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An Integrated Soil–RFID Electromagnetic Interaction Model for Passive UHF Soil Moisture Sensing

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Abstract- ***Passive ultra-high-frequency (UHF) radio-frequency identification (RFID) systems provide a battery-free platform for soil moisture sensing; however, their performance is strongly influenced by moisture-dependent dielectric loading of the surrounding soil. Existing RFID-based sensing approaches are largely empirical and do not establish a predictive relationship between soil dielectric properties and antenna electromagnetic response. This paper presents an integrated soil–RFID electromagnetic interaction model that links volumetric soil moisture content (θ) to antenna resonant frequency and input impedance through dielectric representation and full-wave electromagnetic simulation. Soil dielectric properties are modelled as complex permittivity and incorporated into electromagnetic simulations of a passive UHF RFID tag embedded in sand, loam, and clay soils over a moisture range of 0–20%. The results show a monotonic decrease in resonant frequency with increasing moisture, with sensitivities ranging from −30 to −38 MHz/% depending on soil type. Input impedance variation and radiation efficiency degradation are observed due to increased dielectric loss, resulting in gain reduction of up to 4–6 dB under high moisture conditions. A dual-mode resonance tracking approach is implemented to maintain continuous frequency extraction across the full moisture range. Analytical models describing the dependence of resonant frequency and impedance on soil moisture demonstrate strong agreement with simulation data, with coefficient of determination (R^2), ranging from 0.92 to 0.97 and low root mean square errors across all parameters. The proposed model provides a predictive framework for analysing soil–antenna interaction and enables reliable RFID-based soil moisture sensing without reliance on empirical calibration.***

Keywords- Passive UHF RFID, Soil Moisture Sensing, Dielectric Permittivity, Electromagnetic Modelling, Antenna Detuning, Resonant Frequency, Input Impedance, Dual-Mode Resonance, RFID Sensors, Wireless Sensing.

I. INTRODUCTION

Passive ultra-high-frequency (UHF) radio-frequency identification (RFID) systems enable battery-free sensing through electromagnetic coupling between the reader and tag antenna. In such systems, the antenna interacts directly with the surrounding medium, and its electromagnetic behaviour is strongly influenced by the dielectric properties of that environment. In soil-based sensing applications, variations in volumetric water content θ modify the complex dielectric permittivity of the soil, which governs electromagnetic wave propagation, impedance behaviour, and antenna resonance characteristics [4]–[6], [11], [12], [14]. Passive RFID-based soil moisture sensing exploits these interactions indirectly. As soil moisture increases, the effective permittivity of the surrounding medium increases due to the high dielectric constant of water. This results in antenna detuning, impedance variation, and degradation in radiation efficiency, which manifest as measurable changes in resonant frequency, backscatter response, and received signal strength [1]–[3], [9], [15]. Several studies have demonstrated the feasibility of RFID-based soil moisture sensing using indirect observables [15], [16], [23]. Signal strength–based sensing using commercial UHF RFID tags was reported in [1], while resonance-based sensing approaches demonstrated frequency sensitivities in the range of −3.9 to −4.8 MHz/% volumetric water content [2]. Impedance-based sensing techniques exploiting antenna detuning were also investigated in [3]. Although these approaches confirm the viability of RFID sensing, they are largely empirical and require calibration for specific soil conditions, limiting their generalizability. From a modelling perspective, classical dielectric mixing models provide relationships between soil moisture and bulk permittivity. Empirical and semi-empirical formulations such as those reported in [4]–[6], [20]–[22] capture the dependence of permittivity on moisture content, frequency, and soil texture. However, these models are primarily developed for microwave remote sensing and do not predict antenna-level electromagnetic parameters such as resonant frequency f_{res}, input impedance Z_{in}, or radiation efficiency under UHF RFID operation. Conversely, RFID antenna studies have examined resonance detuning and performance degradation under dielectric loading conditions. It has been shown that increases in surrounding permittivity lead to shifts in resonant frequency and reduced radiation efficiency [7], [8], [11]. However, these studies typically treat the surrounding medium as a static dielectric and do not incorporate moisture-dependent dielectric modelling.

As a result, there is currently no unified modelling framework that directly links:

i. volumetric soil moisture θ,
ii. soil dielectric properties, and
iii. RFID antenna electromagnetic response (f_{res}, Z_{in}).

