

A Long-Range Flexible UHF RFID Tag Antenna with Robust Horizontal Readability

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ABSTRACT: A compact, flexible, ultra-high-frequency (UHF) radio-frequency identification (RFID) tag antenna is proposed for the long-range identification of non-metallic logistics objects with robust horizontal readability. The antenna consists of an open-frame meandered radiator, an upper transverse coupling path, a central interdigital coupling section, and a lower comb-shaped multi-branch section. Together, these coupled sections extend the effective current path, improve antenna-chip power transfer, and establish a distributed current response over the antenna. The fabricated tag measures 40 mm × 29.5 mm × 0.05 mm. Under an effective isotropic radiated power of 3.28 W, the maximum measured read range is 16.6 m at 919 MHz in free space, with a 0°–360° *xy*-plane read range of 15.2–16.6 m. Attachment tolerance is evaluated on PP plastic, folded denim, cardboard, and wood, yielding maximum read ranges of 16.7, 13.2, 11.4, and 11.2 m, respectively. Across all five cases, the horizontal stability coefficient $C_s = R_{\min}/R_{\max}$ is at least 0.895. The proposed coupled multi-section topology provides a distributed-current strategy for simultaneously improving angular readability and attachment robustness in flexible UHF RFID tags.

1. INTRODUCTION

Ultra-high-frequency (UHF) radio-frequency identification (RFID) tags are important components in RFID systems. They enable contactless and batch identification and are widely used in warehousing and logistics [1–4]. In practical applications, tag reading performance is mainly affected by the attached object and interrogation angle. Different attachment conditions may alter the tag performance, while variations in the interrogation direction may reduce reading stability. These uncertainties place higher demands on the adaptability and reliability of UHF RFID tags in complex logistics environments. Therefore, simultaneously achieving long read range, continuous 0°–360° horizontal readability, and robust performance on different non-metallic objects is of particular research and practical interest for UHF RFID tag antennas.

Many UHF RFID tag antennas have been developed to improve angular coverage, read range, or adaptability to different tagged objects. Omnidirectional, quasi-isotropic, and near-3D tag antennas have been proposed to improve readability under varying interrogation directions [5–8]. However, these designs mainly focus on angular coverage and have not been extensively validated across diverse practical application scenarios. Long-range UHF RFID tags have also been developed for various application-specific scenarios, such as water-bottle identification, retail garments, and supply-chain tracking [9–11]. These designs demonstrate long-distance identification for their respective applications, but they are generally optimized for specific tagged objects or attachment conditions, while their angular responses are typically dipole-like or bidirectional rather than continuously omnidirectional. Although

some recent tags have demonstrated long-range operation on multiple non-metallic objects [11], the simultaneous realization of continuous 0°–360° horizontal readability and a thin, flexible, and compact form factor has not been demonstrated. Moreover, such multi-object long-range designs may rely on relatively thick structures, which limits their suitability for flexible, low-profile attachment in practical logistics applications. Therefore, the simultaneous achievement of a thin and flexible form factor, long read range on multiple non-metallic objects without geometrical retuning, and experimentally verified continuous 0°–360° horizontal readability remains insufficiently addressed.

Motivated by these requirements, we propose a compact, flexible UHF RFID tag antenna for long-range, stable identification in logistics applications. The antenna combines an open-frame meandered radiator, an upper transverse coupling path, a central interdigital coupling section, and a lower comb-shaped multi-branch section. These coupled sections extend the effective current path, improve antenna-chip power transfer, and form a distributed current response over the antenna. This design helps maintain long read range and stable horizontal readability while reducing the sensitivity to different non-metallic attachment conditions. The proposed tag is further validated in free space and on several representative non-metallic objects without geometrical retuning.

2. ANTENNA STRUCTURE AND ANALYSIS

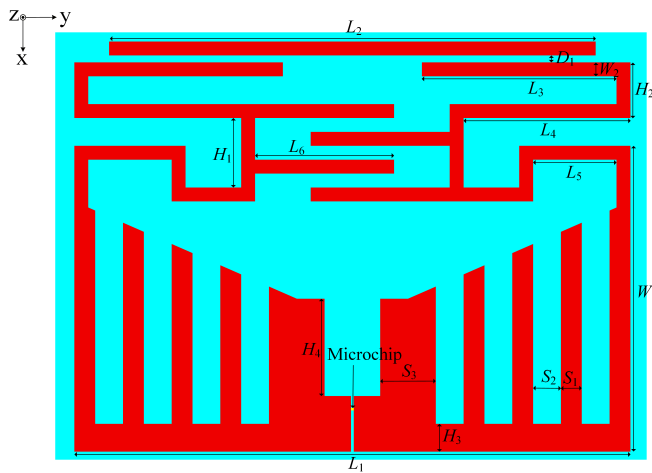
2.1. Antenna Structure

Fig. 1 shows the geometry of the proposed UHF RFID tag antenna. The antenna comprises an open-frame meandered cur-

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TABLE 1. Optimized parameters of the proposed tag antenna.

