Effects of a Metal Plane on a Meandered Slot Antenna for UHF RFID Applications

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Abstract

In this paper, the effects of a metal plane on the performance of a meandered slot RFID antenna are evaluated in a real environment, and 3 metal plane cases are considered (the most likely scenarios in which metal conductive materials are placed near the tag antenna). The metal plane effects can be categorized as matching degradation and antenna gain variation. First, matching degradation due to the antenna's induced mutual impedance is experimentally investigated. In addition, the gain variation is investigated to figure out the change in the radiation characteristics. With the derived antenna parameters, the read range is calculated with the Friis transmission equation and measured to analyze the effects of a metal plane on RFID system performance. The calculated and measured read range varies from 9.3 m to 19.1 m as the distance between the RFID antenna and the metal plane changes.

Key words: RFID, Mutual Impedance, Metal Effects, Friis Transmission Equation, Slot Antenna.

1. Introduction

RFID (Radio Frequency Identification) has gained tremendous attention due to the increasing industrial applications. Several types of RFID frequency bandwidths are categorized according to their use: LF (Low Frequency: 125 kHz), HF (High Frequency: 13.56 MHz), UHF (Ultra High Frequency: 860~960 MHz), and 2.45 GHz. Among these frequency bands, the UHF RFID systems are popular due to the realizable size of the antenna and far-field operation ranging from several meters to more than 10 meters. Each country has different frequency standards for UHF RFID applications; for example, 908 ~ 916 MHz has been established as the industrial standard in Korea.

In overall passive RFID systems, the tag antenna is a critical component that determines the RFID reading range performance. The tag antenna collects power from the reader to operate the tag chip since it does not include an internal power source; thus, the UHF RFID systems cannot operate properly or even be turned on at all if the tag antenna is not functioning properly [1]. In most cases, the output impedance of a tag chip reveals

capacitive characteristics: low output resistance and large negative output reactance. This is why UHF RFID antennas should have inductive impedance to provide complex conjugate matching for maximum power transfer between the antenna and the chip [2], [3].

Many techniques have been proposed to realize low resistance and highly inductive reactance with non-patch type antennas. A conventional method of realizing this condition is the T-matching section methodology that can be used as an impedance transformer [4]~[6]. Another technique is an inductively coupled feed methodology that uses inductive coupling between the feed loop and the radiating body [7]~[9]. These techniques can be implemented directly with any radiation structure at the resonance. In addition, slot techniques reveal complementary properties compared to a conductive antenna. Matching by slot modification with a genetic algorithm has been proposed in [10], and impedance manipulation with a conductive area is proposed in [11].

RFID tag antennas, however, suffer performance degradation in a real environment, since they are designed based on the assumption they will operate in free space. In practice, there are numerous foreign materials adja-

Manuscript received May 2, 2012 ; Revised May 30, 2012 ; Accepted June 5, 2012. (ID No. 20120502-012J)

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cent to tags, and metallic materials in particular significantly affect tag performance. The topic of this paper is the effect of a metal plane on an RFID meandered slot antenna. Metal effects on antennas can be categorized in two ways. The first is the induced mutual impedance that could degrade conjugate matching between the tag chip and the antenna. Various studies [12]~[16] on matching degradation have focused mainly on very near distance operations, such as a few mm from the metal to the tag. However, mutual impedance is generally induced further than a few cm and even more than a half-wave length depending on the orientation and polarizations. In addition, most studies have focused on the bandwidth; very few works have paid attention to the impedance variation profiles [17]. The second is the antenna gain variation that can be modeled with the two-array antenna system based on the image theory. A few studies on the gain variation [13], [18] have considered short distances and only one orientation of the tag antenna and the metal plane.

In this paper, the effects of an electrically large metal plane to the RFID meandered slot antenna are quantitatively investigated. This paper is organized with 4 sec-

Fig. 1. The schematic of the meandered slot antenna and zoomed slot section [11].

