Embedded Metallic Structures as Passive Antennas for Sub-GHz IoT Communication in Smart City

Nurmayanti Zain[a], Farhan Rezki Arifin[b] and Lompo Ramos Emakarim[c]

Department of Electrical Engineering, University of Cokroaminoto Makassar, Tamalanrea-Makassar, Indonesia

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Abstract: The increasing demand for robust and scalable wireless infrastructure in smart city has highlighted the potential of utilizing existing building materials as functional components in communication systems. This study investigates the feasibility of embedded metallic structures, specifically steel elements such as galvanized hollow steel and rebars as passive monopole antennas for sub-GHz Internet of Things (IoT) applications. Focusing on the 700 MHz frequency range, analytical modeling was conducted to examine the electromagnetic behavior of monopole configurations formed by structural elements in a concrete medium. Key parameters such as resonance length, impedance matching, and radiation characteristics were derived based on standard antenna theory. The simulation results confirm that selected metallic structures can support monopole resonance with acceptable return loss and bandwidth performance for IoT communication. The integration of antenna functionality into structural elements opens new possibilities for cost-efficient and unobtrusive wireless systems in smart city environments.

1 INTRODUCTION

The rapid growth of smart city has increased the demand for pervasive, energy efficient, and reliable communication infrastructures, particularly for IoT applications. Wireless communication at Sub-GHz frequency is a key enabler due to its long-range and low-power characteristics, making it suitable for large scale urban deployments. However, deploying conventional antennas in dense urban areas remains challenging due to structural integration and aesthetic constraints (Hussain et al., 2022; Jusoh et al., 2023).

Recent studies have explored embedding antennas into metallic infrastructure elements, such as steel beams, hollow sections, and construction frames, to reduce installation complexity and transform passive components into active communication elements, supporting the vision of ambient intelligence (Vähä-Savo et al., 2022; Kumar et al., 2024). Passive Sub-GHz designs (700–900 MHz) embedded in metallic building elements have shown potential for scalable and covert IoT deployment in smart structures, smart buildings, and smart composite structures (Albzaie, 2024; Inclán-Sánchez, 2023; Hassan et al., 2024).

While prior works have used load bearing wall (Vähä-Savo et al., 2022; Vähä-Savo et al., 2024), SEVA (Structurally Embedded Vascular Antenna) (Bal et al., 2021) or concrete embedded antenna (Tan et al., 2022), this study differs by: (1) Employing galvanized hollow steel tubes as both load-bearing and radiating elements, (2) Implementing a quarter-wavelength monopole precisely tuned for 700 MHz LPWAN (Low Power Wide Area Network) and optimized via Ansys HFSS (High Frequency Structure Simulator), and (3) Achieving full structural integration by embedding the antenna into the main structural element. These address limitations of earlier designs reliant on solid conductors, external mounting, or higher frequency bands.

Research gaps remain, including limited study on the electromagnetic and mechanical performance of hollow galvanized steel tubes, minimal focus on quarter-wavelength resonance at 700 MHz for dense urban LPWAN, lack of designs where antennas are embedded within the main structural elements, and

[a] https://orcid.org/0009-0003-2075-6446
[b] https://orcid.org/0009-0001-3526-6883
[c] https://orcid.org/0000-0002-8005-592X

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the scarcity of comprehensive simulations with realistic geometries and full specifications. To address these gaps, this study employs Ansys HFSS, a 3D (three-dimensional) electromagnetic solver based on the Finite Element Method (FEM) that provides rigorous solutions of Maxwell's equations for high-frequency structures. This paper presents a conceptual and analytical investigation of embedded galvanized hollow steel monopoles in a concrete medium for Sub-GHz smart city IoT, focusing on key design parameters, resonance behavior, and integration scenarios in typical urban infrastructure.

2 METHODOLOGY

This study adopts a simulation-based methodology that integrates theoretical modeling, dimensional resonance analysis, and electromagnetic full-wave simulation to investigate the feasibility of using galvanized hollow steel structures embedded in buildings as passive monopole antennas for sub-GHz communication in smart city environments. The analysis targets the 700 MHz frequency band, which is widely adopted for long-range, low-power Internet of Things (IoT) applications (Albzaie, 2024; Inclán-Sánchez, 2023).

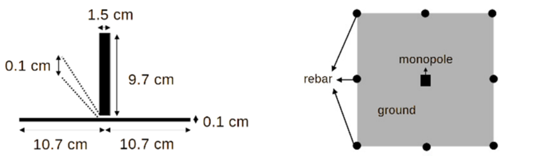
2.1 Structural and Electromagnetic Design

The resonant length of the monopole antenna as a quarter-wavelength radiator is analytically determined based on:

$$L = \frac{1}{4}\lambda = \frac{c}{4f} \tag{1}$$

where:
c is the speed of light (3×10^8 m/s),
f is the target frequency (700 MHz).

