures, proximity to other conductive elements) further exacerbate these problems [3, 4].

An alternative is traditional external antennas, which, by being positioned away from the IoT system's housing, provide significantly better operating conditions. However, the use of external antennas comes with significant practical limitations. First, they generate additional costs related to RF components and installation. Second, they require the use of special feedthroughs or connectors, which complicates ensuring a high degree of enclosure sealing. Third, they are more susceptible to mechanical damage, which in industrial or field environments can significantly reduce the reliability of the entire system [5].

Given these limitations, intermediate solutions are being sought that combine the advantages of integrated and external antennas. One option is to use a coaxial cable antenna, in which the inner conductor serves as both the feedline and the radiating element. In such a properly designed structure, it is possible to achieve resonant radiating properties by controlled exposure of the inner conductor or modification of the shield geometry. This solution allows for the effective radiation of the antenna outside the device housing without the need for a classic external antenna. At the same time, the mechanical integrity of the system and the continuity of its electromagnetic shielding are preserved, which is of critical importance in IoT system applications [6, 7].

An additional advantage of cable antennas is their low production cost, resulting from the use of standard coaxial cables and a simplified manufacturing process. Solutions of this type are also characterized by high design flexibility, allowing the length and geometry of the radiator to be adapted to the required frequency bands. This makes it possible to achieve multiband operation without the need for complex matching circuits [7, 8].

The aim of this work was to design and optimize, using CST, and to experimentally verify a low-cost multiband cable antenna

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intended for use in IoT systems. Particular emphasis was placed on achieving stable antenna performance in bands relevant to modern wireless communication systems, i.e., the 868 MHz band used, among others, in LoRa systems, and the 2.4 GHz band used in WiFi and Bluetooth Low Energy (BLE) standards. Additionally, the antenna's performance in the approximately 790 MHz band was analyzed, which is important from the perspective of electromagnetic compatibility and potential coexistence with other radio systems, such as LTE/5G NR cellular systems in the 800 MHz band (e.g., Band 20), professional mobile radio (PMR) systems, and selected telemetry and M2M systems operating in the UHF band [9].

This paper presents the results of numerical simulations conducted in the CST Studio Suite environment and the results of experimental measurements performed on four identical antenna prototypes. This approach allows not only for an assessment of the EM properties of the proposed solution, but also for an analysis of its manufacturability, which is a crucial aspect in the context of practical industrial implementations.

II. SIMULATIONS

The simulation studies utilized the CST Studio Suite environment, which is one of the leading tools used for modeling and analyzing high-frequency electromagnetic structures in a full three-dimensional model. This software enables accurate representation of antenna geometry, material properties, and boundary conditions, which is crucial for the analysis of antenna structures based on cable and resonant elements.

The developed antenna (Fig. 1) is based on a modified open-sleeve monopole structure, constructed using a standard coaxial cable and a cylindrical conductive element that serves as a resonant sleeve. In the proposed solution, the inner conductor of the coaxial cable serves not only as a feedline but also as a radiating element, while the metal sleeve acts as an additional, coupled resonant element. This approach allows for a significant simplification of the design and a reduction in costs, while maintaining multiband operation capabilities.

A key element of the structure is the proper shaping of the conductor geometry through the controlled exposure of sections of the coaxial cable and the insertion of a conductive sleeve. In the analyzed design, the inner conductor of the coaxial cable serves as the main radiator, responsible for generating the dominant component of EM radiation. At the same time, the outer conductor of the cable (shield), after being partially exposed and electrically connected to the sleeve, forms a secondary sleeve-type radiating element. In the actual design, this connection is achieved through the unbraided shield of the cable, which contacts the inner surface of the sleeve, ensuring effective electromagnetic coupling. This configuration results in a coupled radiating system in which the main monopole radiator and the sleeve interact electromagnetically, creating a multi-resonant structure. Additional resonances arise from both the length of the exposed portion of the radiator and the geometric properties of the sleeve, as well as the degree of coupling between the elements.

The antenna model was developed in the CST environment as a full 3D model, taking into account the actual structure of

the coaxial cable, including the inner conductor, dielectric, and shield. The cylindrical conductive sleeve and its coupling with the cable shield were also modeled. Additionally, the exposed section of the conductor responsible for radiation and the transition zone between the feedline and the radiator were included.