Fig. 2. The simulated and measured impedance response of the AUT (Antenna Under Test).

tions. In section II, the designed meandered slot UHF RFID antenna with a center frequency of 912 MHz is described. After the antenna is described, the matching degradation due to the induced mutual impedance and the gain are discussed in section III as a function of the antenna parameter variation. To quantify the performance variation of an RFID system, the read range as a figure of merit is discussed in section IV with the derived parameter variations from section III.

II . AUT Characteristics

In this work, a meandered slot dipole antenna is chosen for the test antenna based on its inductive impedance characteristics, which can be explained with the complementary relation of Babinet's principle and Booker's relationship. Since conventional dipole antennas have capacitive impedance near the resonance frequency owing to their open-circuited configuration, the complementary structure of the dipole antenna can realize inductive impedance.

The impedance of a slot antenna can be controlled with equation (1) without implementing additional matching networks. Z_{con} is the impedance of the complementary conductive antenna, and η is the intrinsic impedance in the free space. Babinet's principle and Booker's relationship are used to derive the slot impedance equation (1) under the assumption that there is an infinite metal area. Thus, the slot antenna can be matched to the complex conjugated impedance of an arbitrary CMOS (Complementary Metal-Oxide Semiconductor) tag chip by adjusting the length of the slot and the area of the metal area.

Fig. 3. The measured and simulated power reflection coefficient of the AUT.

Fig. 4. Measured read range of AUT in the anechoic chamber.

$$Z_{\text{slot}} = \frac{\eta^2}{2Z_{\text{con}}} \quad (1)$$

Fig. 1 shows the designed slot antenna; note that the slot dipole section is meandered to reduce the size of the overall slot length. The metal area (the grey area in the figure) is further extended to implement the required impedance value, a complex conjugate to the impedance of a Higgs-3 chip [11]. Since the impedance of the chip is $20 - j135 \, \Omega$ at 912 MHz, the AUT (Antenna under Test) is designed to have an impedance of $20 + j135 \, \Omega$ at the operating frequency.

The AUT is fabricated on a flexible substrate with $\epsilon_r = 2.8$ and $\tan(\delta) = 0.008$, and a substrate thickness of 0.028 mm. The design parameters are $L_1 = 12.5$ mm, $L_2 = 14.5$ mm, $W_1 = W_2 = 0.3$ mm, $L_v = 90$ mm, and $L_H = 34$ mm [11]. Fig. 3 shows the measured input impedance in free space. The input reactance increases inductively as expected from Babinet's principle, and the input resistance also increases significantly near the resonance frequency. Fig. 3 shows the return loss response, revealing excellent conjugate matching between the antenna and the tag chip. As a result, the measured 3-dB bandwidth is 80 MHz with about 9 % FBW (Fractional Band Width). The radiation pattern of the slot antenna is similar to that of a conventional short dipole with a simulated gain of 2.17 dBi. The measured read range in an anechoic chamber is shown in Fig. 4 with the omni-directional read range pattern in the E-plane. In the H-plane, the read range pattern reveals null point due to the mini-

mum radiation of the antenna itself.

III. Antenna Parameter Variation

3-1 Experimental Setup

To explore the effect of an adjacent metal plane, the input impedance variation is measured as a function of distance, which is chosen every 1 cm from the metal plane. In addition, the gain variation is calculated to assess the effect of the variation in the radiation pattern due to the metal plane. The size of the metal plane used in this work is $800 \times 800 \text{ mm}^2$, which is electrically large compared to the antenna. Fig. 5 shows three different

Fig. 5. Experiment configurations for mutual impedance and radiation pattern variation for the test antenna due to an adjacent metal plane.

metal plane configurations where the metal plane is separated from the AUT by distance d . These are chosen to take into account most of the possible scenarios in which conductive materials would be placed near the tag antenna. In cases 1 and 2, the metal plane is located in the main lobe of the tag antenna, while in case 3 the metal plane is in the null direction. In particular, case 1 is important since it is directly related to the application of a metal tag antenna.

3-2 Input Impedance Variation Due to Metal Plane

Compared to conventional antennas for purposes other than mobile applications, impedance variation due to mutual coupling caused by nearby objects is a significant problem in RFID antennas. The amount of mutual coupling is negligible if a conductive material is located more than a half-wave length away.

