© MAR 2026 | IRE Journals | Volume 9 Issue 9 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I9-1715763

Deployment-Oriented Evaluation of Passive UHF RFID Soil Moisture Sensing Using System-Level Simulation and Link-Budget Analysis

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Abstract- ***Passive ultra-high-frequency (UHF) radio-frequency identification (RFID) technology offers a scalable, battery-free solution for distributed soil moisture sensing in precision agriculture and environmental monitoring. However, the deployment performance of RFID systems in soil environments is strongly constrained by moisture-dependent electromagnetic losses, which are often not quantified at the system level. This study presents a deployment-oriented evaluation framework that links electromagnetic antenna behaviour to practical RFID performance metrics using system-level simulation and link-budget analysis. A previously developed passive UHF RFID tag antenna was evaluated under soil-embedded conditions across a volumetric moisture range of 0–20% for representative soil textures, including sand, loam, and clay. Electromagnetic simulation outputs—resonant frequency, radiation efficiency, and realized antenna gain—were used as inputs to estimate maximum read range and received signal strength indicator (RSSI). Environmental robustness was further assessed through temperature and salinity variation, while manufacturing variability was analysed using Monte Carlo simulation. Results demonstrate that increasing soil moisture significantly degrades system performance. The maximum read range decreases from approximately 20–22 m under dry conditions to 7–12 m at 20% moisture, representing a reduction exceeding 50–65%. Similarly, RSSI values decrease from approximately −55 to −57 dBm under dry conditions to approximately −67 to −71 dBm at 20% moisture, corresponding to a reduction of approximately 12–16 dB, depending on soil type. Clay soils exhibit the most severe degradation due to higher permittivity and conductivity. Temperature effects are comparatively minor, while increased salinity introduces additional attenuation and further reduces system performance. Monte Carlo analysis confirms that the moisture-dependent sensing behaviour remains robust under realistic fabrication tolerances. The proposed framework provides a physically grounded and scalable approach for evaluating deployment feasibility of passive UHF RFID soil moisture sensing systems. The results offer quantitative design guidelines for optimizing tag placement, reader configuration, and operational limits, enabling reliable implementation of battery-free sensing solutions in real-world agricultural environments.***

Keywords- ***Passive UHF RFID; Soil moisture sensing; Link-budget analysis; Read range; RSSI; Backscatter communication; Electromagnetic modelling; Deployment evaluation; Precision agriculture; Environmental sensing***

I. INTRODUCTION

Soil moisture is a critical parameter in agricultural productivity, hydrological processes, and environmental monitoring, directly influencing plant growth, irrigation efficiency, and water resource management [1]. The increasing demand for scalable and low-cost sensing technologies in precision agriculture has driven interest in wireless and battery-free sensing platforms capable of operating over large spatial areas. Among these, passive ultra-high-frequency (UHF) radio-frequency identification (RFID) technology has emerged as a promising solution due to its low cost, maintenance-free operation, and compatibility with existing Internet-of-Things (IoT) infrastructures [2], [3].

Unlike conventional soil moisture sensors that directly measure volumetric water content, passive RFID-based sensing relies on the interaction between the tag antenna and the surrounding soil medium. Variations in soil moisture alter the soil's complex dielectric properties, which in turn affect key antenna parameters such as resonant frequency, impedance matching, radiation efficiency, and backscatter strength [4]. These changes can be indirectly observed through system-level metrics, including received signal strength indicator (RSSI), activation threshold, and maximum read range. As a result, passive RFID systems provide a unique mechanism for soil moisture sensing through electromagnetic coupling rather than direct contact-based measurement [5], [6].

Despite these advantages, the performance of passive UHF RFID systems in soil environments remains a significant challenge. Soil is a heterogeneous and lossy medium whose dielectric properties vary with moisture content, texture, temperature, and salinity [7], [8]. These variations introduce complex electromagnetic effects, including antenna detuning, radiation efficiency degradation, impedance mismatch, and increased propagation loss. Experimental studies have reported substantial reductions in RFID read range and signal strength when tags are embedded in moist soil, highlighting the difficulty of maintaining reliable communication under realistic field conditions [5], [6].