The simulation in the CST environment involved performing numerical calculations using the Time Domain Solver.

The simulation employed excitation via a waveguide port with a reference impedance of 50Ω , corresponding to standard measurement conditions. The boundary conditions of the computational domain were defined as open, which allowed for the simulation of electromagnetic wave propagation in space.

As a result of the simulations, the frequency-dependent characteristics of the scattering matrix S and the antenna radiation patterns were obtained. These results served as the basis for the experimental validation of the simulated antenna.

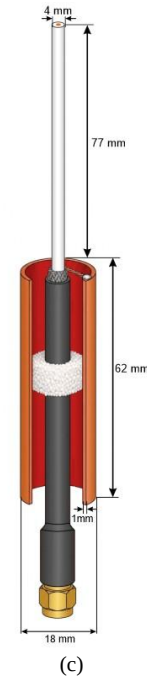


Fig.1. Schematic diagram of the cable antenna under test.

III. PROTOTYPE OF THE ACTUAL ANTENNA DESIGN

The antenna design was initially developed based on numerical simulations performed in the CST Studio Suite environment. Based on these results, a physical prototype was constructed, which was then experimentally tuned to achieve resonance in the 2.4 GHz band. After achieving the desired parameters, four identical, tuned cable antenna prototypes were manufactured. A view of one of them is shown in Fig. 2.

The prototypes were constructed using standard, readily available components. The estimated cost of manufacturing a single antenna is low due to the use of widely available components. A 50Ω coaxial cable of type H-155A01 (the cable's outer diameter is 5.4 mm; the inner conductor consists of a copper strand with a diameter of 1.4 mm), in a length of approximately 1 m, has a unit cost not exceeding a few Polish zlotys. The SMA connector is the relatively most expensive

component of the design, with a price of about a few zlotys per unit. The sleeve element is made of a copper tube, the cost of which—calculated per unit length used in the design—also remains at the level of a few Polish zlotys.

The total cost of the materials needed to build the antenna is therefore no more than a dozen or so zlotys, which confirms that the proposed solution can rightly be classified as low-cost from the perspective of potential applications in IoT systems.

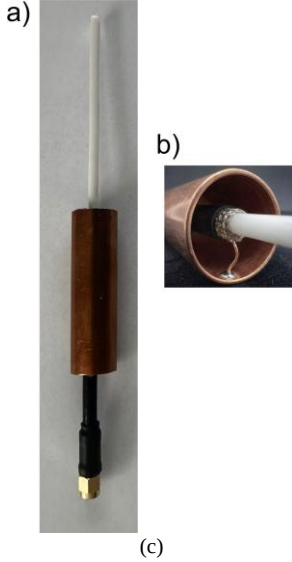


Fig.2. A prototype of a cable antenna (a) and a section showing the connection between the inner conductor and the sleeve surface (b).

The cylindrical sleeve, which is a key component of the antenna's design, is made of copper. When fitted over the coaxial cable, it forms a secondary sleeve-type radiating element. Its geometry—particularly its length and diameter—directly influences the location of additional resonance frequencies and the antenna's operating bandwidth.

The antenna's structure is based on a coaxial cable terminated with an SMA(m) connector, enabling direct connection of the antenna to measurement equipment or communication modules.

Within the sleeve, the coaxial cable structure was modified by removing the outer insulation and exposing the shielding braid. The braid was then unraveled and mechanically bonded to the inner surface of the sleeve. This solution ensures an effective electrical connection between the cable shield and the resonator, which is crucial for the proper operation of the open-sleeve monopole structure. To ensure mechanical stability and secure the coaxial cable inside the sleeve, a dielectric cylinder made of polyurethane foam was used.

The radiating section of the antenna was created by exposing the end of the inner conductor of the coaxial cable. In this area, both the shield and the outer insulation layer of the coaxial cable were removed, leaving the dielectric on the exposed inner conductor. This section serves as the main radiator, and its length was selected to correspond approximately to a quarter-wavelength for the lowest operating band (approximately 800–900 MHz).

Electromagnetic radiation is generated by the entire exposed section of the inner conductor, along which the high-frequency current is distributed. The interaction of this radiator with the

metal sleeve results in the formation of a coupled radiating system with a multi-resonant character.

Since the antenna was intended for operation in outdoor and industrial IoT applications, a dedicated protective enclosure was also developed. The enclosure design and its influence on antenna performance are discussed in the following section.

