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Transforming Building Infrastructure into Communication Systems for Smart City: A Conceptual Analysis of Metallic Structures as Antennas

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Abstract

The transformation of building infrastructure into intelligent communication systems is a key enabler of smart city development. This paper investigates the feasibility of utilizing metallic structural elements such as steel reinforcement bars, hollow sections, and galvanized steel as embedded antenna within building frameworks. To provide validated evidence, this work incorporates full-wave electromagnetic simulations using Ansys HFSS to analyze resonance behavior, impedance matching, radiation patterns, and gain performance in the sub-GHz band, particularly around 700 MHz for IoT applications. The simulation results demonstrate that selected building materials can achieve stable resonance and nearly omnidirectional radiation characteristics, with realized gains up to 0.47 dBi and bandwidths sufficient for LPWAN technologies such as NB-IoT and LoRaWAN. These findings confirm the dual functionality of structural metals, offering both mechanical strength and communication capability. The study provides a validated basis for future experimental prototyping and integration of antenna-embedded infrastructures in smart building environments.

Introduction

The rapid development of smart city concepts worldwide has accelerated the integration of communication technologies with physical urban infrastructure (Zaman et al., 2024; Whaiduzzaman et al., 2022). In this context, Low Power Wide Area Networks (LPWANs) have emerged as a key enabler for Internet of Things (IoT) applications, particularly in environments that demand energy efficiency, space optimization, and reliable connectivity (Ahmed Osman et al., 2020; Mahmood et al., 2022). One of the major challenges in urban IoT deployment lies in the placement of antenna systems that do not compromise the aesthetics, structural integrity, or spatial function of buildings (Hussain et al., 2022; Albzaie, 2024; Khan et al., 2024; Minoli et al., 2017).

To address this challenge, recent studies have explored the potential of metallic structural components, such as steel reinforcement bars (rebars), hollow steel sections, and galvanized steel, as passive antenna elements integrated into building structures (Tan et al., 2022; Um-e-Habiba et al., 2024). Such an approach offers dual functionality: structural support and electromagnetic performance, thus optimizing resource use and supporting the sustainability objectives of smart city (Kumar et al., 2024). Previous research indicates that metallic elements can exhibit electromagnetic resonance at sub-GHz frequencies when their dimensions match specific fractions of the wavelength (Vähä-Savo et al., 2022; Chen et al., 2023). While several studies have relied on conceptual analysis or limited experimental

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validation (Vähä-Savo et al., 2024), there remains a need for simulation-based optimization to assess the actual performance of such embedded antennas under realistic building material conditions.

In this study, several building material structures are analyzed to investigate their potential for integration with embedded antenna functionality. From this comparative analysis, one representative structure is selected for detailed electromagnetic evaluation using Ansys HFSS. The simulation considers the antenna embedded within a representative building material environment to evaluate its reflection coefficient (S11), impedance matching, and radiation characteristics in the sub-GHz range (Gao, 2016; Jocqué et al., 2024). This approach bridges the gap between theoretical dimensioning and practical performance assessment, enabling a more accurate evaluation of feasibility before physical prototyping.

The objective of this paper is to present both the theoretical design process and simulation-based optimization results, highlighting how structural metallic elements could be utilized as embedded passive antennas for LPWAN applications. By integrating the communication function into existing structural elements, this research contributes to the development of efficient and aesthetically compatible smart building infrastructure for IoT-based smart city networks (Khan et al., 2024).

Methods

This study employs a combined theoretical and simulation-based research approach. The methodology consists of several structured stages:

Selection and Justification of Structural Antenna Element

The current investigation has been initiated by an in-depth study of the metallic materials that form the foundation of buildings in urban structures. Instead of taking a traditional, manufacturing-oriented approach to the design of antennas, the case study raised a different question: can materials that, by their very nature, serve as structural imperatives, also have enough electromagnetic agency to play any communicative role without undermining their structural responsibilities? Reinforcement bars, beams, steel plates, hollow rectangular cross-sections, and coated vertical supports were thus not considered as already engineered radiators, but as would-be latent radiators which could support high-frequency currents.