Most existing studies on RFID-based soil moisture sensing focus primarily on antenna-level behaviour or empirical observation of resonance shift and signal variation. While such approaches demonstrate sensitivity to moisture, they often do not extend to system-level performance evaluation or provide a quantitative and system-level assessment of deployment feasibility. In particular, there is limited work that translates electromagnetic simulation outputs into practical performance indicators such as read range, RSSI variation, and robustness under environmental and manufacturing variability. This gap limits the ability to predict real-world performance and hinders the design of deployment-ready RFID sensing systems.

To address this limitation, this study presents a deployment-oriented evaluation of a passive UHF RFID soil moisture sensing system using system-level simulation and link-budget analysis. A previously developed passive RFID tag is evaluated under soil-embedded conditions across a volumetric moisture range of 0–20% for representative soil textures, including sand, loam, and clay. Electromagnetic simulation outputs, including resonant frequency, radiation efficiency, and antenna gain, are used as inputs to system-level models for estimating maximum achievable read range and RSSI behaviour.

In addition to baseline performance evaluation, the study investigates the robustness of the RFID sensing system under varying environmental and operational conditions. Temperature and salinity effects are incorporated to assess environmental sensitivity, while Monte Carlo analysis is employed to evaluate the impact of manufacturing tolerances on system performance. These analyses enable a comprehensive assessment of the reliability and stability of RFID sensing under realistic deployment scenarios.

The main contribution of this work is the development of a system-level evaluation framework that links electromagnetic antenna behaviour to practical RFID performance metrics relevant to field deployment. By integrating electromagnetic simulation outputs with link-budget-based performance modelling, the study provides quantitative insight into the feasibility, limitations, and sensitivity of passive UHF RFID soil moisture sensing systems across different soil conditions. The findings offer guidance for the design and deployment of scalable, battery-free sensing systems for precision agriculture and environmental monitoring applications.

II. LITERATURE REVIEW

Soil moisture sensing has been extensively studied due to its critical role in agricultural productivity, hydrological processes, and environmental monitoring. Conventional techniques such as gravimetric analysis, time-domain reflectometry (TDR), and capacitance-based sensors provide direct measurements of volumetric water content but are often limited by cost, power requirements, and scalability for large-area deployment [1], [9]. These limitations have motivated the development of low-cost, distributed sensing technologies suitable for precision agriculture applications.

Passive ultra-high-frequency (UHF) radio-frequency identification (RFID) technology has emerged as a promising platform for battery-free environmental sensing. In passive RFID systems, the tag harvests energy from the incident electromagnetic field and communicates via backscatter modulation, eliminating the need for an onboard power source [2], [3]. This enables large-scale deployment with minimal maintenance requirements. The fundamental operation and performance limitations of passive RFID systems have been extensively analysed using link-budget and backscatter communication models [4], [10].

Several studies have demonstrated the feasibility of using passive RFID tags for soil moisture sensing through electromagnetic interaction with the surrounding medium. Wang et al. [5] showed that commercial UHF RFID tags exhibit measurable variations in resonant frequency and RSSI under different soil moisture conditions. Similarly, Shen et al. [6] developed a passive RFID sensing platform capable of monitoring moisture and temperature in agricultural environments. Other recent works have explored antenna-based sensing mechanisms, including impedance variation and frequency detuning, as indirect indicators of moisture content [11], [12].

The sensing mechanism is fundamentally governed by the dielectric properties of soil, which vary significantly with moisture content. Classical dielectric models, such as those proposed by Dobson et al. [7] and Hallikainen et al. [13], describe the relationship between soil composition and microwave permittivity. More advanced models, such as the generalized refractive mixing dielectric model developed by Mironov et al. [8], incorporate bound and free water contributions to improve accuracy across soil types. These models demonstrate that increasing moisture leads to higher dielectric constant and loss factor, resulting in increased electromagnetic attenuation and altered antenna behaviour.