Parameter	Dimension (mm)	Parameter	Dimension (mm)	Parameter	Dimension (mm)	Parameter	Dimension (mm)
W_1	22	W_2	1	L_1	40	L_2	35
L_3	14	L_4	12	L_5	6	L_6	10
S_1	1.5	S_2	2	S_3	4	H_1	5
H_2	4	H_3	2	H_4	7	D_1	0.5

**FIGURE 1.** Configuration of the proposed tag antenna.

rent path, an upper transverse coupling path, a central interdigital coupling section, and a lower comb-shaped multi-branch section. The meandered path increases the effective current length for compact resonance tuning. The transverse and interdigital coupling sections redistribute the current over the upper and central regions, whereas the lower comb-shaped branches introduce additional coupling paths near the chip feed. The proposed structure facilitates chip conjugate matching and supports balanced horizontal radiation. The antenna was fabricated on a flexible polyethylene terephthalate (PET) substrate with a relative permittivity of 3.0, a loss tangent of 0.002, and a thickness of 0.05 mm. An NXP UCODE 9 chip was mounted across the central feed gap. The chip impedance is approximately $(10 - j191) \Omega$ at 915 MHz, and the chip sensitivity is -24 dBm. Therefore, the proposed structure was optimized to realize chip conjugate matching and promote horizontally uniform radiation while preserving a thin, flexible form factor.

The proposed tag antenna was designed and analyzed using Ansys High Frequency Structure Simulator (HFSS). The optimized dimensions are presented in Table 1.

2.2. Design Analysis

For a passive UHF RFID tag antenna, the available chip power is governed by conjugate matching between the antenna and the chip. Therefore, the impedance-matching performance is evaluated using the power transmission coefficient defined as

follows [12]:

$$\tau = \frac{4R_A R_{\text{chip}}}{|Z_A + Z_{\text{chip}}|^2}, \quad (1)$$

where $Z_A = R_A + jX_A$ is the antenna input impedance, and $Z_{\text{chip}} = R_{\text{chip}} + jX_{\text{chip}}$ is the chip impedance. Under the same reader transmit power and reader-antenna gain, a larger τ indicates a more efficient power transfer from the antenna to the chip, and therefore contributes to a longer read range. In addition to achieving a high power transfer at the target frequency, the tag antenna should employ distributed current paths. This design reduces sensitivity to local dielectric perturbations from attached objects and helps alleviate detuning and angular read-range degradation.

Fig. 2 shows the structural evolution of the proposed antenna. Fig. 3 compares corresponding simulated power transmission coefficients, and Fig. 4 shows realized-gain patterns. Antenna I is an initial open-frame radiator. It consists of an outer conducting frame and upper folded current paths, with the chip feed located at the bottom central gap. Although this structure provides a compact current route, its matching peak appears at approximately 1.301 GHz, which is far above the target UHF RFID band. Moreover, the current is mainly supported by the outer frame and folded arms, leading to a relatively localized dipole-like radiation behavior and evident angular dependence in the xy plane.

In Antenna II, an upper transverse parasitic path was introduced above the open-frame radiator. This path increases the effective current length and provides an additional coupling channel in the upper region. Consequently, the matching peak shifted downward to approximately 1.122 GHz. More importantly, the added transverse path redistributes the current over a wider region. Consequently, the dependence on a single dominant current path is reduced, and the continuity of the horizontal radiation response is improved.

Antenna III introduces a central transverse coupling path and an interdigital region between left and right bending sections. The interdigital coupling increases the equivalent capacitance and shifts the matching peak to approximately 898 MHz. Meanwhile, the central transverse path strengthens the coupling between the antenna's two sides and promotes current spreading over upper, central, and feeding areas. Consequently, the antenna has a distributed, mutually coupled current distribution rather than a simple localized dipole mode. This feature is beneficial for horizontal readability because radiation is supported by multiple coupled current sections instead of a single narrow current path.