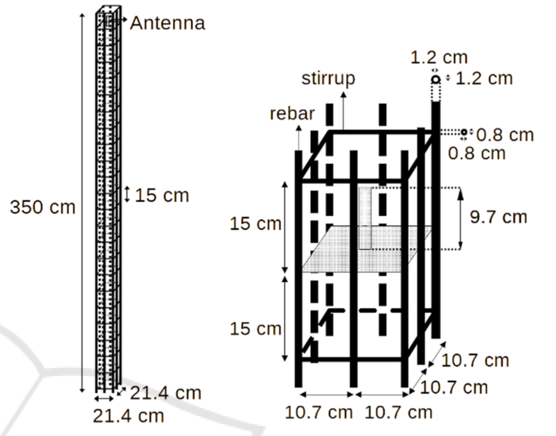
The nominal resonant length of the hollow steel monopole is calculated to be approximately 10.7 cm. Considering the finite conductor diameter, the effective length is slightly reduced to around 9.7 cm, in accordance with standard diameter correction factors, as illustrated in Figure 1.



(a) (b)

Figure 1: Antenna Design: (a) Monopole with Ground Plane, (b) Top View Antenna Configuration.

The metallic material chosen is galvanized hollow steel, modeled as the antenna and embedded within a reinforced concrete structure to represent realistic construction components and evaluate the fundamental electromagnetic behavior of the monopole antenna. Galvanized hollow steel is selected for its mechanical strength, durability, and common use in building construction, while its hollow form enables efficient integration with structural elements, as illustrated in Figure 2.



(a) (b)

Figure 2: Structural Design: (a) Concrete Column Structure, (b) Embedded Antenna within Rebar Structure.

The quarter-wavelength monopole antenna is integrated into a reinforced structural column, replacing one of the stirrups in an arrangement of eight stainless steel rebars. Appropriate dielectric properties are assigned to the surrounding materials to evaluate their effects on the antenna's resonant frequency, impedance matching, and radiation characteristics.

2.2 Simulation Setup

Electromagnetic simulations are performed using Ansys HFSS, a full-wave 3D FEM solver widely employed in antenna design. HFSS is selected due to its capability to accurately model complex geometries, account for material properties, and predict the electromagnetic behavior of antennas under realistic structural and environmental conditions.

Figure 3 illustrates the simulation model. The model consists of an air box with radiation boundary conditions, a concrete column structure, a ground plane, and a lumped port located at the monopole base to emulate excitation from an IoT radio. Adaptive meshing and a frequency sweep from 100 MHz to

1.400 MHz are applied to ensure accurate evaluation of reflection coefficients and electromagnetic field distributions.

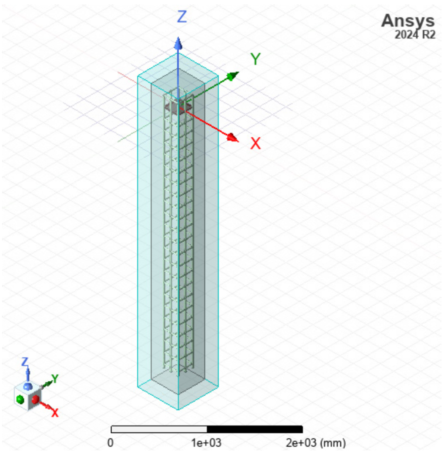


Figure 3: Simulation Model.

The quarter-wavelength monopole antenna is positioned above an aluminum ground plane, with a surrounding vacuum region of approximately 2 cm, as shown in Figure 4. The vacuum layer is introduced to prevent direct contact with the concrete, ensuring that the antenna is not immediately influenced by the surrounding cement. This configuration allows precise evaluation of the antenna characteristics, considering its integration within structural elements to preserve performance.

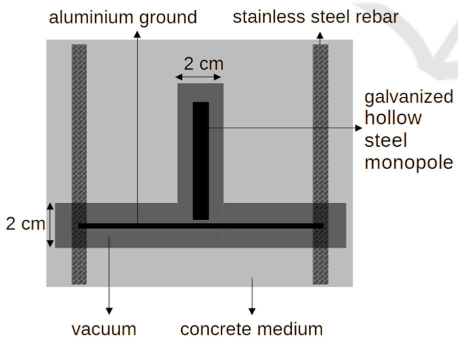


Figure 4: Monopole Antenna in Concrete Medium.