From an electromagnetic perspective, soil acts as a lossy medium that introduces attenuation, impedance mismatch, and radiation efficiency degradation. Theoretical foundations for electromagnetic wave propagation and antenna behaviour in lossy media are well established in classical texts such as Balanis [14] and Ulaby et al. [15]. These works provide the basis for understanding how soil dielectric properties influence antenna performance and signal propagation in RFID systems.

Despite these advances, most RFID-based soil moisture sensing studies focus on antenna-level characterization or empirical calibration of resonance shifts. While these approaches demonstrate sensitivity to moisture, they often lack a system-level perspective that translates electromagnetic behaviour into practical performance metrics such as read range and RSSI. In particular, limited attention has been given to integrating electromagnetic simulation outputs with link-budget modelling to evaluate deployment feasibility under realistic conditions.

Backscatter communication theory provides a rigorous framework for system-level modelling of passive RFID systems. According to Nikitin and Rao [4], the received signal at the reader is governed by a two-way propagation process, resulting in a squared dependence on path loss. This significantly reduces the received signal strength compared to forward-link communication. Practical RFID system design therefore requires consideration of antenna gain, radiation efficiency, modulation loss, and reflection characteristics [2], [3], [10].

Recent studies have begun to explore system-level performance evaluation of RFID sensing systems, including read-range estimation and RSSI-based sensing [16], [17]. However, these approaches often rely on simplified models or do not fully incorporate environmental variability such as temperature, salinity, and soil heterogeneity. Furthermore, the combined effects of electromagnetic behaviour, environmental conditions, and manufacturing tolerances are rarely considered within a unified framework.

Environmental factors such as temperature and salinity further influence soil dielectric properties and, consequently, RFID system performance. Increased salinity leads to higher electrical conductivity and greater signal attenuation, while temperature variations affect permittivity and relaxation behaviour of water molecules [18], [19]. In addition, manufacturing tolerances introduce variability in antenna geometry and impedance matching, affecting system performance and reliability [20].

Based on the reviewed literature, a clear gap exists in the development of integrated frameworks that combine electromagnetic simulation outputs with system-level performance evaluation for passive RFID soil moisture sensing. Existing studies rarely provide a comprehensive assessment of read range, RSSI variation, environmental robustness, and manufacturing variability within a unified modelling approach.

To address this gap, this work develops a deployment-oriented system-level evaluation framework that links soil moisture–dependent electromagnetic behaviour to practical RFID performance metrics using link-budget analysis. By incorporating realistic backscatter modelling and environmental variability, the proposed approach provides a physically consistent and scalable method for assessing the feasibility and limitations of passive UHF RFID soil moisture sensing systems in real-world deployment scenarios.

III. METHODOLOGY

3.1 System Overview

This study adopts a simulation-driven, system-level evaluation approach to assess the deployment performance of a passive UHF RFID soil moisture sensing system. Rather than focusing on antenna design or dielectric model development, the methodology translates electromagnetic simulation outputs into practical RFID performance metrics relevant to field deployment. The evaluation framework establishes a direct link between soil moisture variation and system-level observables, including maximum read range and received signal strength indicator (RSSI), under varying environmental and operational conditions.

A previously developed passive UHF RFID tag antenna is used as the sensing element. The antenna is assumed to be embedded within a soil medium, where its electromagnetic response is influenced by moisture-dependent dielectric loading. Electromagnetic performance parameters obtained from prior full-wave simulations are used as inputs to system-level models for performance evaluation.

3.2 Soil Conditions and Simulation Parameters

The evaluation is conducted across representative soil environments to capture variability in dielectric behaviour and propagation conditions. Three soil types are considered: Sand, Loam and Clay.

Volumetric soil moisture content (θ) is varied over the range of 0–20% in incremental steps, representing typical field-relevant conditions for agricultural applications. For each soil type and moisture level, corresponding dielectric properties are assigned within the electromagnetic simulation environment to capture moisture-dependent loading effects, consistent with established soil dielectric models [7], [8], [13].