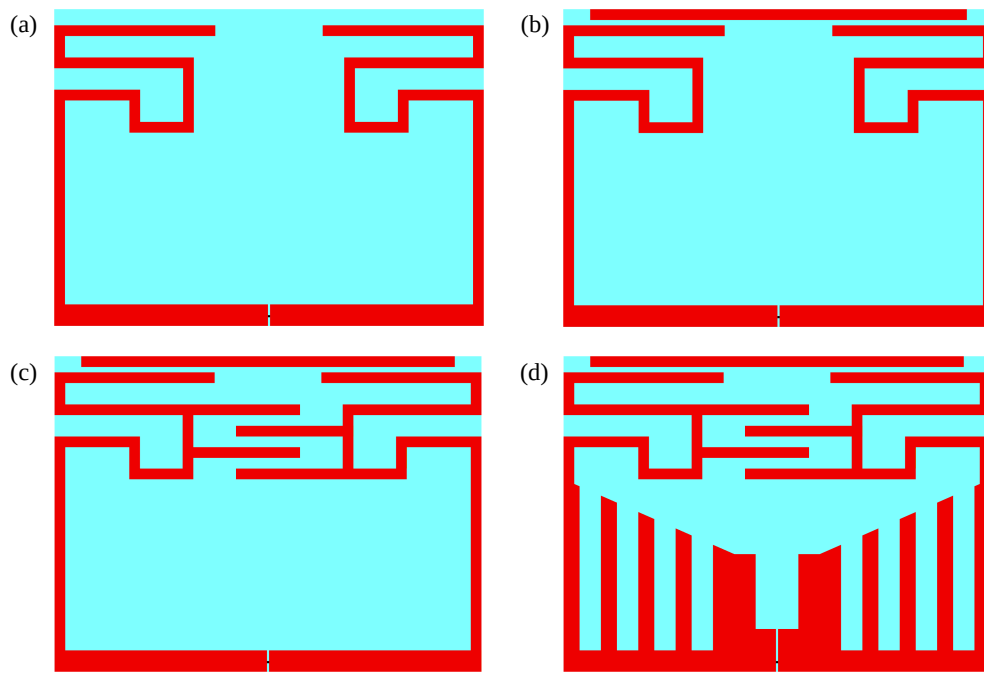


FIGURE 2. Structural evolution of the proposed tag antenna design: (a) Antenna I, (b) Antenna II, (c) Antenna III, and (d) Antenna IV.

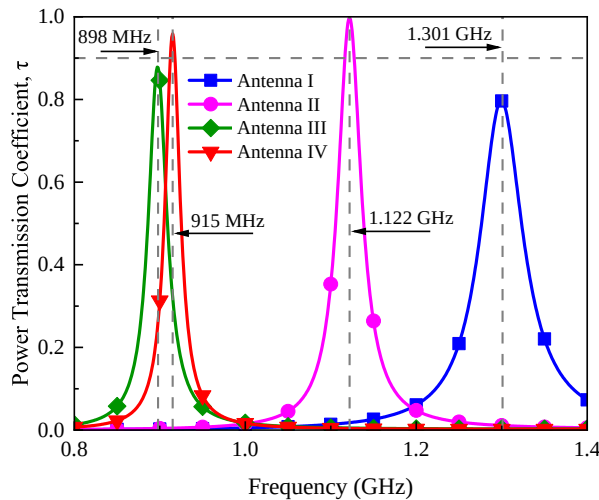


FIGURE 3. Simulated power transmission coefficients τ of Antennas I–IV during the structural evolution.

Finally, a lower comb-shaped multi-branch section is added to Antenna IV. The comb-shaped branches introduce additional edge capacitance and weak inter-branch coupling near the feed region, thereby tuning the antenna impedance toward the chip conjugate condition at approximately 915 MHz. The simulated power transmission coefficient increased from approximately 0.88 to 0.96, accompanied by an approximately 0.2 dB improvement in the realized gain. Therefore, Antenna IV achieves both efficient power transfer and a more balanced current distribution. The lower multi-branch section also provides several parallel coupled current paths near the chip.

Fig. 5 shows the simulated surface current distribution of the final antenna at 915 MHz. Strong currents were observed on the outer frame, upper transverse strip, central interdigital section, and lower comb-shaped branches. Together, these sections es-

tablish a distributed coupled-current response over the antenna. The outer frame mainly supports the compact resonant path, and the upper and central sections broaden the current distribution, and the lower branches preserve coupling between the feed region and chip. Consequently, attachment-induced dielectric perturbations are distributed over several coupled current regions rather than being concentrated on a single dominant path, which helps reduce their influence on antenna-chip power transfer and horizontal radiation. This distributed-current mechanism provides the physical basis for the attachment tolerance and continuous horizontal readability evaluated in Section 3.

2.3. Parametric Studies

To clarify the resonance-tuning mechanism of the final antenna, we investigated two representative geometrical parameters. The first is the interdigital-finger length L_6 , which mainly controls the capacitive coupling in the center loading region. The second is the open-ended meandered-arm length L_3 , which mainly changes the effective current path.

Figure 6 shows the simulated matching response when L_6 is varied. Increasing L_6 enlarges the coupling length between adjacent interdigital fingers and therefore increases the antenna's equivalent capacitance. Consequently, the resonant frequency shifts toward the lower-frequency region. This result confirms that the interdigital-finger length is the dominant tuning parameter for shifting the antenna resonance into the UHF RFID band.

Figure 7 shows the simulated matching response for different values of L_3 . As L_3 increases, the effective current path of the open-ended strip increases, and the resonant frequency decreases accordingly. Within the investigated range, L_6 produced a larger resonance shift than L_3 , indicating that the length of the interdigital finger is the more sensitive tuning parameter.