The simulation parameters for the embedded metallic structures are summarized in Table 1. This setup enables assessment of the antenna's performance under realistic structural conditions, accounting for material properties, geometric dimensions, and spatial arrangement of the metallic components. By replicating practical construction scenarios, the simulation provides insight into the antenna's resonant frequency, input impedance, and radiation characteristics, ensuring the results are relevant for real-world structural integration.

Table 1: Simulation Parameters.

Parameter	Value
Target Frequency	700 MHz
Frequency Range	100–1.400 MHz
Antenna Type	Quarter-Wavelength Monopole
Antenna Material	Galvanized Hollow Steel
Physical Length	10.7 cm
Optimized Length	9.7 cm
Hollow Dimensions	1.5 × 1.5 cm (outer) 1.28 × 1.28 cm (inner)
Wall Thickness	0.11 cm
Ground Plane	21.4 × 21.4 cm Aluminium
Reinforcing Bar	8 Stainless Steel
Reinforcing Bar Height	350 cm
Stirrup Spacing	15 cm
Embedding Medium	Concrete
Boundary Condition	Radiation (Open)
Excitation	Lumped Port 50 Ω (Base)

2.3 Performance Metrics

The antenna performance is evaluated based on the following key electromagnetic parameters: (1) Return loss (S_{11}) to determine the resonance frequency and impedance matching, (2) Radiation pattern to assess the omnidirectional coverage typical of monopole antennas, (3) Gain to evaluate power conversion effectiveness and suitability for low-power IoT devices.

Table 2: Material Properties Used in Simulation.

Parameter	Galvanized Steel	Concrete
Relative Permittivity (ε_r)	1.0	6.5
Relative Permeability (μ_r)	100	1.0
Bulk Conductivity (S/m)	1.6×10^6	0.01
Conductivity	Zinc layer: 1.1×10^6 Steel core: 6.99×10^6	Low Conductivity Cementitious Material
Loss Tangent ($\tan \delta$)	0	0.02

Parameter	Galvanized Steel	Concrete
Density (kg/m³)	7850	2400

Metallic and dielectric materials are modelled with physical parameters closely representing actual construction materials, including relative permittivity, permeability, bulk conductivity, and density, as summarized in Table 2. These parameters provide a practical reference for future experimental validation and potential large-scale deployment in real-world smart city environments. This methodology enables assessment of the embedded monopole antenna's performance using standard structural geometries and Sub-GHz communication requirements.

3 RESULTS AND DISCUSSION

The electromagnetic performance of an embedded metallic monopole antenna, designed using a galvanized hollow steel in a concrete column structure, was evaluated through full-wave simulation in Ansys HFSS. The monopole antenna was modeled with an optimized height of 9.7 cm, corresponding quarter-wavelength at the target frequency of 700 MHz, to ensure more efficient performance. This section presents the return loss characteristics, radiation behavior, and implications for smart city communication infrastructure.

3.1 Return Loss and Resonant Frequency

The simulated return loss of the embedded monopole antenna is presented in Figure 5.

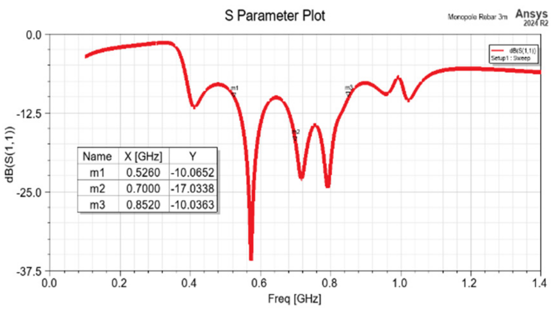


Figure 5. Simulated Return Loss.

A distinct resonance is observed at 700 MHz with a return loss of −17.03 dB, indicating efficient impedance matching and minimal reflection at the feed point. The −10 dB bandwidth spans approximately 326 MHz, covering the frequency range from 526 MHz to 852 MHz, which is remarkably wide and sufficient to accommodate multiple LPWAN technologies such as NB-IoT (Narrowband IoT) and LoRaWAN (Long Range Wide Area Network). The exceptionally broad bandwidth ensures robust performance over a wide range of operating frequencies, enhancing the antenna's versatility for sub-GHz applications. The pronounced return loss together with the accurate resonant frequency validates the effectiveness of the antenna's structural dimensioning and integration within the concrete medium.