The analysis assumes homogeneous soil conditions surrounding the RFID tag and considers far-field UHF operation within the standard frequency range of 860–960 MHz [10]. Environmental parameters, including temperature and salinity, are incorporated in subsequent analyses to evaluate system robustness under non-ideal conditions.

3.3 Electromagnetic Performance Inputs

Electromagnetic simulation outputs serve as the primary input to the system-level evaluation framework. These outputs were obtained from full-wave electromagnetic simulations of the RFID tag embedded in soil and include: Resonant frequency (f_res), Radiation efficiency (η_rad) and Realized antenna gain (G_{realized}).

These parameters capture the impact of soil dielectric loading on antenna behaviour, including detuning, radiation degradation, and efficiency loss. The extracted values are used directly, without further modelling, to ensure that the system-level analysis reflects physically consistent electromagnetic behaviour, as recommended in electromagnetic antenna modelling practice [14].

3.4 Read-Range Estimation Using Link-Budget Analysis

The maximum achievable read range of the passive RFID system is estimated using a link-budget formulation derived from the Friis transmission principle, adapted for passive backscatter communication [4], [10]. The read range is expressed as:

$$R_{\max} = \frac{\lambda}{4\pi}\sqrt{\frac{P_t\, G_t\, G_{tag}\, \eta_{\text{rad}}}{P_{\text{th}}}} \tag{1}$$

where:

λ= wavelength of the transmitted signal (m)

P_t= transmitted power from the RFID reader (W)

G_t= gain of the reader antenna (linear scale)

G_{tag}= gain of the tag antenna (linear scale)

η_{rad}= radiation efficiency of the tag antenna

P_{th}= minimum power required to activate the RFID chip (W)

This formulation incorporates the effects of antenna gain and radiation efficiency degradation due to soil loading, enabling estimation of the maximum interrogation distance under varying moisture conditions. The model assumes fixed reader parameters consistent with regulatory limits for UHF RFID systems [10].

3.5 RSSI and Backscatter Power Estimation

In addition to read range, the received signal strength indicator (RSSI) is evaluated as a function of soil moisture. RSSI serves as a practical sensing observable, representing the strength of the backscattered signal received by the reader.

$$RSSI_{dBm} = EIRP_{dBm} + 10\log_{10}(G_{realized}) + Gr - 2FSPL_{dB} - L_m - L_{bs}$$

where:

$$G_{\text{realized}} = G \cdot \eta_{\text{rad}}$$

$$FSPL_{\text{dB}} = 20\log_{10}\left(\frac{4\pi R}{\lambda}\right)$$

L_m= modulation loss (≈ 3 dB)

L_{bs}= backscatter loss (≈ 30 dB)

The term $2\,FSPL_{\text{dB}}$ accounts for the two-way propagation loss inherent in passive RFID backscatter communication, while L_{bs} represents the finite radar cross-section and reflection efficiency of the tag [4], [2], [3].

The backscattered signal level is influenced by:

i. antenna gain and efficiency,

ii. impedance matching conditions,

iii. propagation loss through the soil medium.

By incorporating electromagnetic performance parameters into the link-budget framework, RSSI variation with moisture is estimated to assess the detectability and sensitivity of the RFID sensing mechanism. This formulation ensures physically realistic RSSI estimation consistent with passive RFID backscatter theory [4].

3.6 Environmental Robustness Analysis

To evaluate system performance under realistic environmental conditions, robustness analysis is conducted with respect to temperature and salinity variations.

i. Temperature Analysis: The effect of temperature variation on dielectric properties and system performance is evaluated over a representative environmental range. Variations in temperature influence soil permittivity, thereby affecting both propagation loss and antenna response [18].

ii. Salinity Analysis: The impact of soil salinity on conductivity and dielectric loss is assessed. Increased salinity results in higher conductive losses, leading to additional electromagnetic attenuation and reduced system performance [9].