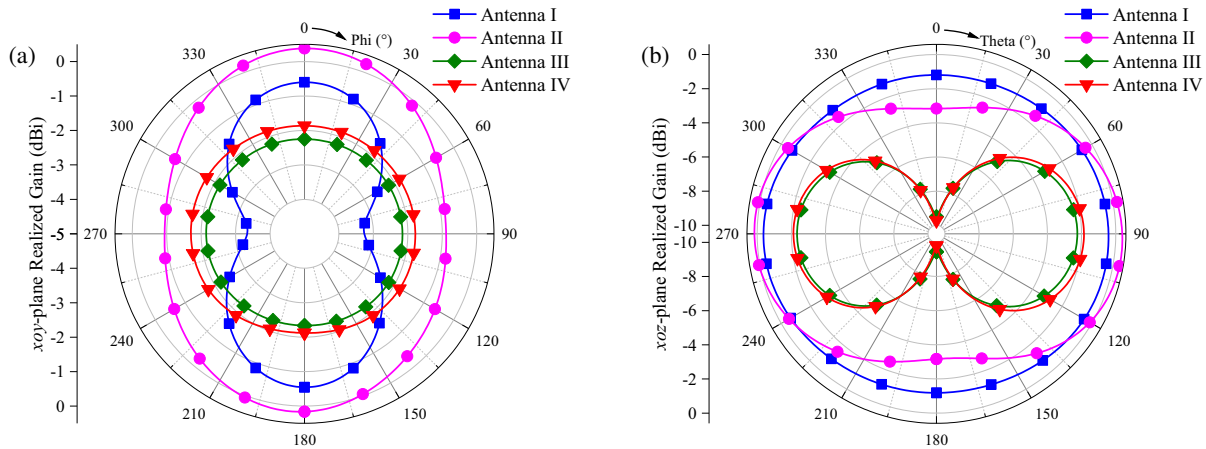


FIGURE 4. Simulated realized-gain patterns of Antennas I–IV in the (a) xoy plane and (b) xoz plane.

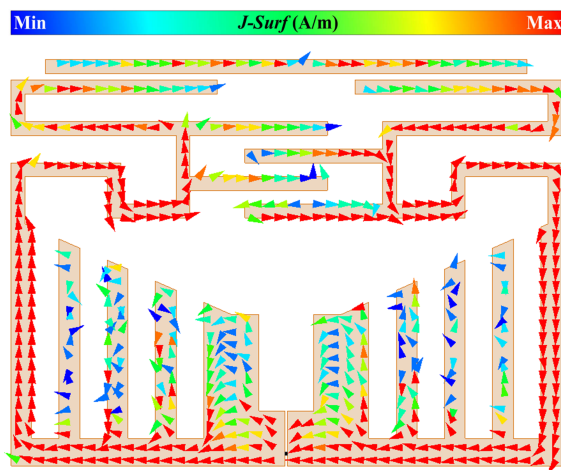


FIGURE 5. Simulated surface current distribution of the final antenna at 915 MHz.

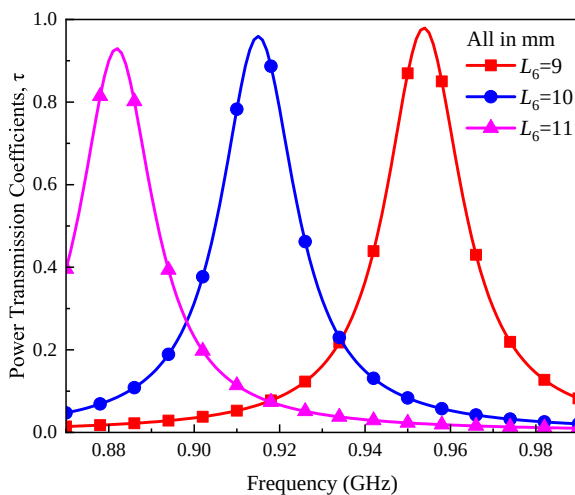


FIGURE 6. Effect of L_6 on the simulated power transmission coefficient τ of the proposed tag antenna.

These results provide a practical tuning strategy, in which L_6 is suitable for coarse resonance placement, whereas L_3 can be used for fine adjustment after the main loading topology has been fixed. Therefore, the operating frequency can be tuned

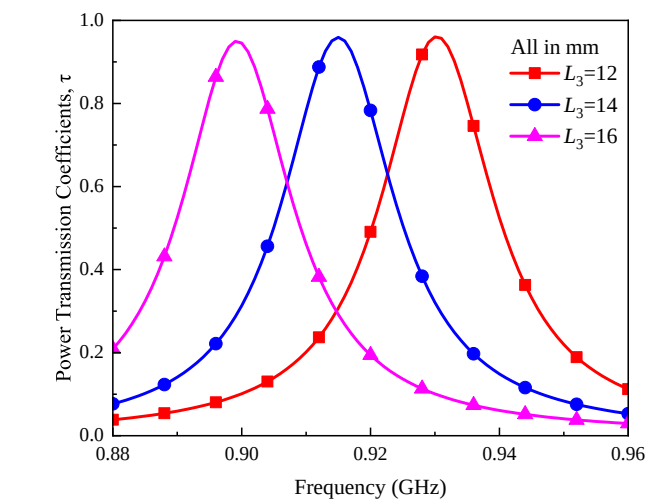


FIGURE 7. Effect of L_3 on the simulated power transmission coefficient τ of the proposed tag antenna.

without altering the overall coupled-current topology of the antenna, while maintaining a favorable power transmission coefficient between the antenna and the chip.

