Tilt and Tamper Sensing UHF RFID Security Tag

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Abstract

A passive tag is proposed for indicting mishandling of items in the supply chain. The tag signals excessive tilting by varying its read range and as a measure against counterfeiting, it is deactivated should it be removed from its original platform.

1 Introduction

While UHF Radio-frequency identification (RFID) technologies bring many benefits to automated parcel tracking [1], they do not sense if parcels have been mishandled by tilting, and also tags may be transferred to counterfeit items [2]. While delaminating tag labels reduce the risk of tag transfer in counterfeiting, it is still possible for the RFID transponder IC to be taken from the original tag and attached to a different antenna.

To address these issues, a totally integrated sensing tag is created for the following scenario. Initially, the tag has a very short read range when it is attached to a parcel and the tag EPC code is set and logged using a handheld reader. After mounting, the tag read range is maximum for reliable detection by readers several metres away. Should the parcel be tilted, the tag read range falls to around half of the maximum value. The reduced read range indicates a tilt event has occurred prior to the read. If the tag is removed from the parcel, the transponder IC is ripped from its pins and the tag is rendered useless.

2 Tag Mechanisms

To enable passive operation and the memorization of state occurrences, the tag uses integrated mechanical mechanisms as illustrated in Fig. 1. The antenna is suspended a distance \( h_1 \) above a conducting ground and mount detection is enabled by adjusting \( h_1 \) between two discrete values (0.5mm before mounting, and 5 mm when mounted). The detuning that occurs between the 2 values affects the RFID read range and this signals if the tag is mounted.

Tag removal, or tamper detect is achieved through a clip-lock attachment that directly fixes the transponder IC to the inside of the top cover. The RF pins of the SOT-232 package are soldered to the antenna terminals and before mounting, the chip is separate from the top cover. When mounted on a surface, the antenna substrate is pushed against the springs and the IC becomes clip-locked to the inside of the cover. If the tag is subsequently unmounted, the springs push the substrate from the upper cover but the IC remains within its clip-lock. The spring separating force breaks the IC pins from the SOT package and the chip is rendered unusable.

Tilt detection is achieved through the incorporation of two rectangular pads with the antenna port as shown in Fig. 1(b). When the tag is tilted a conducting disk drops through a routed channel in the cover. The disk ends up in close proximity to the antenna pads and the capacitive loading detunes the antenna in a controlled way.

3 Antenna Design

The tag antenna in Fig. 2 is a coplanar feed half wave dipole on FR4 dielectric. It differs from other embedded T-matched designs [3] through its multilayer substrate, incorporated sensing pads and rear ground plane. Fig. 2(c) shows the transponder chip connection and the inset sensing pads.

The antenna length was initially calculated from:

\[
L_1 = 0.47 \cdot \frac{c}{f_{res} \cdot \epsilon_{re}} \tag{1}
\]

where \( f_{res} \) is the resonance frequency and \( \epsilon_{re} \) is the effective relative permittivity of the substrate and air layers between the antenna and the ground plane. Since the conducting ground is only 13% larger than the antenna, the structure resembles a parallel plate capacitor and the \( \epsilon_{re} \) of the material stack is calculated from [3]:

\[
\epsilon_{re} = \epsilon_{sub} \left( \frac{\epsilon_{air} + \epsilon_{h_1}}{2} \right) \tag{2}
\]

In the mounted state \( (h_1 = 5\text{mm}) \), the antenna was tuned for maximum power transfer with a conjugate match to the RFID chip by adjusting slot dimensions \( L_2 \) and \( S \) together with the feed line width \( W_2 \).