In this larger context, hollow rectangular forms which were made out of hot-dip galvanized steel were chosen as the main simulation specimen. The choice criteria was based on pragmatism rather than aesthetics: these hollow sections will be positioned in vertical structural location that will allow a consistent and uninterrupted current flow; these hollow sections will be conductively reliable even following galvanization; and the hollow sections will be durable enough to justify long term inclusion in infrastructure without having to be overly maintained or replaced. Moreover, the geometry of hollow hollow rectangular steel sections is inherently predictable in a current-flow perspective, and this makes it possible to have a useful theoretical resonance model well before that simulation can be refined..

Material Electromagnetic Parameter Modeling

When the structural prototype has been selected, the emphasis of the research shifted to the material modeling. The analysis made the intention to avoid idealized assumptions; instead electromagnetic constants of standard building materials were used. Conductivity and magnetic permeability of steel core were specified based on values found in literature of structural-grade galvanized steel, which recognizes that the zinc coating does not override the conductive characteristic of the underlying steel. The relative permittivity of concrete as the embedding medium in most urban columns was given a representative value that most urban columns are made of dry, cured, construction-grade concrete.

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The fact that concrete was viewed as a signal-attenuating medium did not receive any consideration as a reason why it should not be used; instead, it was seen as an inseparable environmental factor. Any infrastructure embedded must deal with the dielectric properties of concrete; therefore, realistic permittivity and low conductivity values allowed the simulation to recreate the predicted radio coupling, resonance shift and impedance loss that would occur realistically under the conditions of architectural embedding, rather than artificially enhancing the suitability of the material to support wireless performance.

Theoretical Antenna Dimensioning

The antenna geometry initialisation was based on an analytical reasoning and, as such, the design was not based on the well-founded electromagnetic theory but without laying any very strict boundaries. Classical half-wave dipole relationships were used to obtain an approximate electrical length at the desired operating frequency of 700 00 MHz. In free space, the half-wavelength of the corresponding dipole is approximately 21.43 1 cm, which is used to form two 10.71 cm dipole arms. The method provides an initial point of reference as opposed to a final specification, allowing the model to be constructed physically with purpose of later computational enrichment.

The conductor diameter, dielectric loading and the coupling effects of the nearby metallic structures of the embedded radiators, especially in reinforced concrete applications, are bound to affect the embedded radiators; thus, the length theoretically was expected to vary during simulation. This was expected evolution and not denied and geometric reduction or resonance migration were treated as inherent in the design interpretation and not as artefacts of model inaccuracy.

3D Electromagnetic Simulation and Numerical Optimization

Ansys HFSS was applied in the overall three dimensional modelling and field analysis. It was selected due to the fact that the solver allows analysis of the metallic geometry of dielectrically loaded structures in realistic conditions and it also offers the ability to control the radiating of the boundary, and this makes it suitable in a study that considers buildings as spectrum-interacting systems, as opposed to an antenna accessory. The dipole form was laid inside a simplified concrete column which has 4 parallel stainless-steel rebars which represent a plausible structural hosting situation without having to confuse the geometry with architecturally ornamental asymmetry.

To match the excitation of a low-power transceiver in the IoT without necessarily assuming direct contact of metal and concrete at the feed point, a 2cm vacuum gap was placed around the modeled dipole arms. This is not a gap that was to exclude dielectric influence but simply to add it more controllably, so that the behavior of power reflection and VSWR can be more easily understood and yet material proximity sufficient to induce realistic resonance contraction is preserved. The adaptive meshing would be resumed until convergence of electromagnetic field is achieved and the frequency is then swept to 100MHz to 1,000 MHz to ascertain the presence of resonance, impedance movement, robustness of allowed bandwidth and continuity of azimuthal planes radiations.

By trial and error through manipulation of the numbers the dipole obtained a steady resonant state at a shortened total length 18.8 cm, equivalent to 9.4 cm/arm. This geometric contraction was seen as a result of dielectric loading and metallic coupling instead of distortion of parameters. The study did not impose the antenna on the theoretically accepted length of the antenna in free space, but instead kept record of the optimization direction to the real resonance as a sort of digital confirmation of the viability of structural antennas.