3. ROBUSTNESS VALIDATION UNDER ATTACHMENT CONDITIONS

3.1. Validation Scenarios and Evaluation Metrics

To evaluate the practical horizontal readability of the proposed tag antenna, we conducted simulations and measurements in free space and on four representative non-metallic surfaces, namely PP plastic, folded denim jeans, cardboard, and wood. These materials correspond to common logistics and warehousing objects such as plastic boxes or trays, textile products, paper packages or cartons, and wooden pallets or boards. The dielectric properties used in the simulations are listed in Table 2 [13–17]. These values were selected from reported RF/microwave material-characterization results and typical engineering parameters. In this work, robustness refers to the ability of the tag to maintain usable RFID link performance under representative

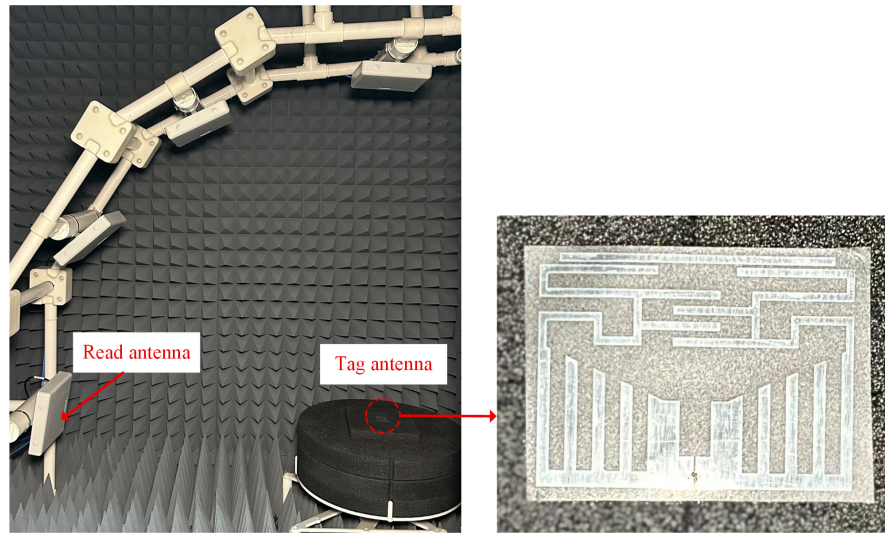


FIGURE 8. Measurement setup and fabricated prototype of the proposed tag antenna.

TABLE 2. Dielectric properties and representative scenarios of different attachment materials.

Surface	ε_r	$\tan \delta$	Representative scenario
Free space	1.00	0	Reference case
PP plastic	2.20	0.002	Plastic boxes and trays
Folded Denim Jeans	1.67	0.085	Textile products
Cardboard	1.78	0.055	Paper packages and cartons
Wood	1.83	0.076	Wooden pallets and boards

non-metallic attachment conditions while preserving continuous horizontal readability without geometrical retuning.

Fig. 8 shows the measurement setup and fabricated prototype. The tag antenna was fabricated on a flexible PET substrate and characterized in an RFID anechoic chamber using the Voyantic Tagformance Pro system. During the angular test, the tag was placed at the center of a rotating platform, whereas the reader antenna was fixed. The azimuth angle is defined in the xoy plane of Fig. 1, with 0° corresponding to the positive x direction. For each attachment case, the tag was directly attached to the tested surface without additional matching or geometric adjustment. The effective isotropic radiated power was set to 3.28 W for all cases to ensure a fair comparison among the different attachment conditions. The read range was obtained from the minimum transmitted power required to activate the chip at each frequency and angle using the Voyantic Tagformance Pro system.

For a passive UHF RFID tag antenna, the theoretical read range can be estimated using the Friis-based RFID link equation reported in [18]:

$$d = \frac{\lambda}{4\pi} \sqrt{\frac{P_t G_t G_{\text{tag}} \tau}{P_{\text{th}}}} = \frac{\lambda}{4\pi} \sqrt{\frac{\text{EIRP} G_{\text{tag}} \tau}{P_{\text{th}}}}, \quad (2)$$

where λ is the operating wavelength; P_t is the transmitted power of the reader; G_t is the reader antenna gain; $\text{EIRP} = P_t G_t$ denotes the effective isotropic radiated power; G_{tag} is the radiation gain of the tag antenna; τ is the power transmission coefficient between the tag antenna and the chip; and P_{th} is the minimum threshold power required to activate the chip. Eq. (2) indicates that the read range is jointly determined by the impedance matching, radiation gain, and chip sensitivity.

Fig. 9 shows representative attachment scenarios. In addition to the maximum read range, the horizontal omnidirectional stability was evaluated using four metrics: the maximum read range R_{max} , minimum read range R_{min} , read-range fluctuation $\Delta R = R_{\text{max}} - R_{\text{min}}$, and stability coefficient $C_s = R_{\text{min}}/R_{\text{max}}$. A smaller ΔR and larger C_s indicate better angular stability in the xoy plane. These metrics distinguish the absolute read-range reduction caused by material loading from the loss of horizontal readability caused by azimuthal blind directions.