These analyses provide insight into the sensitivity of RFID sensing performance to environmental variability beyond moisture content.

3.7 Manufacturing Tolerance Analysis

A Monte Carlo–based tolerance analysis is performed to assess the impact of manufacturing variations on system performance. Key antenna parameters, including geometrical dimensions and material properties, are perturbed within defined tolerance ranges.

For each simulation instance, variations in resonant frequency and read range are recorded, enabling statistical characterization of performance variability. The resulting distributions provide insight into the robustness and reliability of the RFID sensing system under practical fabrication uncertainties [20].

3.8 Deployment Readiness Assessment

The final stage of the methodology integrates electromagnetic performance, system-level metrics, and robustness analysis to evaluate deployment readiness. The assessment considers:

i. read-range limitations under increasing moisture,

ii. RSSI detectability thresholds,

iii. environmental sensitivity (temperature and salinity),

iv. manufacturing-induced variability.

This integrated evaluation framework provides a comprehensive basis for assessing the feasibility and reliability of passive UHF RFID soil moisture sensing systems under realistic field conditions.

IV. RESULTS AND DISCUSSION

4.1 Moisture-Dependent Electromagnetic Response

As shown in Fig. 1, the resonant frequency decreases monotonically with increasing soil moisture across all soil types, confirming the strong dielectric loading effect of the surrounding medium.

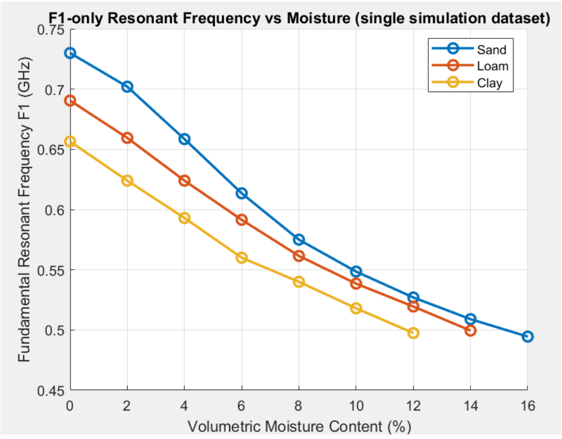

Fig. 1. Resonant Frequency vs Soil Moisture

This behaviour is primarily attributed to the increase in effective relative permittivity (εr) of the soil as moisture content rises. The higher permittivity increases the electrical length of the antenna, resulting in a downward shift in resonant frequency. Additionally, the presence of bound and free water introduces dielectric dispersion and loss mechanisms, further influencing the antenna response.

A consistent frequency sensitivity of approximately −4 to −8 MHz per percentage increase in volumetric water content is observed across all soil types. This indicates a strong coupling between the antenna electromagnetic response and the surrounding dielectric environment. The effect is more pronounced in clay soils due to their higher water retention capacity, leading to increased εr and loss tangent (tanδ).

In addition to frequency detuning, both radiation efficiency (η_rad) and realized gain (G_{realized}) exhibit progressive degradation with increasing moisture. This degradation is caused by increased dielectric loss (ε″) and effective conductivity (σ) of the soil, which result in greater electromagnetic energy dissipation in the near-field region of the antenna. The reduction in radiation efficiency is illustrated in Fig. 2, while the corresponding decrease in realized gain is presented in Fig. 3.