IV. INFLUENCE OF THE PROTECTIVE ENCLOSURE ON ANTENNA PERFORMANCE

One of the practical requirements for IoT devices operating in industrial and outdoor environments is the ability to maintain stable antenna performance when enclosed in a protective housing. The final antenna enclosure was designed using commercially available PVC components and sealing elements to provide protection against environmental factors such as moisture and dust. The enclosure consists of a PVC tube, an end cap, a cable gland, and mounting elements. The complete assembled antenna and the individual enclosure components are presented in Fig. 3.



Fig.3. Protective housing developed for the proposed cable antenna: (a) exploded view of the enclosure components prior to assembly, (b) fully assembled antenna integrated inside the PVC enclosure.

V. EXPERIMENTAL SETUP

The antenna parameters were measured using a vector network analyzer (VNA), which allowed the S_{11} reflection coefficient to be determined as a function of frequency (Fig. 4). Analysis of this parameter is a fundamental tool for evaluating the antenna's impedance matching and identifying resonance frequencies.

The measurement setup consisted of the network analyzer, a measurement cable, and the antenna under test. Before starting the measurements, the measurement path was calibrated using the SOL (Short–Open–Load) method, which allowed for the elimination of the effects of mismatch and losses in intermediate components, such as cables and connectors. The calibration was performed in the reference plane corresponding to the antenna connection point.

Measurements were carried out over a wide frequency range covering the analyzed operating bands, i.e., from approximately 700 MHz to 3 GHz.

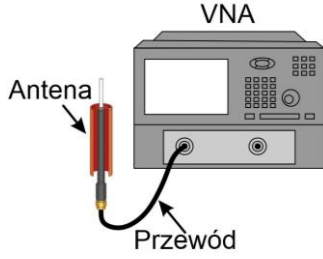


Fig.4. Schematic diagram of the measurement setup for measuring the EM parameters of the cable antennas under test.

VI. RESULTS

To evaluate the influence of the enclosure on the antenna performance, measurements were carried out for two configurations: the antenna operating in free space without the enclosure and the antenna installed inside the final PVC protective housing. Figure 5 presents the measured reflection coefficient S_{11} for both cases, while the main resonance frequencies are summarized in Table 1.

The obtained results indicate that the presence of the enclosure does not deteriorate the antenna performance. For the lower resonance band around 868 MHz, only minor variations of the reflection coefficient were observed. In the higher-frequency region around 2.4 GHz, the enclosure slightly improved the impedance matching, reducing the value of S_{11} from approximately -6.89 dB to -11.02 dB at 2.4 GHz and from -15.71 dB to -17.77 dB at 2.48 GHz.

This behavior can be attributed to the dielectric properties of the PVC enclosure, which slightly modify the near-field distribution around the radiating structure and alter its effective electrical length. Despite this effect, no significant degradation of antenna performance was observed. The results confirm that the proposed antenna can be successfully integrated into a protective enclosure without requiring additional matching circuits or structural modifications.

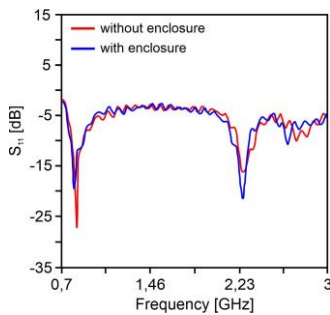


Fig.5. Measured reflection coefficient (S_{11}) of the proposed cable antenna operating with and without the protective enclosure in the frequency range from 0.7 to 3 GHz.

TABLE I
COMPARISON OF MEASURED REFLECTION COEFFICIENT VALUES FOR
ANTENNA WITHOUT AND WITH THE PROTECTIVE ENCLOSURE

Frequency	Without enclosure	With enclosure
790 MHz	-8,71 dB	-12,01 dB
868,9 MHz	-12,53 dB	-12,01 dB
2,40 GHz	-6,89 dB	-11,02 dB
2,48 GHz	-15,71 dB	-17,77 dB

The analysis of the antenna's matching quality utilized the S_{11} reflection coefficient, which directly describes the degree of impedance matching between the antenna and the feedline. This parameter allows for the identification of resonance frequencies and the determination of the operating bandwidth, making it a sufficient and widely used criterion for evaluating antenna properties in experimental studies.