3.2. Frequency-Domain Consistency under Different Scenarios

Based on dielectric parameters in Table 2, Fig. 10 first examines the power transmission coefficient between the antenna and the chip for the proposed tag in free space and under representative non-metallic attachment conditions. Compared with free space, the attached materials introduce moderate resonance shifts because the surrounding effective permittivity and loss change the current-path loading. Nevertheless, the peak values of τ remain distinct within the UHF RFID band, indicating that the coupled interdigital and comb-shaped sections tolerate realistic dielectric perturbations without geometric retuning.

The measured read-range spectra in Fig. 11 show frequency-shift trends consistent with simulated transmission-coefficient responses in Fig. 10. The frequencies corresponding to the maximum measured read ranges remain within the UHF RFID band. The free space and PP plastic exhibited stronger radiation performance near the designed operating region. Folded denim jeans, cardboard, and wood shifted the optimum frequency downward, which was consistent with the simulated

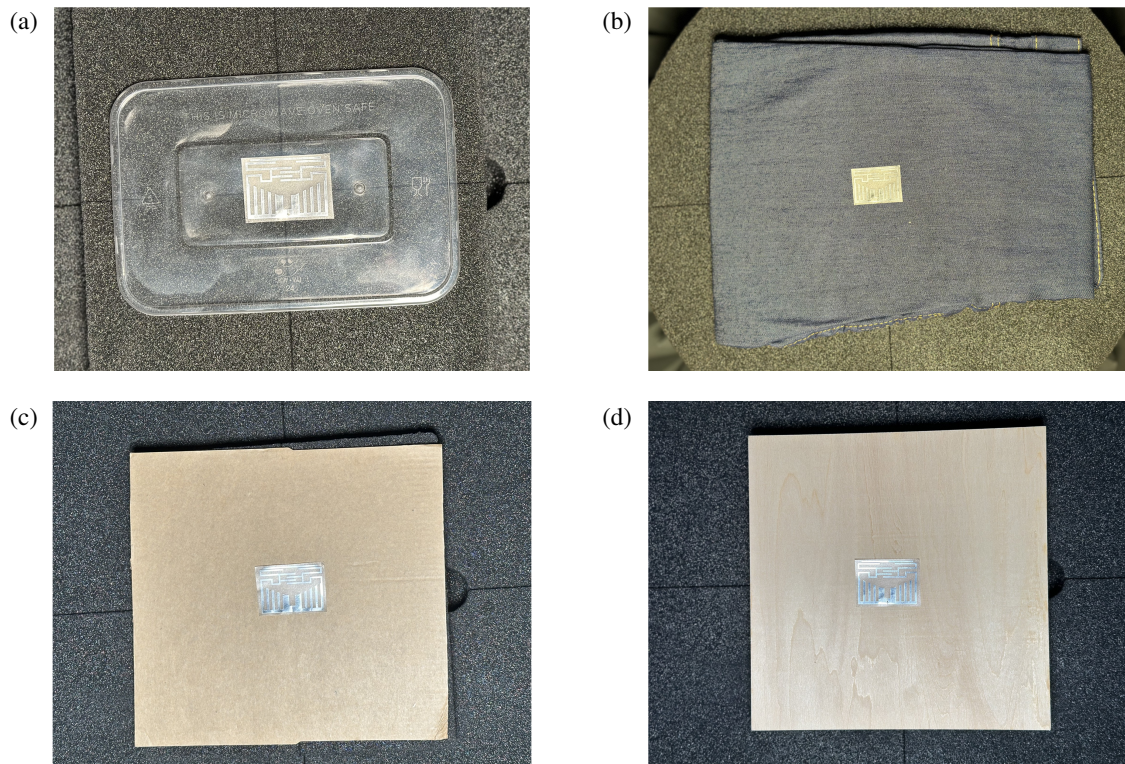


FIGURE 9. Measurement scenarios of the proposed tag attached to different materials: (a) PP plastic, (b) folded denim jeans, (c) cardboard, and (d) wood.

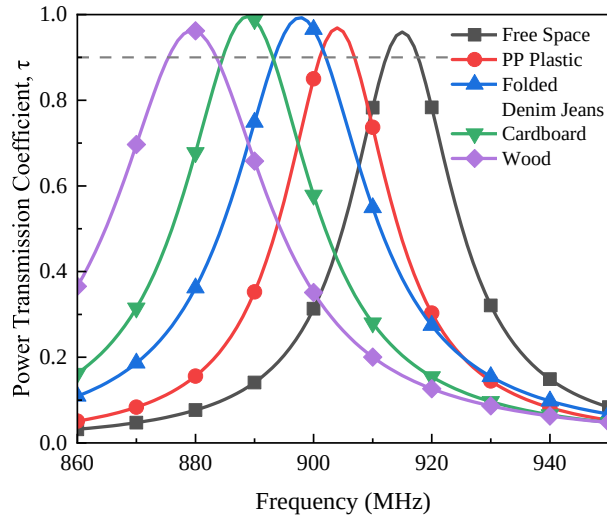


FIGURE 10. Simulated τ curves of the proposed tag antenna in free space and on different attachment materials.