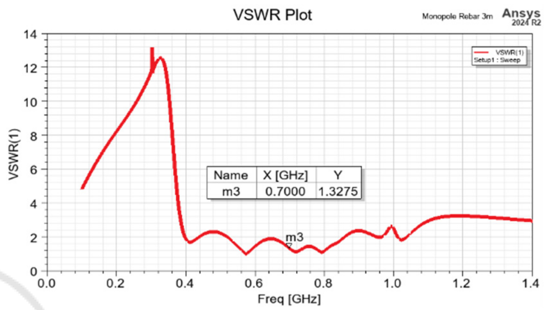


Figure 6: Simulated VSWR.

To further validate antenna matching quality, simulated VSWR (Voltage Standing Wave Ratio) values were evaluated as shown in Figure 6. The antenna achieves a VSWR of less than 1.33 at the resonant frequency (700 MHz) and maintains VSWR values well below 2 throughout the operating bandwidth (526–852 MHz). These results clearly demonstrate excellent impedance matching and efficient power transmission, making the antenna highly suitable for low-power IoT communication in smart city deployments.

These results confirm the theoretical prediction based on monopole resonance, validating that the physical dimension of the structure supports quarter-wavelength operation. The sharpness of the resonance peak and low return loss indicate that the structure behaves as a high quality passive radiator suitable for sub-GHz IoT applications (Rita et al., 2022).

3.2 Radiation Characteristics

The radiation characteristics were evaluated to assess the antenna's directionality and gain performance. The 2D (two-dimensional) patterns provide angular cuts in the principal planes (E-plane and H-plane) to analyze radiation symmetry and beamwidth, whereas the 3D patterns offer a complete spatial visualization of power distribution. Together, these evaluations deliver critical insights into the antenna's coverage efficiency and its capability to radiate power effectively toward the intended direction.

The radiation characteristics, specifically the 2D radiation pattern, were evaluated to assess the antenna's directionality and gain performance, as illustrated in Figure 7.

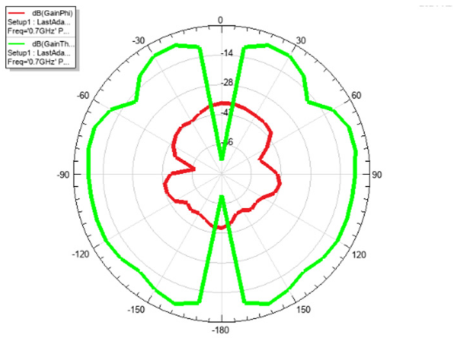


Figure 7: Radiation Pattern.

The 2D polar plots indicate that the H-plane (Phi=0°–360°) radiation pattern is nearly omnidirectional, providing predominantly uniform horizontal coverage around the monopole, which is advantageous for consistent signal reception in all azimuthal directions.

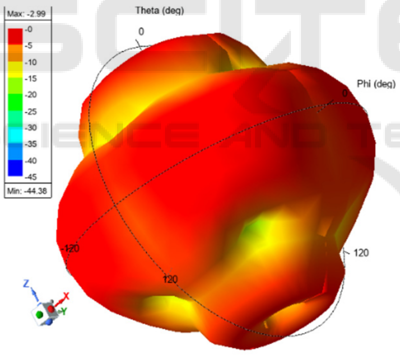


Figure 8: Gain 3D Polar Plot.

As shown in Figure 8, the E-plane (Theta) exhibits a doughnut-shaped pattern with nulls at 0° and 180°, characteristic of monopole antennas. The 3D radiation pattern further confirms uniform power distribution in the horizontal plane, with radiation concentrated around (θ=90°), while maintaining symmetry and minimal backlobes.

The peak realized gain of 2.99 dBi, though moderate, is sufficient for embedded antenna in dense smart city environments where uniform short-range coverage is prioritized (Chen & Zheng, 2023). The combination of nearly omnidirectional H-plane coverage and typical E-plane behavior ensures reliable performance for sub-GHz LPWAN applications, such as NB-IoT and LoRaWAN, within built environments.

To achieve the radiation performance described above, the monopole antenna is embedded within a reinforced concrete column by replacing one of the stirrups in an eight rebars configuration. Compared to traditional monopoles fabricated on substrates (Hussain et al., 2022), this structural integration not only preserves the desired radiation characteristics but also provides a mechanically robust solution, allowing the metallic element to function simultaneously as reinforcement and as a radiating antenna. Such an approach aligns with previous investigations on building and wall integrated antenna systems (Vähä-Savo et al., 2022; Vähä-Savo et al., 2024), confirming that embedded antennas can meet the performance requirements for LPWAN deployment in smart city environments (Khan et al., 2024).

3.3 Application Potential in Smart City

The use of galvanized hollow steel as a functional antenna element enables seamless integration into urban structures while reducing costs, minimizing visual clutter, and maintaining both durability and aesthetics. The specifications summarized in Table 3 demonstrate that the proposed embedded quarter-wavelength monopole antenna satisfies the required electromagnetic performance targets as well as the practical considerations for smart city deployment.