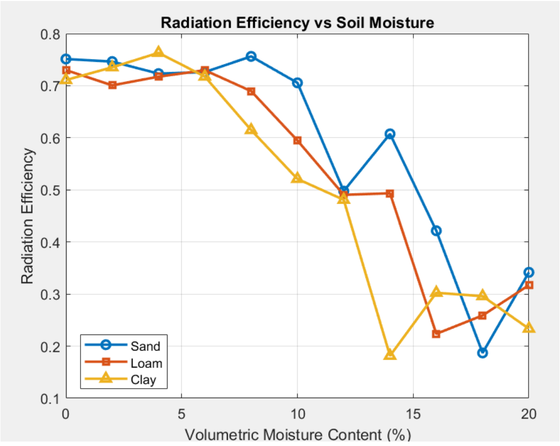

Fig. 2. Radiation efficiency vs Soil Moisture

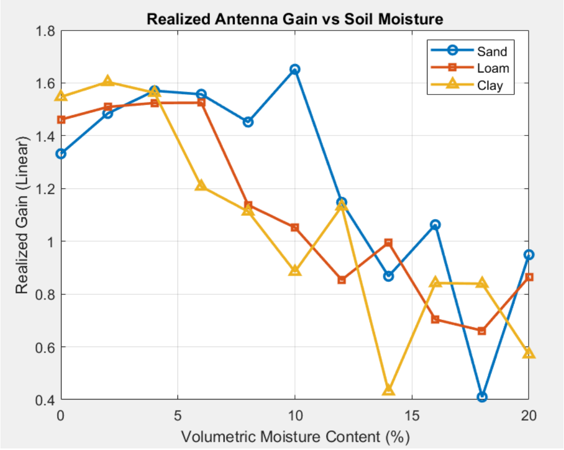

Fig. 3. Antenna Gain vs Soil Moisture

4.2 Read-Range Variation with Soil Moisture

The maximum achievable read range was estimated using the system-level link-budget model. As shown in Fig. 4, a substantial reduction in read range is observed with increasing soil moisture across all soil types.

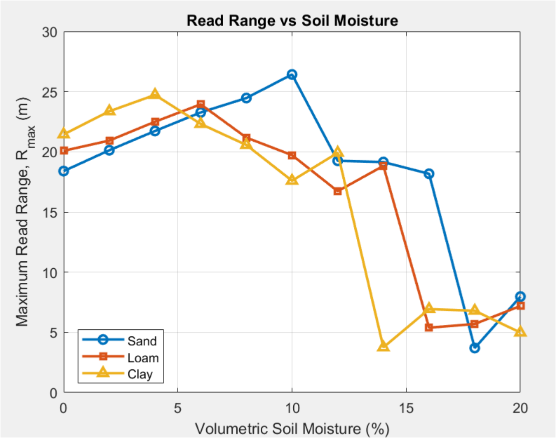

Fig. 4. Read Range vs Soil Moisture

Under dry soil conditions, the RFID system achieves a maximum read range of approximately 20–22 m, depending on soil type. At moderate moisture levels, slight variations in read range may be observed due to impedance matching and resonance tuning effects; however, as the moisture content increases further to 20%, the read range reduces significantly to approximately 7–12 m, corresponding to a reduction of over 50–65%.

This behaviour can be directly explained using the link-budget formulation in (1), where the read range is proportional to the square root of the product of transmitted power, antenna gains, and radiation efficiency. As soil moisture increases, the reduction in radiation efficiency (η_{rad}) and realized gain (G_{realized}), combined with increased propagation attenuation in the lossy soil medium, leads to a significant decrease in the received backscattered power and, consequently, the achievable read range.

Furthermore, the increased dielectric loss (ε'') and effective conductivity (σ) of moist soil introduce additional attenuation in both the forward (reader-to-tag) and reverse (tag-to-reader) propagation paths, effectively reducing the signal-to-noise ratio at the reader. This results in a higher activation threshold requirement and reduced communication distance.

Representative numerical values of the read range are summarized in Table 1.

Table 1. Representative maximum achievable RFID read-range values

Soil Texture	Moisture θ (%)	Read Range (m)
Sand	0	20.73
Sand	10	22.37
Sand	20	11.80
Loam	0	21.41
Loam	10	16.40
Loam	20	10.85
Clay	0	21.74
Clay	10	14.07
Clay	20	7.57

Among the soil types, clay exhibits the most severe read-range degradation due to its higher effective permittivity and electrical conductivity, which significantly increase electromagnetic attenuation. In contrast, sandy soil, characterized by lower dielectric loss, maintains comparatively higher read ranges under similar moisture conditions.