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Antenna Parameter Interpretation and Feasibility Assessment

The interpretation of the performance of antennas took place in a holistic approach, with S11 return loss used to give clarity to the resonance, VSWR stability used to determine the continuity of the impedance, azimuthal symmetry used to determine the credibility of the omnidirectional coverage, and realized gain used to give credibility to passive communication within the LPWAN transmission budgets. All these parameters were not discussed as independent goals but rather as a connected chain of viability indicators that identify the ability of the structural metal to act as a reliable low-profile passive antenna component in sub-GHz IoT systems.

This evaluation is deliberately not enhanced by adopting the antenna past the nature of passive dipolar systems, but rather it is presented as a built-in communication facilitator, which has not lost the structure (structural identity) but has still shown to be computationally feasible to be experimentally validated in the future. The methodological rationale of the study ends not with statements of an immediate deployment, but rather with a theoretical statement, that structural metals, when dimensioned using theoretical analysis and optimized using the full-wave simulation, can radiate with adequate effectiveness to warrant physical prototyping.

Results and Discussion

Conceptual Analysis of Metallic Structures

Reinforcement bars (rebars) and stirrups are critical metallic components embedded within concrete columns to provide tensile strength and shear resistance in structural systems. Rebars, typically made of carbon steel, act as the primary load-bearing elements, while stirrups encase them in looped configurations to resist shear forces and preserve the overall stability of the column. Together with the surrounding concrete, these components form reinforced concrete columns, widely used for their strength and durability.

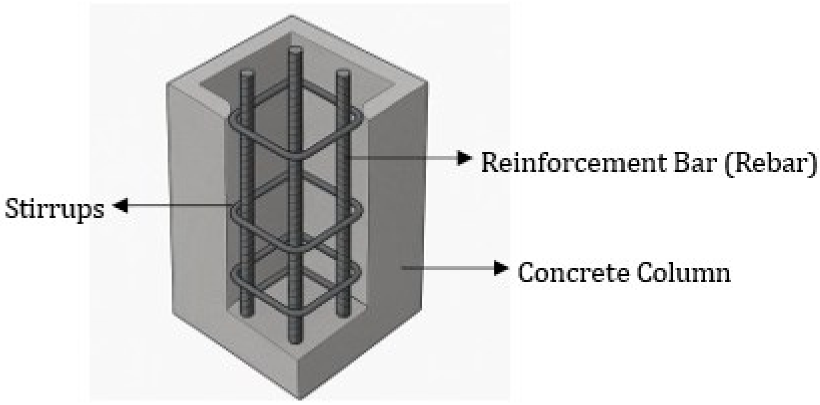

Figure 1. Structural Elements

From an electromagnetic perspective, concrete behaves as a dielectric medium with very low conductivity, causing significant attenuation of wireless signals. Although rebars and stirrups are metallic in principle, their low electrical conductivity within concrete renders them unsuitable as effective radiating elements (Vizi et al., 2016; Barbhuiya et al., 2025; Azarsa & Grupta, 2017). Therefore, to enable embedded antenna functionality, a selected metallic structural element with higher conductivity and accessible geometry is considered for integration within the concrete environment.

The structural elements examined in this study, including WF beams, hollow structural sections, U-channel (UNP) and C-channel (CNP), L-angle steel, steel plates, and steel pipes, were further assessed according to their material composition. Table 1 provides a comparative

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overview of their physical properties, typical applications, and potential for integration as embedded antennas within smart building systems.

Table 1. Conceptual Evaluation of Metallic Structural Elements for Antenna Integration