Table 3: Specification and Requirements for Antennas in Sub-GHz IoT Smart City Applications.

Category	Specification / Requirement	Justification
Operating Frequency	700–960 MHz (target 700 MHz in this study)	Provides long-range coverage for LPWAN
Antenna Type	A quarter-wavelength monopole (embedded in structure)	Omnidirectional in H-plane; nulls on vertical axis E-plane; uniform street-level coverage
Impedance	50 Ω nominal; lumped port or coaxial feed	Matches standard IoT radio ports
Return Loss	$S_{11} \leq -10$ dB across operating band	Efficient power transfer and low reflection losses
VSWR	≤ 2.0 across operating band	Acceptable performance
Bandwidth	≥ 100 MHz	Complies with regulations

Peak Gain	0–3 dBi (≥ 1 dBi desirable)	Adequate link budget

3.4 Practical Considerations and Limitations

Passive embedded antennas present notable advantages such as resilience to weather conditions, resistance to vandalism, and minimal maintenance requirements, making them promise for long-term deployment in smart city infrastructures (Shailesh et al., 2024).

Nevertheless, several practical considerations and limitations must be carefully addressed. From a material perspective, galvanized hollow steel, although highly conductive, is still vulnerable to corrosion over time, particularly in humid or coastal environments where gradual deterioration of the zinc layer may contribute to increased RF losses. When antennas are embedded in concrete, the relatively high dielectric constant ($\varepsilon_r = 6.5$) and loss tangent ($\tan \delta = 0.02$) introduce dielectric loading that shifts the resonance frequency and decreases radiation efficiency.

Moreover, variability in concrete composition, moisture content, and curing conditions leads to inconsistent dielectric properties, thereby complicating accurate antenna tuning. Consequently, antenna dimensions require careful optimization to preserve resonance at the desired frequency despite the dielectric loading effect.

Beyond electromagnetic aspects, structural and mechanical factors also pose challenges. Embedded antennas must withstand long-term mechanical loading, thermal expansion, and vibrations within the building structure, while any misalignment during installation can permanently alter the radiation pattern or coverage area since repositioning is not possible once integrated. Environmental influences, such as seasonal humidity variations, temperature cycling, and pollution, further exacerbate these challenges by modifying both the conductivity of metals and the dielectric characteristics of concrete. In addition, proximity to reinforcement bars, electrical wiring, or other metallic components may introduce parasitic coupling and electromagnetic interference that detune the antenna and degrade system performance.

To mitigate these limitations, several strategies have been proposed, including the adoption of reconfigurable antenna designs, adaptive impedance matching, and AI-based optimization techniques to dynamically maintain resonance under varying environmental conditions (Spachos et al., 2021; Mishra et al., 2022).

However, such approaches require further validation through long-term experimental studies, especially under real-world loading and environmental stresses. Therefore, while passive embedded antennas hold significant promise for smart city communication systems, their practical deployment demands careful material selection, robust design methodologies, and rigorous durability testing. Comprehensive experimental investigations will be addressed in future studies as a critical part of the research roadmap to ensure reliable performance over extended operational lifetimes (Majumder et al., 2025).

4 CONCLUSIONS

This study has demonstrated, through rigorous full-wave electromagnetic simulations, the novel contribution of employing galvanized hollow steel as an embedded passive monopole antenna within reinforced concrete columns for sub-GHz IoT communication in smart city infrastructure.

By utilizing the inherent conductivity of galvanized hollow steel within structural elements, a 9.7 cm monopole designed for operation at 700 MHz achieved efficient impedance matching (−17.03 dB return loss), a wide operational bandwidth (526–852 MHz), and an nearly omnidirectional radiation pattern with a peak gain of 2.99 dBi.

These findings confirm the feasibility of integrating communication functionality directly into construction materials, thereby supporting the development of smart urban infrastructure with minimal additional cost and adaptive structural modification.

This research demonstrates the embedding of passive antennas within concrete column structures, preserving their structural function while enabling sub-GHz IoT communication. The approach addresses practical urban challenges such as limited space, aesthetic integration, and efficient deployment, thereby supporting the development of scalable, resilient, and low-profile IoT networks for smarter and more sustainable urban environments.

Future research will focus on experimental validation of the embedded antenna and the evaluation of their performance under realistic environmental conditions. These studies aim to bridge the gap between theoretical design and practical implementation in complex urban scenarios, ensuring the embedded antenna operates reliably and maintains long-term durability.

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