4.3 RSSI Variation with Soil Moisture

The received signal strength indicator (RSSI) was evaluated to assess the detectability of the backscattered signal under varying soil conditions. In passive UHF RFID systems, RSSI represents the power of the signal received at the reader after two-way propagation (reader-to-tag and tag-to-reader). Therefore, a backscatter-based link-budget formulation was adopted to ensure physically realistic estimation of received signal levels.

As shown in Fig. 5, RSSI exhibits an overall decreasing trend with increasing soil moisture across all soil types. However, slight non-monotonic variations are observed at intermediate moisture levels due to impedance-matching and antenna-tuning effects under moderate dielectric loading.

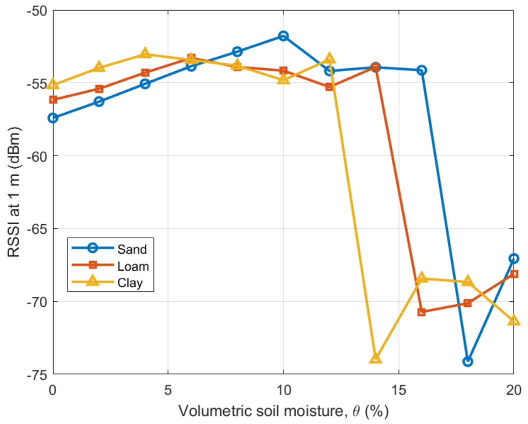

Fig. 5. RSSI vs Soil Moisture

At higher moisture levels, pronounced reductions in RSSI are observed, particularly beyond approximately 14–18% depending on soil type. These abrupt decreases correspond to resonance mode transitions from the fundamental mode (F1) to higher-order modes (F2), which occur under strong dielectric loading conditions. At these transition points, the antenna experiences significant degradation in impedance matching and radiation efficiency, resulting in reduced backscatter efficiency and a corresponding drop in received signal strength. This behaviour is consistent with electromagnetic theory for antennas operating in lossy dielectric media, where increased permittivity and loss tangent alter current distribution and resonance characteristics [14], [15].

When the full backscatter propagation model is applied, RSSI values fall within the expected negative dBm range for passive RFID systems. At a reference distance of 1 m, RSSI values range from approximately −55 to −57 dBm under dry conditions to approximately −67 to −71 dBm at 20% moisture, depending on soil type. These values are consistent with typical passive UHF RFID received signal levels reported in the literature.

The observed reduction, on the order of approximately 14–16 dB across the 0–20% moisture range, is attributed to the combined effects of increased dielectric loss (ε″), higher effective conductivity (σ), and reduced antenna radiation efficiency (η_rad). These factors contribute to attenuation in both the forward (reader-to-tag) and reverse (tag-to-reader) propagation paths, effectively doubling the impact of path loss in the system.

From a system-level perspective, the reduction in RSSI reflects a decrease in the backscattered signal power received at the reader, which directly impacts detection reliability, link margin, and communication robustness. As soil moisture increases, the reduced link margin makes the system more sensitive to environmental variability and operational constraints.

Representative RSSI values at selected moisture levels are presented in Table 2.

Table 2. RSSI values at 1 m using backscatter link-budget model

Soil Texture	Moisture θ (%)	RSSI (dBm)
Sand	0	-57.41
Sand	10	-51.79
Sand	20	-67.06
Loam	0	-56.17
Loam	10	-54.17
Loam	20	-68.11
Clay	0	-55.16
Clay	10	-54.82
Clay	20	-71.37

The reduction in RSSI is more pronounced in clay soils due to their higher dielectric loss and conductivity, confirming the strong influence of soil composition on electromagnetic attenuation. Despite this degradation, the overall moisture-dependent trend, including the observed mode-transition effects at higher moisture levels, demonstrates that RSSI remains a reliable observable for indirect soil moisture estimation within the system-level sensing framework.

4.4 Environmental Robustness Analysis

The robustness of the RFID sensing system was evaluated under variations in temperature and soil salinity. The results indicate that both factors influence system performance primarily through their impact on dielectric properties.