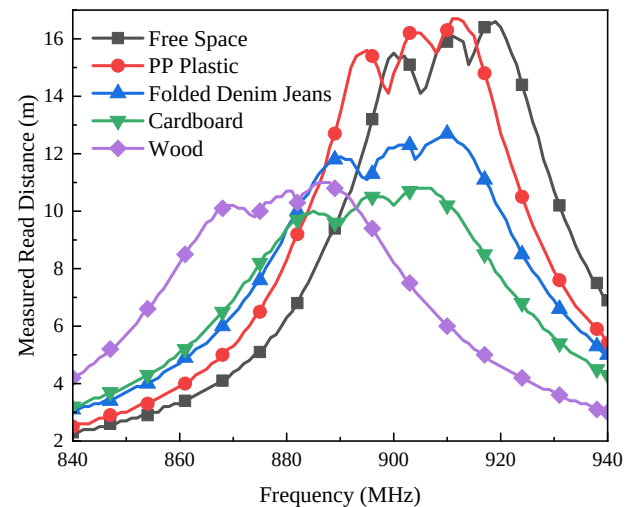


FIGURE 11. Measured read range versus frequency in free space and on different attachment materials.

detuning trend. Nevertheless, all tested cases maintained maximum read ranges exceeding 11 m.

Figure 12 compares simulated and measured maximum reading ranges. The simulated read-range values were calculated from Eq. (2) using the simulated realized gain and power transmission coefficient. Although small deviations arise from fabrication tolerance, chip mounting, and uncertainty in practical material parameters, simulation and measurement results show consistent trends. The measured maximum read ranges were

16.6 m in free space and 16.7 m on PP plastic, and remained 13.2 m, 11.4 m, and 11.2 m on folded denim jeans, cardboard, and wood, respectively. Thus, all tested scenarios maintained maximum read ranges above 10 m. These results are consistent with the distributed-current mechanism, which reduces antenna sensitivity to perturbations of any single local current path. The agreement among Figs. 10–12 therefore verifies that the proposed antenna combines long read range, attachment robustness, and reliable simulation-to-measurement consistency.

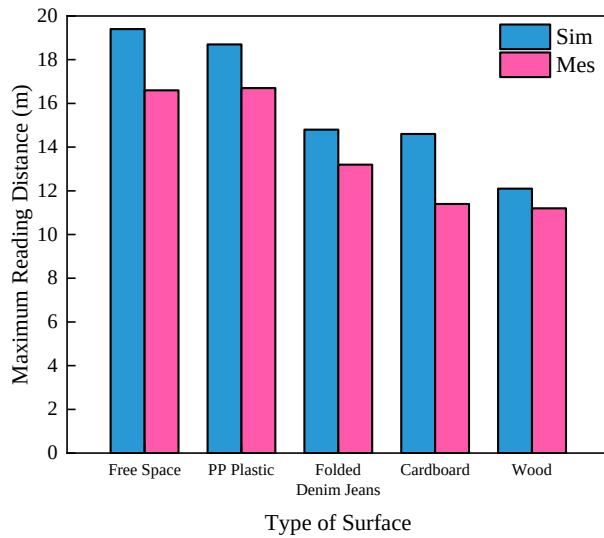


FIGURE 12. Comparison of the simulated and measured maximum read ranges in free space and on different attachment materials.

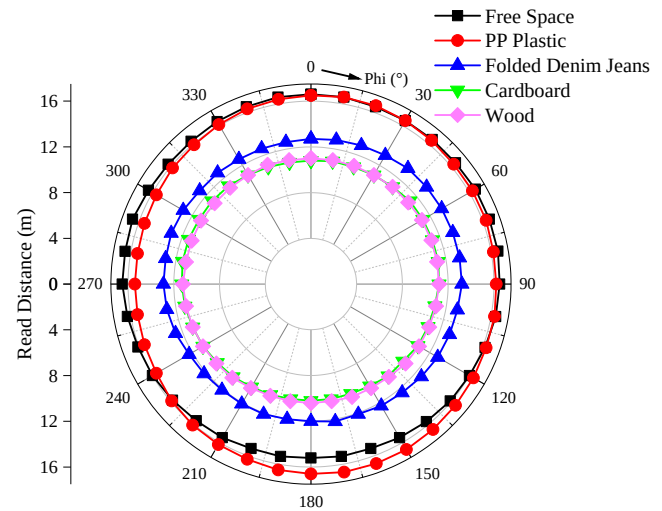


FIGURE 13. Measured read-range distributions from 0° to 360° in the *xoy* plane under different attachment materials.

TABLE 3. Horizontal omnidirectional stability metrics under different attachment scenarios.