Fig. 6 shows the frequency characteristics of the S_{11} reflection coefficient obtained in simulation studies (red) and experimental studies (blue) for the proposed cable antenna. Analysis of the waveforms in the frequency range from 0.7 GHz to 3 GHz confirms that the tested structure is multi-resonant.

The first resonance occurs in the frequency range of approximately 0.78–0.82 GHz. In the simulation plot, the minimum reflection coefficient occurs near 0.79 GHz. It reaches a value of approximately -25 dB. In contrast, on the measured response, this minimum is shifted to a frequency of approximately 0.81 GHz, with a value of approximately -18 dB. For the simulation characteristics, assuming an $S_{11} < -10$ dB matching criterion, the operating band in the lower frequency range covers the interval of approximately 0.75–0.88 GHz, corresponding to a bandwidth of approximately 130 MHz. For the measured characteristics, the operating band, also defined for an S_{11} level of < -10 dB, covers the range of approximately 0.77–0.90 GHz, corresponding to a bandwidth of approximately 130–150 MHz. The relative bandwidth measured in both cases is approximately 16–18%, which confirms the broadband nature of the resonance.

The second resonance occurs in the higher frequency band, in the range of approximately 2.40–2.80 GHz. In the simulation results, the minimum reflection coefficient occurs near 2.77 GHz and reaches a value of approximately -14 dB. In contrast, for the measured results, this minimum is shifted to a lower frequency, approximately 2.43 GHz, with a value of approximately -22 dB. In the simulation characteristics, assuming a matching criterion of

$S_{11} < -10$ dB, the operating band in this range covers the interval of approximately 2.65–2.90 GHz, which corresponds to a bandwidth of about 250 MHz. In the case of the measured response, the operating band, also defined for $S_{11} < -10$ dB, covers the range of approximately 2.35–2.50 GHz, corresponding to a bandwidth of about 150 MHz. The relative bandwidth is approximately 9% for the simulation results and approximately 6–7% for the measured results, indicating a significantly narrower resonance compared to the lower band. The observed shift in the resonance frequency in the upper band, despite accounting for the role of the housing in the simulation model, is likely due to an inaccurate representation of material parameters and imperfections in the electrical connections in the actual design. The quality of contact between the cable braid and the sleeve has a particularly significant impact; in the simulation model, this contact is treated as ideal, whereas in reality it may exhibit inhomogeneities and contact resistance.

To assess the repeatability of the manufacturing process, measurements were taken for four identical antenna prototypes. Due to space limitations, not all S_{11} reflection coefficient characteristics for individual units are presented. The obtained S_{11} characteristics indicate relatively small variations in parameters among the analyzed prototypes.

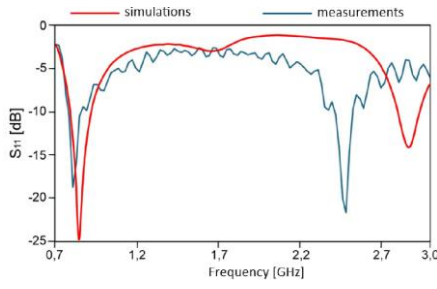


Fig.6. Comparison of simulated and measured reflection coefficient S_{11} characteristics.

Analysis of the measurement results showed that the resonance frequency spread for the lower band does not exceed approximately 20–30 MHz, while for the 2.4 GHz band it is approximately 80–120 MHz. This indicates moderate sensitivity of the design to manufacturing tolerances and good repeatability of the manufacturing process.

The S_{11} analysis confirmed the existence of two dominant resonances and satisfactory impedance matching in the frequency bands of interest. However, proper antenna operation must also be verified in terms of radiation performance. Therefore, the radiation characteristics of the proposed structure were investigated by analyzing the three-dimensional far-field patterns and directivity at the resonance frequencies. Figure 7 shows the three-dimensional radiation patterns for frequencies of 868 MHz (a) and 2.4 GHz (b), respectively. The results indicate that the antenna exhibits properties typical of monopole structures, with quasi-omnidirectional characteristics in the horizontal plane. The directivity values are approximately 2.17 dBi for the 868 MHz band and approximately 4.0 dBi for the 2.4 GHz band, respectively, which confirms the effective radiation of electromagnetic energy by the analyzed structure.