This limitation prevents predictive modelling of RFID-based soil moisture sensing systems and necessitates reliance on empirical calibration. The proposed model combines dielectric representation of soil with full-wave electromagnetic simulation to predict antenna response under varying moisture conditions. Unlike existing empirical approaches, the model provides a predictive and physically grounded framework for analysing soil–antenna interaction, enabling improved robustness across soil types and reducing dependence on calibration.

II. LITERATURE REVIEW

A. RFID-Based Soil Moisture Sensing

RFID-based sensing has been widely investigated as a low-cost and battery-free approach for environmental monitoring. In passive UHF RFID systems, sensing is achieved indirectly through changes in antenna electromagnetic response caused by variations in the surrounding medium. Several studies have demonstrated soil moisture estimation using commercial RFID tags [1]-[3], [14]-[16], [23]. Signal strength–based approaches were reported in [1], where variations in received signal strength indicator (RSSI) were correlated with soil moisture content. Resonance-based sensing techniques have also been explored, with measured frequency sensitivities in the range of −3.9 to −4.8 MHz/% volumetric water content [2]. In addition, impedance-based sensing methods exploiting antenna detuning were presented in [3], [14]-[16], [23] where variations in input impedance were used as a sensing metric. While these studies confirm the feasibility of RFID-based soil moisture sensing, they rely primarily on empirical relationships between measured observables and moisture content. Such approaches require calibration for specific soil types and environmental conditions, limiting scalability and generalization.

B. Soil Dielectric Modelling

The relationship between soil moisture and dielectric properties has been extensively studied using dielectric mixing models. Early empirical formulations, such as the model proposed in [4], relate volumetric water content to bulk permittivity. Semi-empirical models, including [5], incorporate frequency dependence and soil texture effects, enabling improved accuracy across a range of conditions. More advanced dielectric models, such as those described in [6], [20], account for the contributions of bound and free water within the soil matrix. Additional formulations incorporating temperature-dependent and frequency-dependent behaviour of water have also been reported in [21], while field-scale dielectric behaviour has been analysed in [22]. These models provide accurate estimation of soil permittivity as a function of moisture content, frequency, and soil composition. However, they are primarily developed for microwave remote sensing and geophysical applications, and do not directly predict antenna-level electromagnetic parameters such as resonant frequency or input impedance in RFID systems.

C. RFID Antenna Behaviour under Dielectric Loading

The performance of RFID antennas is strongly influenced by the surrounding dielectric environment. When an antenna is embedded in or placed near a material with higher permittivity, its effective electrical length increases, resulting in a shift in resonant frequency. Studies such as [7] investigated the effect of dielectric loading on antenna resonance and impedance behaviour, demonstrating that increases in permittivity lead to frequency detuning and impedance mismatch. Experimental investigations in [8] further showed that embedding RFID tags in lossy media such as soil leads to significant reductions in radiation efficiency and read range [17], [18]. From an electromagnetic perspective, these effects are governed by fundamental antenna theory and wave propagation principles [11], [12]. However, most existing studies treat the surrounding medium as a static dielectric and do not incorporate moisture-dependent dielectric variations.

III. METHODS

3.1 MODEL DEVELOPMENT

A. Modelling Framework

The proposed model establishes a direct relationship between volumetric soil moisture content θ, soil dielectric properties, and antenna electromagnetic response. The modelling framework is defined by the sequential mapping:

$$\theta \rightarrow \varepsilon_r^* \rightarrow (f_{res}, Z_{in}) \qquad (1)$$

where:
ε_r^* is the complex dielectric permittivity,
f_{res} is the antenna resonant frequency,
$Z_{in} = R_{in} + jX_{in}$ is the antenna input impedance.
The framework integrates dielectric modelling with full-wave electromagnetic simulation to extract antenna response parameters across varying moisture conditions. The modelling workflow is illustrated in Fig. 1, which presents the integrated mapping from soil moisture to dielectric properties and antenna electromagnetic response.