Structural Element	Material	Conductivity (S/m)	Relative Permeability (μr)	Relative Permittivity (εr)	Antenna Suitability	Potential Antenna Type	Common Application
WF Beam	Structural Steel	6.99×10^6	100	1	High	Dipole, Patch, Monopole	Heavy structural beams, bridges, multi-story buildings
Hollow Structural Sections	Galvanized Steel	1.6×10^6	100	1	High	Dipole, Monopole, Slot Antenna	Columns, beams, roof frames, truss structures
UNP (U-Channel) & CNP (C-Channel)	Carbon Steel	5×10^6	100	6–12	Medium	Slot Antenna	Roof frames, wall framing, structural supports
Angle Steel (L-Angle)	Carbon Steel	5×10^6	100	6–12	Medium	Reflector Element, Yagi-Uda Structure	Door/window frames, structural supports, storage racks
Steel Plate	Carbon Steel	5×10^6	100	6–12	High	Patch Antenna, Ground Plane Reflector	Structural flooring, wall cladding, roof decking, panels
Steel Pipes	Galvanized Steel	1.6×10^6	100	1	High	Dipole, Loop, Monopole Antenna	Structural columns, telecom towers, vertical supports
Reinforcing Bar	Carbon Steel	5×10^6	100	6–12	Low	Not Recommended	Concrete columns, beams, slabs
Concrete Column (Without Rebars)	Concrete	$10^2 - 10^3$	1	6–12	Not Suitable	Not Applicable	Structural support columns

Among the evaluated structural elements, several exhibit high potential for integration as embedded antennas due to their combination of mechanical robustness, high electrical conductivity, and favorable geometry. WF beams, hollow structural sections, and steel pipes demonstrate high conductivity and relative permeability, which support efficient electromagnetic radiation. Their shapes also allow the implementation of various antenna types, including dipoles, loops, monopoles, and patch antennas.

Hollow galvanized steel sections were selected as the representative material for simulation because of their availability, structural durability, corrosion resistance, and geometry suitable for embedding within concrete (Cao et al., 2022; Wang, 2025; Al Nuaimi et al., 2020). Following this selection, the antenna was designed using classical antenna theory to assess its resonance behavior and electromagnetic performance in a concrete environment.

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Antenna Configuration and Simulation

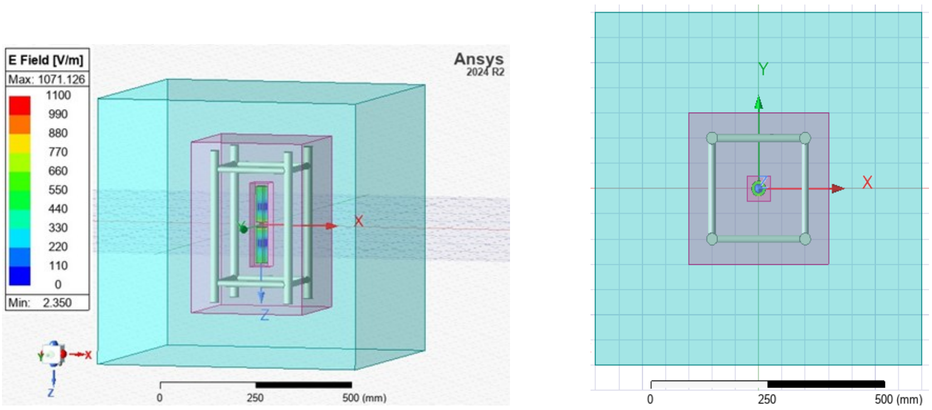
The initial design was based on a half-wave dipole configuration, where each arm corresponds to a quarter-wavelength of the target frequency. The dipole length was calculated using standard resonance formulas, as presented in the following equations:

$$\text{Dipole antenna length} \quad : L = \frac{c}{f} = \frac{\lambda}{2} \qquad (1)$$

$$\text{Each arm (quarter-wave)} \quad : L = \frac{c}{f} = \frac{\lambda}{4} \qquad (2)$$

where c represents the speed of light in vacuum (approximately 3 x 108 m/s) and f denotes the operating frequency in hertz (Hz). For the target sub-GHz LPWAN frequency of 700 MHz, the half-wave dipole length is 21.43 cm, with each arm measuring approximately 10.71 cm.

The half-wave dipole antenna was modeled as embedded within a reinforced structural column by replacing one of the stirrups in an arrangement of four stainless steel rebars, as shown in Figure 2. The surrounding concrete and metallic components were assigned their respective dielectric and conductive properties in the simulation. The optimized embedded dipole exhibited resonance at a total length of 18.8 cm (9.4 cm per arm), which is shorter than the theoretical λ/2 value at 700 MHz. This reduction is attributed to conductor diameter effects, dielectric loading from the concrete, and electromagnetic coupling with adjacent rebars.