The ground plane isolates the tag from the mounting surface and moves between 2 discrete \( h_1 \) separations from the antenna to signal that the tag is either in an unmounted, or mounted state. The distinct state based approach is used to avoid inaccuracies in exact ground plane positioning. It is therefore necessary to establish the antenna performance as a function of ground plane separation.
caused 62 MHz detuning, with marginal change in the tag performance. The metal springs were found to have no significant effect on the antenna gain (5.9 dBi) or total efficiency (78%), where the latter includes radiation, material, and input losses.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground plane $L \times W$</td>
<td>155 x 42</td>
</tr>
<tr>
<td>Dipole $L_1 \times W_1$</td>
<td>134 x 35</td>
</tr>
<tr>
<td>Slot $L_2 \times S$</td>
<td>109 x 3</td>
</tr>
<tr>
<td>Feed line length $W_2$</td>
<td>3</td>
</tr>
<tr>
<td>Pad $L_3 \times W_3$</td>
<td>3.5 x 3.5</td>
</tr>
<tr>
<td>Pad recess, $L_4 &amp; W_4$</td>
<td>10 &amp; 4</td>
</tr>
<tr>
<td>Air gap height, $h_1$</td>
<td>0.5 &amp; 5</td>
</tr>
<tr>
<td>FR4 substrate height, $h_2$</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 1: Tag dimensions ($f_{res} = 915$ MHz).

For small $h_1$ values the proximity of the ground plane causes a reduction in radiation resistance and high input reflection loss. Simulated resonance frequency and total efficiency for varying ground plane separation identified the optimal $h_1$ to be 5 mm. Therefore, $h_1$ values of 0.5 mm and 5 mm were chosen to give the maximum variation in read range from before the tag is mounted, to when it is attached.

The antenna, enclosed in its ABS casing, was simulated with CST MWS® to tune to the American UHF RFID band, resulting in the dimensions in Table 1. Removal of the casing

### 4 Antenna Parametric Analysis

To establish a design guide for input match at $h_1 = 5$ mm, the tag was simulated for various values of slot width $S$. Fig. 3(a) shows how the real part of the antenna impedance decreases for wider slots, and the reactance becomes less inductive. $S = 3$ mm is selected to provide the required inductance at the antenna port to conjugate match an Alien Higgs 3 chip ($Z_{in} = 25 - j149 \Omega$) [4].

![Diagram of passive tag mechanical sensing mechanisms](image1)

Fig. 1. Passive tag mechanical sensing mechanisms. (a) Mounting sensor & Tamper detecting mechanism (side view), (b) Tilt detect and memory mechanism (top view).

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![Diagram of tag antenna geometry](image2)

Fig. 2. (a) Tag antenna geometry, (b) side view, (c) close view of feed and tilt sensor pads. Dimensions are given in Table I.

![Diagram of antenna T-match slot](image3)

Antenna T-match slot (beneath routed channel)

![Diagram of tilt mechanism](image4)

Tilt clockwise (top) & return (bottom)

![Diagram of sensing pads](image5)

Sensing pads, RFID ASIC, Rear ground plane
it is mounted, and when it is mounted on metal, first un-tilted, then tilted. The low surface current before mounting, Fig. 4(a), is due to the proximate rear ground plane. After mounting the tag is well matched and strong surface currents are observed in Fig. 4(b). However, a noticeable reduction in current magnitude is observed in Fig. 4(c) after tilting as the tag is now partially mismatched.

Fig. 4. Tag antenna surface current at 915 MHz on (a) no mount ($h_t = 0.5$ mm), (b) metal plate ($h_t = 5$ mm) – no tilt, (c) tilted.

The effect on tag performance for these states can be appreciated by considering the read range $d$ [5]:

$$d \leq \frac{3}{4\pi} \sqrt{EIRP \times G_{tag} \times \tau / P_{th}} \quad (3)$$

where $EIRP$ is the reader effective isotropic radiated power, $G_{tag}$ is the tag antenna gain and $P_{th}$ is the chip turn-on power. The power transfer coefficient $\tau$ between the antenna and the chip is related to the voltage reflection coefficient $\Gamma$ of the tag antenna port by [6]:

$$\tau = 1 - |\Gamma|^2 = 4R_{ic}R_{ant} / (Z_{ic} + Z_{ant})^2 \quad (4)$$

where $Z_{ic}$ and $Z_{ant}$ are of opposite reactance types and represent the complex port impedances of the transponder chip and the antenna respectively, while $R_{ic}$ and $R_{ant}$ are the corresponding real parts. The voltage reflection coefficient is [7]:

$$\Gamma = (Z_{ic} - Z_{ant}) / (Z_{ic} + Z_{ant}) \quad (5)$$

Tilt detection is achieved by the sensing pads in Fig. 2(c). The pads are open circuit when the tag is un-tilted and the pad impedance $Z_t$ is connected in parallel with the antenna port impedance. However, when the tag is tilted beyond a predefined angle, a metallic disk with a thin polymer coating makes capacitive contact with the pads causing the impedance $Z_t$ to appear across the antenna port. From (5), the port voltage reflection coefficient is given by:

$$\Gamma = \left( Z_{ic} - \frac{Z_{ant}Z_{1,2}}{Z_{ant} + Z_{1,2}} \right) / \left( Z_{ic} + \frac{Z_{ant}Z_{1,2}}{Z_{ant} + Z_{1,2}} \right) \quad (6)$$

5 Tilt Sensing by Antenna Impedance Mismatch

Fig. 4 shows the simulated surface currents for the tag before and after tilting.
where \( Z_{12} \) represents the impedance of the open circuit pads and the pads + disk respectively.

| \( Z_{an} \) | \( C \) (\( \mu F \)) | \( L \) (\( nH \)) | \( R \) (\( \Omega \)) | \( X \) (\( j\Omega \)) | \( |\Gamma| \) from (5) | \( d \) (m) from (3) |
|----------------|
| Antenna alone (\( Z_{an} \)) | 19 | 25 | 110 |
| Sensing pad (un-tilted: \( Z_i \)) | 0.35 | 0.52 | -492 |
| Sensing pad (Tilted: \( Z_2 \)) | 1.02 | 0.06 | -169 |
| Antenna & pads (un-tilted) | 27 | 56 | 155 | 0.42 | 17 |
| Antenna & pads (tilted) | 36 | 212 | 202 | 0.79 | 11 |

Table 2: Simulated sensor pad effect on tag port impedance, calculated reflection coefficient, and RFID read range. Platform = air with tag activated (\( h_t = 5 \) mm, frequency = 915 MHz, reader \( EIRP = 36 \) dBm, \( G_{tag} = 5.7 \) dBi, and \( P_n = -15 \) dBm).

The un-tilted tag is designed for maximum power transfer so \( \Gamma_{un-tilted} \) has a low magnitude. When tilted, the mismatch associated with \( Z_2 \) in (6) results in a higher magnitude for \( \Gamma_{tilted} \). Table 2 gives the simulated impedances respectively for \( Z_{un-tilted}, Z_i, \) and \( Z_2 \). Port values are also given for the connected antenna and pad impedances in both states together with the corresponding reflection coefficients calculated from (5). Read range values obtained from (3) are also given. It can be seen that the tilted read range falls to half of the un-tilted value, and it is this significant difference that allows discrimination between the un-tilted and tilted states.

6 Measured Tilt Signalling

The fabricated tag is shown in the tilted (Fig. 5(a)), and tampered states (Fig. 5(b)). The read range \( d \) was measured from 800 to 1000 MHz using Voyant equipment [8].

The read ranges at 915 MHz for the initial (un-mounted), mounted (on metal) and tilted (on metal) states were 1.1, 20.3 and 7.5 m respectively with sufficient bandwidth to cover the American RFID band. In the tilted state, the read range decreased by 63% with less than 10 MHz shift in the peak frequency. This demonstrates good discrimination between the states. In the initial state, the tuned frequency decreased by more than 70 MHz giving a measured read range of 1 m in the tag deployment stage where a handheld reader is used.

7 Conclusions

A rugged cased tag is described for tamper and tilt sensing on different platforms, where the use of a stud-lock system attached to the tag ASIC prevents fraudulent swapping of transponders to counterfeit tag antennas. Discrete state antenna impedance detuning due to the interaction of conducting discs passively memorises inappropriate tilting events.

References