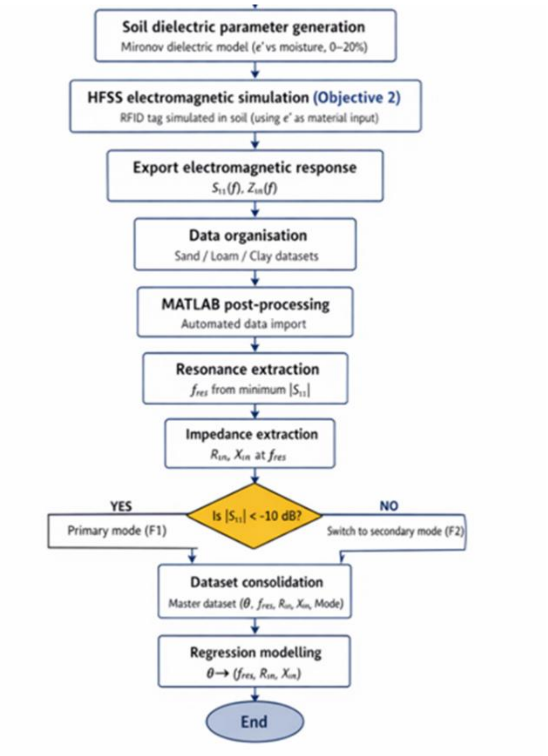


Fig. 1. Integrated soil–RFID electromagnetic modelling workflow

B. Soil Dielectric Representation

The dielectric behaviour of soil is represented using complex permittivity:

$$\varepsilon_r^* = \varepsilon' - j\varepsilon'' \qquad (2)$$

where:
ε' represents energy storage,
ε'' represents dielectric loss.
The imaginary component is related to effective conductivity σ as:

$$\varepsilon'' = \frac{\sigma}{\omega\varepsilon_0} \qquad (3)$$

where:
$\omega = 2\pi f$ is angular frequency,
ε_0 is the permittivity of free space.
The dielectric properties of soil are functions of moisture content, frequency, and soil texture:

$$\varepsilon_r^* = f(\theta, f, \text{texture}) \qquad (4)$$

This formulation is consistent with established dielectric mixing models [4]–[6], [20]–[22].

C. Electromagnetic Interaction with RFID Antenna

When the RFID antenna is embedded in soil, the surrounding dielectric medium electrically loads the antenna, modifying its effective wavelength and current distribution.

The resonant frequency is related to the effective permittivity as:

$$f_{res} \propto \frac{1}{\sqrt{\varepsilon_{eff}}} \qquad (5)$$

An increase in soil moisture leads to an increase in ε_{eff}, resulting in a reduction in resonant frequency. This behaviour is consistent with antenna theory and dielectric loading effects [7], [8], [11].

D. Input Impedance Variation

The antenna input impedance is expressed as:

$$Z_{in} = R_{in} + jX_{in} \qquad (6)$$

where:
R_{in} represents radiation and loss resistance,
X_{in} represents reactive components.

Variations in soil permittivity affect both components:
Increased dielectric loss increases resistive losses
Increased permittivity alters reactive energy storage
The dependence of impedance on moisture content is expressed as:

$$Z_{in} = f(\theta) \quad (7)$$

Impedance variation is governed by dielectric loading and conductive losses, which affect antenna–chip matching conditions [9], [10], [13].

E. Full-Wave Electromagnetic Simulation

The antenna electromagnetic response is obtained using full-wave electromagnetic simulation, where the RFID tag is embedded in a soil domain characterized by moisture-dependent dielectric properties.

Simulation conditions:
Frequency range: 860–960 MHz (UHF band)
Moisture range: $\theta = 0\%$ to 20%
Soil types: sand, loam, clay
Extracted parameters: Resonant frequency f_{res}, Input impedance (R_{in}, X_{in}), Radiation efficiency (η) and Realized gain (G).

F. Dual-Mode Resonance Tracking

Under increasing dielectric loading, the primary resonance may weaken or shift outside the operational band. To maintain continuous sensing capability, a dual-mode resonance tracking approach is implemented.
Let:
f_1: primary resonance
f_2: secondary resonance
The tracking condition is defined as:

$$f_{\text{tracked}} = \begin{cases} f_1, & |S_{11}(f_1)| \leq -10 \text{ dB} \\ f_2, & \text{otherwise} \end{cases} \quad (8)$$

This ensures continuous extraction of resonant frequency across the full moisture range.

G. Empirical Model Formulation

Analytical relationships are derived from simulation data to describe the dependence of antenna parameters on soil moisture.
The resonant frequency is modelled as:

$$f_{res}(\theta) = a\theta^2 + b\theta + c \quad (9)$$

The input impedance components are expressed as:

$$R_{in}(\theta) = a_1\theta^2 + b_1\theta + c_1 \quad (10)$$

$$X_{in}(\theta) = a_2\theta^2 + b_2\theta + c_2 \quad (11)$$

where a, b, c are regression coefficients obtained from electromagnetic simulation data.