(a) (b)

Figure 2. Simulation Model: (a) Trimetric, (b) Top View

Electromagnetic analysis is performed with Ansys HFSS (High Frequency Structure Simulator), a full-wave three-dimensional solver based on the finite element method (FEM) and extensively utilized in the design of antennas and electromagnetic structures. HFSS is selected owing to its ability to accurately represent intricate geometries, integrate comprehensive material characteristics, and evaluate antenna performance under practical structural and environmental scenarios.

The simulation model consists of an air box with radiation boundary conditions and a concrete column structure. A half-wave dipole antenna is embedded within the column, with a lumped port placed at the feed gap between the two dipole arms to emulate excitation from an IoT transceiver. To prevent direct interaction with the concrete, the dipole is surrounded by a vacuum region of approximately 2 cm. This configuration ensures that the antenna is not immediately influenced by the concrete medium, thereby enabling precise evaluation of its reflection coefficients and electromagnetic field distributions while considering its integration within structural elements. Adaptive meshing is employed, and a frequency sweep from 100

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MHz to 1.000 MHz are applied to ensure accurate and reliable simulation results. The key simulation parameters for the embedded metallic structures are presented in Table 2.

Table 2. Simulation Parameters

Parameter	Value
Target Frequency	700 MHz
Frequency Range	100–1,000 MHz
Antenna Type	Half-Wave Dipole
Antenna Material	Galvanized Hollow Steel
Physical Length	21.43 cm
Optimized Length	18.8 cm
Hollow Dimensions	1.5 × 1.5 cm (outer) / 1.28 × 1.28 cm (inner)
Wall Thickness	0.11 cm
Reinforcing Bar	4 Carbon Steel
Stirrup Spacing	15 cm
Embedding Medium	Concrete
Boundary Condition	Radiation (Open)
Excitation	Lumped Port 50 Ω (Base)

Interpretation of Results

The antenna performance is assessed using the following fundamental electromagnetic parameters: (1) Return loss (S11), which indicates the resonance frequency and the quality of impedance matching; (2) Radiation pattern, used to evaluate the omnidirectional coverage that is characteristic of half-wave dipole antennas; and (3) Gain, which reflects the efficiency of power conversion and the suitability of the antenna for low-power IoT applications.

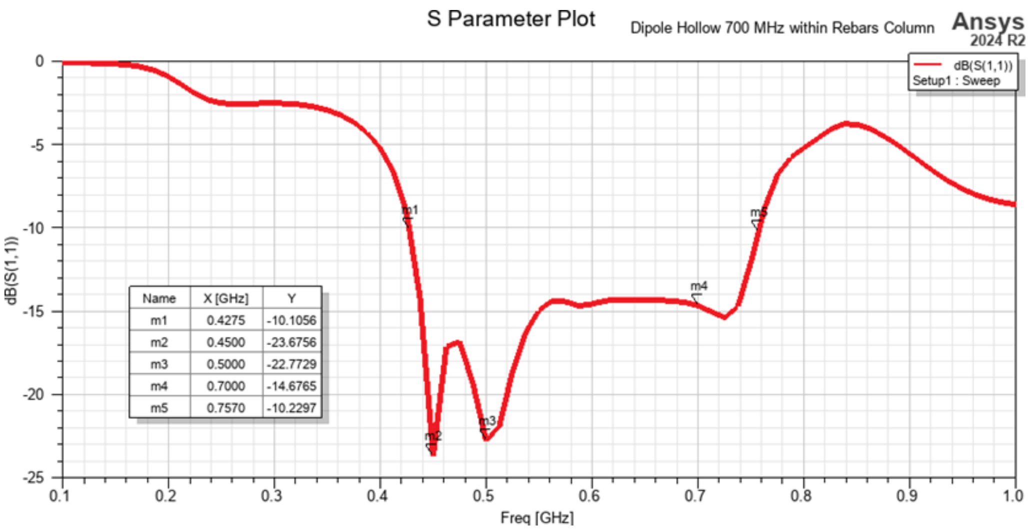

Figure 3. Simulated Return Loss of Embedded Dipole Antenna

A distinct resonance is achieved at the target operating frequency of 700 MHz, yielding a return loss of −14.68 dB, which demonstrates effective impedance matching with minimal signal reflection at the feed point. The −10 dB bandwidth reaches approximately 329 MHz, covering a wide frequency range from 428 MHz to 757 MHz. This exceptionally broad bandwidth ensures robust compatibility with various low-power wide-area network (LPWAN) standards, including NB-IoT and LoRaWAN.