Temperature variation results in moderate changes in dielectric permittivity, leading to slight shifts in resonant frequency and marginal variations in read range. However, these effects are less significant compared to moisture-induced changes, indicating that the system remains relatively stable under typical environmental temperature conditions.

In contrast, increased soil salinity introduces higher conductive losses, leading to additional attenuation of electromagnetic waves. This results in further reductions in both read range and RSSI, particularly at higher moisture levels. The combined effect of moisture and salinity therefore represents a critical consideration for deployment in saline or coastal environments.

4.5 Manufacturing Tolerance Analysis

A Monte Carlo–based analysis was conducted to evaluate the impact of manufacturing variations on system performance. Variations in antenna geometry and material properties result in observable shifts in resonant frequency and corresponding changes in read range.

The results indicate that manufacturing tolerances introduce a measurable spread in performance, with deviations in read range and resonant frequency depending on the extent of parameter variation. However, the overall moisture-dependent trends remain consistent, indicating that the sensing mechanism is robust to moderate fabrication uncertainties.

4.6 Deployment Readiness Assessment

The combined analysis of electromagnetic response, read range, RSSI behaviour, and robustness provides a comprehensive assessment of deployment readiness.

The results demonstrate that while passive UHF RFID sensing is feasible under soil-embedded conditions, system performance is strongly constrained by moisture-induced losses. The significant reduction in read range at higher moisture levels indicates that reader–tag distance and placement must be carefully optimized for reliable operation.

Furthermore, the consistent and overall moisture-dependent variation of both resonant frequency and RSSI confirms the viability of using RFID observables for indirect soil moisture sensing. However, environmental factors such as salinity and manufacturing variability must be considered to ensure stable and repeatable performance.

Overall, the findings establish that system-level metrics such as read range and RSSI provide meaningful insight into the practical performance limits of passive UHF RFID soil moisture sensing systems, enabling informed deployment and design decisions.

V. CONCLUSION

This study presented a deployment-oriented evaluation of a passive UHF RFID soil moisture sensing system using system-level simulation and link-budget analysis. By translating electromagnetic simulation outputs into practical performance metrics, the work provides a quantitative and physically grounded assessment of RFID system behaviour under soil-embedded conditions. The results demonstrate that soil moisture has a dominant influence on system performance. The maximum read range decreases from approximately 20–22 m under dry conditions to approximately 7–12 m at higher moisture levels, corresponding to a reduction of over 50–65%. This degradation is primarily driven by increased effective permittivity, dielectric loss, and soil conductivity, which reduce antenna radiation efficiency and increase propagation attenuation. Similarly, RSSI values range from approximately −55 to −57 dBm under dry conditions to approximately −67 to −71 dBm at higher moisture levels, with an overall decline of approximately 12–16 dB across the 0–20% moisture range. This reduction reflects the combined effects of two-way propagation loss in backscatter communication, reduced antenna gain, and increased electromagnetic attenuation in the lossy soil medium. The observed trends are more pronounced in clay soils due to their higher dielectric loss and conductivity, highlighting the strong dependence of RFID sensing performance on soil texture. Environmental robustness analysis indicates that temperature variations introduce relatively minor changes in system performance, whereas increased salinity significantly degrades both read range and RSSI due to enhanced conductive losses. Monte Carlo tolerance analysis further demonstrates that although manufacturing variations introduce measurable performance spread, the overall moisture-dependent sensing behaviour remains stable and predictable. Overall, the findings confirm that passive UHF RFID technology is viable for soil moisture sensing under soil-embedded conditions. However, system performance is fundamentally constrained by moisture-induced electromagnetic losses and environmental variability. The proposed system-level evaluation framework provides a practical and scalable basis for assessing deployment feasibility and supports informed design decisions regarding tag placement, reader configuration, and operational limits. This approach enables more reliable deployment of battery-free RFID sensing systems for precision agriculture and environmental monitoring applications.

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