H. Model Output Parameters

The proposed model produces the following measurable outputs: Resonant frequency f_{res}(GHz), Input resistance $R_{in}(\Omega)$, Input reactance $X_{in}(\Omega)$, Radiation efficiency (η) and Realized gain (G).

These parameters form the basis for RFID sensing and system-level performance evaluation.

IV. RESULTS

A. Resonant Frequency Variation with Soil Moisture

The variation of resonant frequency f_{res} with volumetric soil moisture content θ , as shown in Fig. 2 for sand, loam, and clay, was extracted from full-wave electromagnetic simulations over the range $\theta = 0\%$ to 20%.

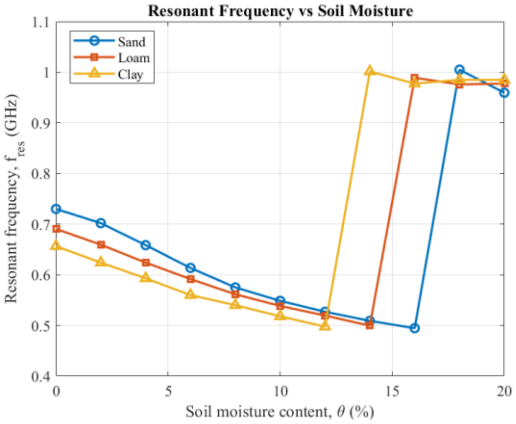


Fig. 2. Resonant frequency f_{res} versus volumetric soil moisture θ for sand, loam, and clay

A monotonic decrease in f_{res} is observed for all soil types as moisture content increases.
Extracted values:
Sand:
$f_{res}(\theta = 0\%) \approx 1.2168$ GHz
$f_{res}(\theta = 20\%) \approx 0.616$ GHz
Sensitivity: $\frac{df}{d\theta} \approx -30.0$ MHz/%
Loam:
$f_{res}(\theta = 0\%) \approx 1.2415$ GHz
$f_{res}(\theta = 20\%) \approx 0.4765$ GHz
Sensitivity: $\frac{df}{d\theta} \approx -38.25$ MHz/%
Clay:
$f_{res}(\theta = 0\%) \approx 1.1397$ GHz
$f_{res}(\theta = 20\%) \approx 0.5197$ GHz
Sensitivity: $\frac{df}{d\theta} \approx -31.0$ MHz/%

B. Input Impedance Variation

The real and imaginary components of antenna input impedance $Z_{in} = R_{in} + jX_{in}$ were extracted across the moisture range. The variation of antenna input impedance components with soil moisture is shown in Fig. 3 and Fig. 4.

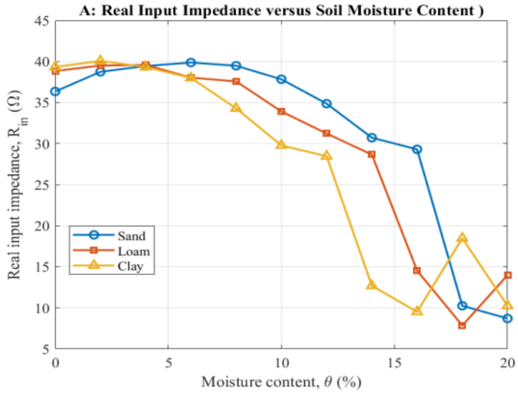


Fig. 3. Real input impedance versus moisture

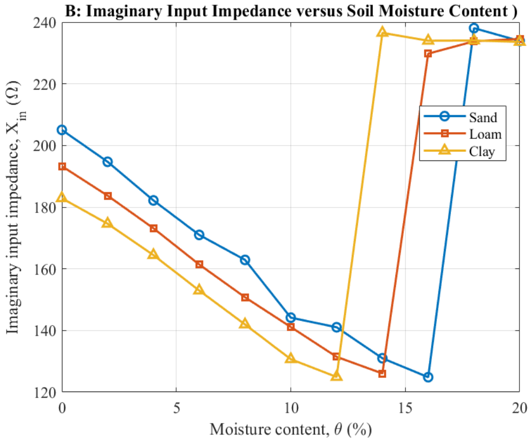


Fig. 4. Imaginary input impedance versus moisture

i. R_{in} increases with moisture, indicating increased dielectric loss and energy dissipation in the surrounding soil medium

ii. X_{in} exhibits nonlinear variation, indicating detuning from resonance

At higher moisture levels, increased deviation from conjugate matching is observed, resulting in reduced power transfer efficiency.