To further evaluate the antenna's matching performance, the simulated VSWR results are shown in Figure 4. The antenna maintains a VSWR below 1.45 at frequency 700 MHz and remains well under 2 across the entire 428–757 MHz spectrum. These outcomes confirm the

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antenna’s excellent impedance characteristics, wideband capability, and efficient power transmission, underscoring its strong potential for low-power IoT communications in smart city environments.

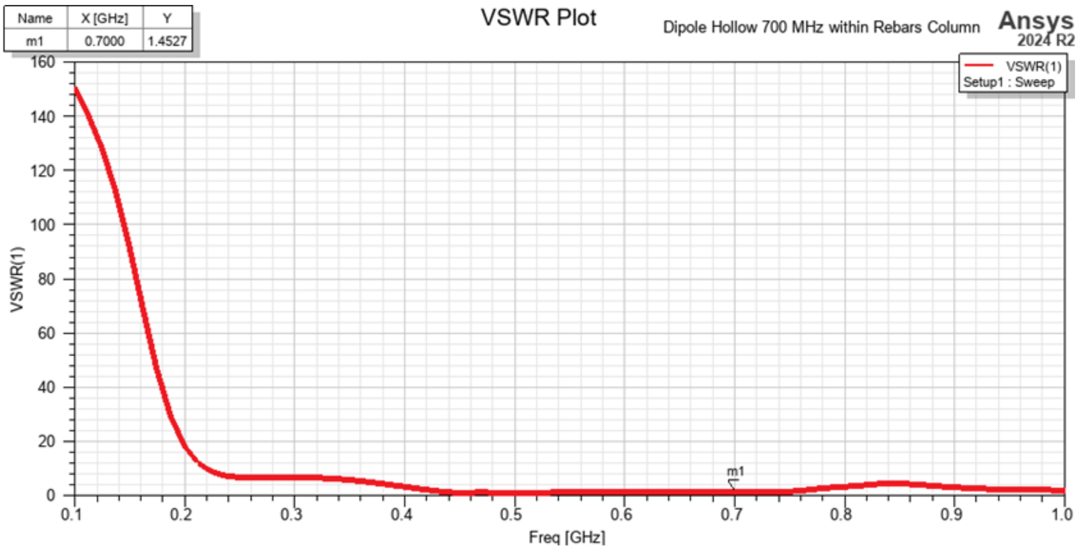
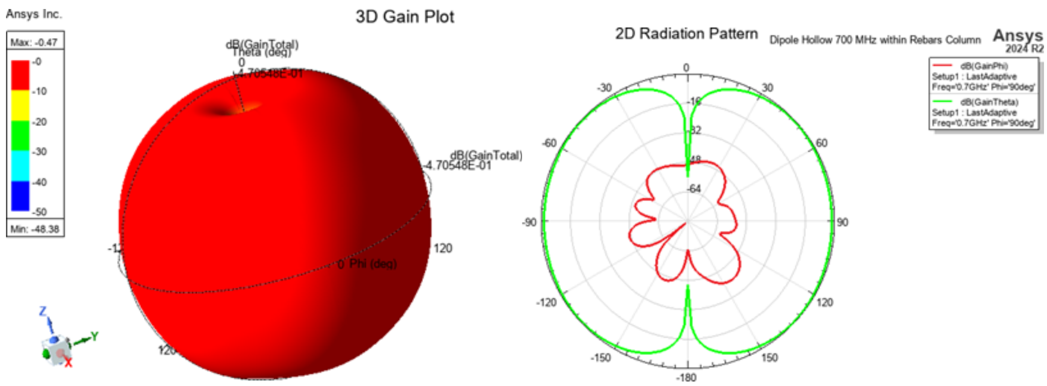


Figure 4. Simulated VSWR of Embedded Dipole Antenna

The radiation characteristics were evaluated in both 3D and 2D to assess directionality and gain performance, as shown in Figure 5. The results indicate a nearly omnidirectional pattern, making the antenna suitable for wide-area IoT coverage.