Scenario	Optimum f (MHz)	$R_{\max}$ (m)	$R_{\min}$ (m)	ΔR (m)	$C_s = R_{\min}/R_{\max}$
Free space	919	16.6	15.2	1.4	0.916
PP plastic	912	16.7	15.4	1.3	0.922
Folded Denim Jeans	910	13.2	12.0	1.2	0.909
Cardboard	904	11.4	10.2	1.2	0.895
Wood	886	11.2	10.4	0.8	0.929

3.3. Horizontal Omnidirectional Readability and Performance Comparison

Fig. 13 evaluates the horizontal omnidirectional read performance by rotating the tag from 0° to 360° in the *xoy* plane. All five cases exhibited continuous angular read-range distributions without obvious blind directions. Free space and PP plastic showed nearly circular distributions with relatively high absolute read ranges, whereas folded denim jeans, cardboard, and wood maintained reduced but still continuous angular responses. Therefore, the material loading slightly changes the optimal frequency and maximum read range, but does not disrupt the horizontal reading continuity.

Table 3 summarizes stability metrics to convert qualitative polar distributions into quantitative evidence. The free-space, PP-plastic, folded-denim, cardboard, and wood cases yielded ΔR values of 1.4 m, 1.3 m, 1.2 m, 1.2 m, and 0.8 m, respectively, with corresponding C_s values of 0.916, 0.922, 0.909, 0.895, and 0.929. Even in the most fluctuating case, C_s remained close to 0.90, indicating that the read range was mainly reduced by material loading rather than by the formation of azimuthal blind directions. Therefore, the measured full-angle data confirm the robust horizontal readability of the proposed tag. This limited performance variation agrees with the distributed-current mechanism discussed in Section 2. The

upper transverse coupling path, central interdigital region, and lower comb-shaped branches form multiple coupled current paths that jointly support chip coupling and radiation. Consequently, representative non-metallic attachment materials may shift the resonant frequency and reduce the absolute read range, but they do not introduce deep azimuthal nulls, allowing the antenna to maintain continuous 0°–360° read responses.

Table 4 presents a comparison between the proposed antenna and recently reported UHF RFID tag antennas. For consistency, the reported read ranges were normalized to an EIRP of 3.28 W and a chip sensitivity of –24 dBm. Existing designs have demonstrated long-range identification on multiple non-metallic objects [11], thin and flexible configurations for specific applications [12, 21], or stable azimuthal readability in metallic environments [19, 20]. However, these features are generally achieved separately. In comparison, the proposed tag combines a thin 0.05 mm flexible profile, long read range on multiple representative non-metallic surfaces without geometrical retuning, and experimentally verified continuous 0°–360° horizontal readability. Measured maximum read ranges remain above 11 m in all evaluated cases, with horizontal stability coefficients no lower than 0.895. These results demonstrate a favorable combination of long-range identification, attachment tolerance, and stable horizontal readability for logistics and warehousing applications.

TABLE 4. Comparison between the proposed antenna and recent related UHF RFID tag antennas.

Ref.	Tag Volume (mm ³)	Surface tagged	Max Read Distance	Horizontal 0°–360° Validation
This work	40 × 29.5 × 0.05	Free space PP plastic Folded Denim Jeans Cardboard Wood	16.6 m 16.7 m 13.2 m 11.4 m 11.2 m	Yes
[11]	75 × 28 × 1.6	Free space Plastic Bottle Plastic box Wood Cardboard	17.1 m 17.6 m 14.3 m 7.4 m 14.7 m	Not reported
[12]	28 × 16 × 0.05	Free space Curved plastic bottle	10.7 m 8.4 m	Not reported
[19]	35 × 35 × 3.20	Metal plate	12.0 m	Yes
[20]	$\pi \times 17^2 \times 2$	Metal plate	5.9 m	Yes
[21]	40 × 14 × 0.05	Water bottle IV solution bag Blood bag	3.3 m 2.8 m 1.7 m	Not reported

The read distance represents the result calculated using EIRP of 3.28 W and chip sensitivity of −24 dBm.

4. CONCLUSION

A compact, flexible UHF RFID tag antenna was developed for long-range identification and stable horizontal readability under different non-metallic attachment conditions. The key design feature is the distributed coupled-current response formed by the open-frame radiator, transverse coupling path, interdigital section, and lower multi-branch structure. This configuration simultaneously supports antenna-chip conjugate matching and distributes the current over multiple coupled regions, reducing the sensitivity of the overall radiation response to local dielectric perturbations. Under an EIRP of 3.28 W, the measured maximum read range reached 16.6 m at 919 MHz in free space, and the 0°–360° read range in the *xoy* plane remained within 15.2–16.6 m. When mounted on PP plastic, folded denim, cardboard, and wood, the tag achieved maximum read ranges of 16.7, 13.2, 11.4, and 11.2 m, respectively. Corresponding horizontal stability coefficients were not lower than 0.895, indicating stable azimuthal reading performance under different non-metallic loading conditions. These results demonstrate the suitability of the proposed tag for long-range, continuous horizontal identification of representative non-metallic logistics and warehousing items.

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