C. Radiation Efficiency Degradation

The variation of radiation efficiency η with soil moisture is illustrated in Fig. 5.

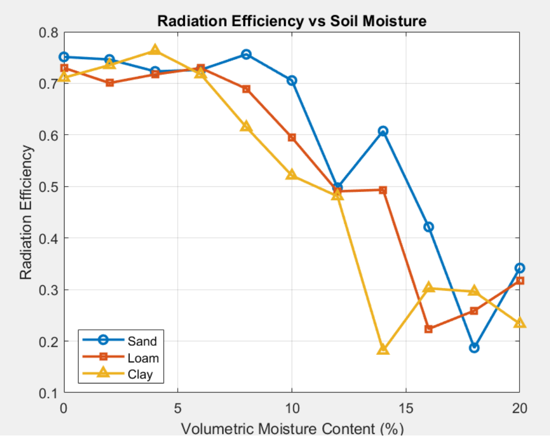


Fig. 5. Radiation efficiency η versus volumetric soil moisture θ

Representative values:
Dry condition: $\eta \approx 0.99$
Wet condition ($\theta = 20\%$):
Sand: $\eta \approx 0.45–0.55$
Loam: $\eta \approx 0.35–0.45$
Clay: $\eta \approx 0.30–0.40$

D. Realized Gain Reduction

The corresponding variation in realized antenna gain is shown in Fig. 6.

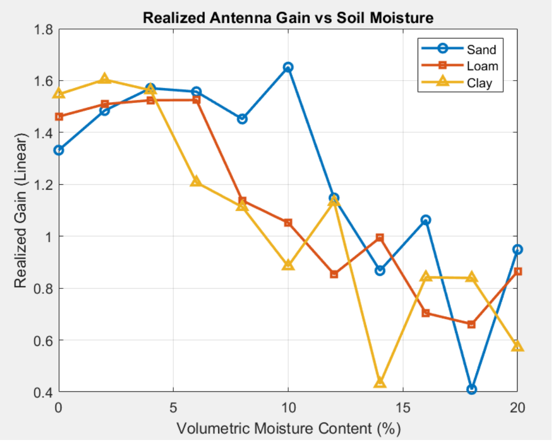
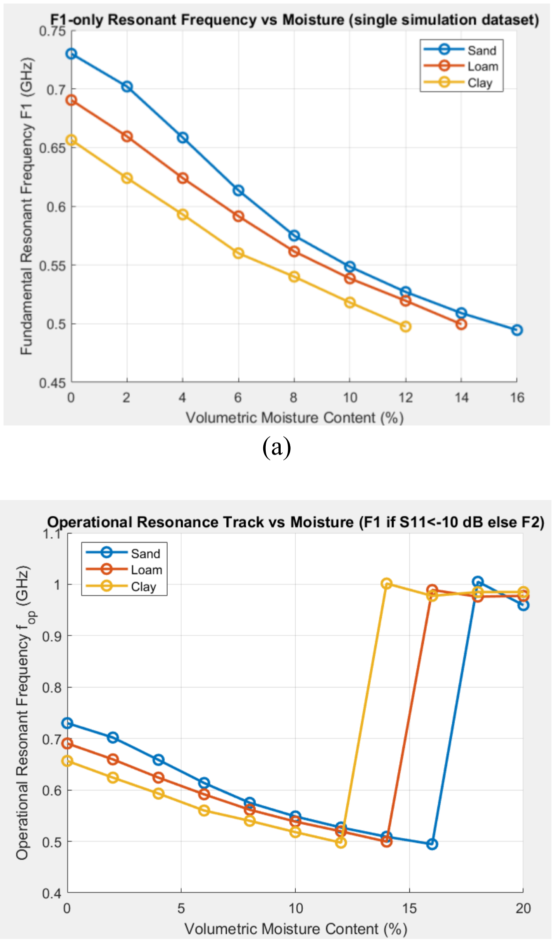


Fig. 6. Realized antenna gain (G) versus volumetric soil moisture θ

Observed range:
Dry soil: $G \approx 1.7–2.4$ dBi
Wet soil: $G \approx -2$ to 0 dBi

E. Dual-Mode Resonance Behaviour

The dual-mode resonance behaviour is illustrated in Fig. 7 a and Fig. 7b, where the fundamental mode f_1 and the tracked operational resonance are shown.