(a) *(b)*

Figure 5. Radiation Characteristics: (a) Gain 3D Polar Plot, (b) 2D Radiation Pattern

As illustrated in Figure 5(a), the 3D radiation pattern exhibits a peak realized gain of 0.47 dBi, with the radiated power concentrated around θ = 90°. The distribution remains symmetric with minimal backlobes, ensuring stable coverage in the azimuthal plane. Although the gain is modest, it is well-suited for passive dipole antennas applied in dense smart city environments where uniform, short-range connectivity is prioritized (Shailesh et al., 2024).

The complementary 2D polar plots in Figure 5(b) further illustrate these characteristics. The H-plane (Φ = 0°–360°) exhibits a nearly omnidirectional response, confirming uniform horizontal coverage, whereas the E-plane (θ) displays the characteristic figure-eight, or doughnut-shaped, radiation pattern of dipole antennas, with nulls along the axis at 0° and 180°.

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The findings of this study align with recent advances in antenna-structure integration. Prior research has demonstrated that antennas can be embedded within building materials without compromising aesthetics or structural integrity, including 3D-printed transparent mesh antennas (Inclán-Sánchez, 2023), structurally embedded vascular antenna (SEVA) arrays (Bal et al., 2021), and antennas in composite materials verified through microwave NDT and X-ray computed tomography (Hassan et al., 2024). Building upon these developments, this study explores the potential of conventional metallic structural elements, such as rebars, hollow sections, and steel stirrups, to function simultaneously as load-bearing and communication components. Such integration addresses common challenges in urban IoT deployment, including limited installation space, aesthetic considerations, and infrastructure costs, while supporting smart city objectives for reliable, discreet, and cost-efficient connectivity (Milarokostas et al., 2022; Salih et al., 2025; Mahomed & Saha, 2025; Goumopoulos, 2024).

Embedding antennas into structural elements offers promising solutions for smart city IoT deployment, but several limitations exist. Material properties, geometry, and surrounding environment directly affect performance, while structural constraints may restrict optimal placement (Lee & Xie, 2022; Alhembar et al., 2023; Zhou et al., 2023). Maintenance and inspection are challenging once antennas are integrated into permanent structures, and environmental factors such as moisture, temperature, and corrosion can degrade functionality. Regulatory compliance and safety must also be considered. Finally, while simulations indicate feasibility, experimental validation in real-world urban conditions is necessary to confirm performance under complex propagation and interference scenarios.

Future research will focus on the experimental validation of embedded antennas and the evaluation of their performance under realistic environmental conditions. These studies will form part of a broader research roadmap aimed at bridging the gap between theoretical design and practical implementation in complex urban scenarios, ensuring reliable operation, long-term durability, and effective integration of communication functionality within structural elements.

Conclusion

This conceptual study explores the potential of transforming conventional metallic structural elements, such as rebars, hollow sections, and steel stirrups, into passive antennas for low-power IoT communication in smart city environments. For the simulation, a half-wave dipole using galvanized hollow was selected as the representative antenna element, embedded within a reinforced concrete column with rebars. Simulation results indicate a distinct resonance at 700 MHz with a return loss of −14.68 dB, a −10 dB bandwidth of approximately 329 MHz (428–757 MHz), and a peak realized gain of 0.47 dBi. The antenna exhibits a VSWR below 1.45 at 700 MHz and remains under 2 across the operating bandwidth, while the radiation pattern shows an omnidirectional H-plane and a figure-eight E-plane typical of dipoles.

Integrating communication capability directly into building materials addresses key challenges in urban IoT deployment, including space constraints, aesthetic concerns, and infrastructure costs. Despite these promising findings, practical deployment requires careful consideration of material properties, installation constraints, and long-term reliability. Future research, as part of a comprehensive research roadmap, will focus on experimental validation and performance assessment under realistic environmental conditions to ensure effective, durable, and efficient operation.

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