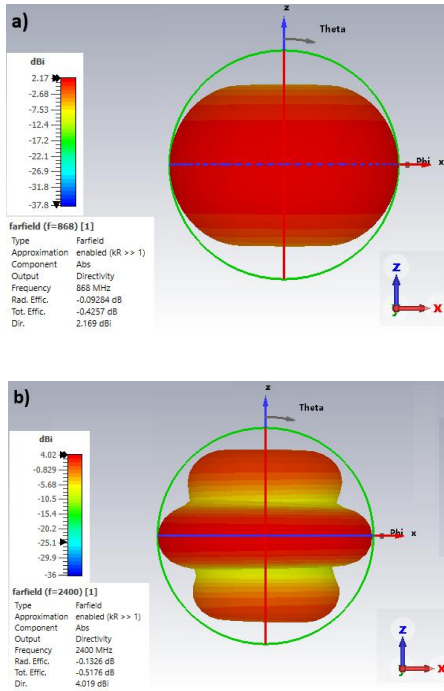


Fig.7. Three-dimensional far-field radiation patterns of the analyzed cable antenna: a) at 868 MHz, b) at 2.4 GHz.

In addition to the electrical performance, the proposed design offers practical advantages related to manufacturability and deployment. The antenna can be fabricated using commercially available components without requiring specialized manufacturing processes. Furthermore, integration within a sealed PVC enclosure enables operation in harsh environmental conditions while preserving satisfactory impedance matching characteristics. These features make the proposed antenna particularly attractive for low-cost industrial and environmental IoT applications.

CONCLUSION

Simulation studies and experimental measurements have confirmed that the proposed open-sleeve monopole cable antenna exhibits distinct multiband characteristics and can be effectively used in Internet of Things (IoT) systems. Two dominant resonances were identified in the analyzed frequency range, corresponding to bands around 0.8 GHz and 2.4 GHz, which is consistent with the design assumptions.

The first resonance, occurring in the sub-GHz band, is characterized by a wide operating bandwidth and good agreement between simulation and measurement results. The relative bandwidth of approximately 16–18% indicates the broadband nature of this resonance, typical of a quarter-wave monopole. At the same time, the slight shift in the resonance frequency between simulation and measurement confirms that the lower operating band is relatively insensitive to environmental changes and manufacturing tolerances.

The second resonance, located in the 2.4 GHz band, exhibits a significantly narrower bandwidth and greater sensitivity to changes in design parameters. A significant shift in the resonance frequency of approximately 300 MHz was observed between the simulation and measurement results. This is primarily due to the influence of the antenna's actual operating conditions, such as the presence of the housing, the dielectric properties of the materials, and manufacturing imperfections. This resonance is associated with the coupling of the monopole to the sleeve element, which makes it more sensitive to geometric and environmental changes.

Analysis of the radiation patterns showed that the antenna exhibits quasi-omnidirectional characteristics in the horizontal plane, typical of monopole structures. The obtained directivity values are approximately 2.17 dBi for the 868 MHz band and approximately 4.0 dBi for the 2.4 GHz band, which confirms that the observed resonances are associated with actual radiation of electromagnetic energy, and not merely with local resonance effects.

The measurements conducted for the four prototypes demonstrated good design repeatability. The resonance frequency spread is approximately 20–30 MHz for the lower band and 80–120 MHz for the 2.4 GHz band, respectively, indicating moderate sensitivity of the antenna to manufacturing tolerances.

The results indicate that the proposed design enables the use of two useful operating bands while maintaining a relatively simple and low-cost structure. It is particularly important that one of the bands covers the frequency range used in sub-GHz systems (e.g., LoRa), while the other corresponds to the popular 2.4 GHz band used in technologies such as Wi-Fi and Bluetooth Low Energy.

An additional advantage of the proposed solution is the ability to integrate the antenna into the device housing without the need for traditional external antennas. This makes it possible to maintain a high degree of environmental protection and mechanical resistance, which is crucial in industrial and environmental applications.

In summary, the proposed cable antenna represents an attractive alternative to conventional antenna solutions in IoT systems, combining simplicity of design, low manufacturing cost, and the ability to operate in two important frequency bands. The results obtained indicate the need to account for the impact of actual operating conditions as early as the design stage, particularly with regard to resonance in the higher band. In future work, it seems advisable to expand the research

to include an analysis of radiation characteristics, antenna efficiency, and the impact of the target device housing on its electromagnetic parameters.

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