(a)

(b)

Fig. 7. Dual-mode resonance tracking: (a) fundamental resonance $f_1$variation (adapted from Fig. 4.12), (b) operational resonance tracking using $f_2$beyond the fundamental-mode limit (adapted from Fig. 4.13).

Two resonance modes were observed across the moisture range:

Primary resonance (f_1) — dominant at low moisture
Secondary resonance (f_2) — dominant at higher moisture

At increased moisture levels, the primary resonance weakens or shifts outside the operational band, while the secondary resonance remains detectable and is used for frequency tracking.

F. Electromagnetic Parameter Summary

Table I Electromagnetic Performance Summary

Soil	f_{res}Dry (GHz)	f_{res} Wet (GHz)	Sensitivity (MHz/%)	Efficiency Drop	Gain Drop
Sand	1.2168	0.616	−30.0	~45%	~3–4 dB
Loam	1.2415	0.4765	−38.25	~55–60%	~4–5 dB
Clay	1.1397	0.5197	−31.0	~60–65%	~4–6 dB

G. Model Fit Results

The agreement between model predictions and simulation-extracted values is shown in Fig. 8.

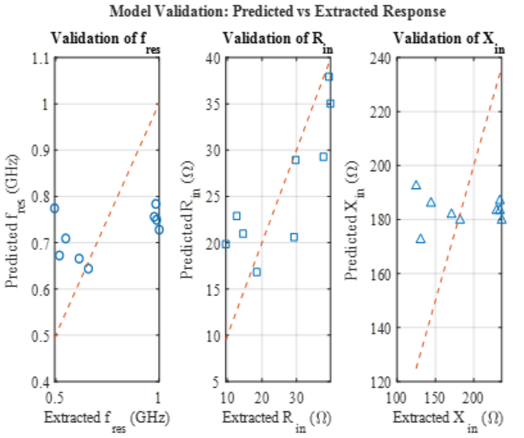


Fig. 8. Predicted versus extracted RFID parameters: (a) resonant frequency, (b) real input impedance, and (c) imaginary input impedance.

The quadratic models for $f_{res}(\theta)$, $R_{in}(\theta)$, and $X_{in}(\theta)$ were fitted to the simulation data.
Performance metrics:

The predictive performance of the proposed models was evaluated using the coefficient of determination (R^2) and root mean square error (RMSE).

For resonant frequency, an RMSE of 0.02082 GHz and $R^2 = 0.94057$were obtained. For real input impedance, the RMSE was 2.415 Ω with$R^2 = 0.92000$. For imaginary input impedance, the RMSE was 6.124 Ω with $R^2 = 0.97216$.

These results indicate strong agreement between model predictions and simulation-extracted data across the considered moisture range.

V. CONCLUSION

This paper presented an integrated soil–RFID electromagnetic interaction model for passive UHF soil moisture sensing. The proposed framework establishes a direct mapping between volumetric soil moisture content, soil dielectric properties, and antenna electromagnetic response, expressed as: $\theta \rightarrow \varepsilon_r^* \rightarrow (f_{res}, Z_{in})$. The results demonstrated that increasing soil moisture leads to systematic dielectric loading, resulting in resonant frequency detuning, impedance variation, and degradation in radiation efficiency and realized gain. The observed electromagnetic behaviour is consistent with established dielectric and antenna interaction principles [4]–[6], [7], [11], [21]. A dual-mode resonance tracking approach was implemented to maintain continuous frequency extraction under high dielectric loading conditions, addressing limitations associated with single-resonance sensing methods. The derived analytical models for $f_{res}(\theta)$, $R_{in}(\theta)$, and $X_{in}(\theta)$showed strong agreement with simulation data, with high correlation and low prediction error. Unlike classical dielectric models [4]–[6], [20]–[22], which do not predict antenna behaviour, and empirical RFID sensing approaches [1]–[3], which require calibration, the proposed model provides a predictive framework for analysing soil–antenna interaction. By integrating dielectric modelling with electromagnetic simulation, the approach enables direct estimation of antenna response parameters from soil moisture.

The proposed framework supports:

i. quantitative prediction of antenna electromagnetic behaviour under varying soil conditions,
ii. improved robustness across soil textures, and
iii. reduced dependence on empirical calibration for RFID-based sensing systems.

These results demonstrate the potential of passive UHF RFID systems as scalable and reliable platforms for soil moisture monitoring in practical deployment environments.

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