As illustrated in the previous section, the input impedance of AUT located at various distances from a metal plane is investigated to identify the effect of the mutual coupling on the RFID performance. The input impedance is measured with the test fixture proposed in [19] in conjunction with the vector network analyzer. Fig. 6 shows the measured input impedances as a function of distance between the antenna and the metal plane. As expected, the amount of mutual coupling is different for different arrangements due to the unequal induced current distribution on the metal plane. The induced surface current is most significant when the metal plane is located in the main lobe and faced with AUT. Fig. 6(a) shows the input impedance of the AUT that changes more dramatically compared to other cases since the planar metallic plane is located in the main lobe region and faced with AUT. Fig. 6(b) shows a variation in the input impedance when the metallic plane is placed in the horizontal direction of the AUT. As expected, the antenna impedance changes less drastically than case 1 as expected. In case 3, the metal plane is located in the null direction of the AUT, revealing the least variation of the input impedance. The input resistance and the reactance increase sharply when the distance is small since the induced image source is in the same direction in contrast to cases 1 and 2. As discussed in the previous section, the increased mutual impedance results in matching degradation. In overall RFID systems, this matching degradation can be expressed with τ , PTC (the Power Transmission Constant), which is defined as the delivered power and the available power. The reflection coefficient is determined with equation (2), and the PTC is derived from the reflection coefficient with equation (3).

Fig. 6. Three measured input impedance variance profiles due to the adjacent metal plane.

$$\Gamma = \frac{Z_{\text{chip}} - Z_{\text{ant}}^*}{Z_{\text{chip}} + Z_{\text{ant}}} \quad (2)$$

$$\tau = 1 - |\Gamma|^2 \quad (3)$$

Fig. 7. The PTC variation of each case due to induced mutual impedance on the AUT.

The ratio of the power transfer between the tag chip and the tag antenna can be explained directly with the PTC, and the result is plotted in Fig. 7. As expected, the PTC at 16 cm is very close to 1, which implies the maximum power transfer from the RFID chip to the antenna. However, the PTC gradually decreases as the distance decreases due to the increased mutual impedance of the antenna. The PTC behaves differently for different metal-AUT configurations, and case 1 reveals the most widely varying PTC due to its face-to-face arrangement.

3-3 Gain Variation Due to the Metal Plane

The input impedance and the radiation pattern are affected by a nearby metal plane. The metal plane effectively produces the image radiation current source behind the metal plane. Therefore, the radiation pattern of the AUT with the adjacent metal plane can be seen as an array antenna. The radiation pattern of a two-element array is theoretically composed with opposite-directed current source in cases 1 and 2, but the same direction for case 3. In general, 2-antenna array configurations can be divided into 3 cases according to the direction of the array axes, which are the x-, y-, and z-directions. The array factor for these 3 cases can be derived using the image theory.

$$AF_1 = 2j \sin[kh \sin(\theta) * \cos(\phi)] \quad (4a)$$

$$AF_2 = 2j \sin[kh \sin(\theta) * \sin(\phi)] \quad (4b)$$

$$AF_3 = 2 \cos[kh \cos(\theta)] \quad (4c)$$

Furthermore, the element pattern is chosen as an infinitesimal dipole antenna because the radiation pattern

Fig. 8. Calculated and simulated antenna gain variations profiles due to the metal plane in 3 cases.

of a slot antenna array can be modeled with a dipole antenna by Babinet's principle [20]:

$$EF = \sin(\theta) \quad (5)$$

With the derived factors, the overall antenna gain of each case is estimated based on the assumption of an infinite ground plane. Fig. 8 shows the gain variation profiles. Cases 1 and 2 reveal that the gain of the test antenna increases greater than 8 dBi and fluctuates as the distance varies. Case 3 shows a relatively small variation compared to cases 1 and 2; note that the simulation result deviates from the estimated result as the distance increases. The metal plane in the simulation is finite [21], [22], while the calculation assumes an infinite PEC ground plane so that the back lobe cannot propagate through the ground plane.

The radiation patterns in cases 1 and 2 are similar, and the antenna gains are precisely predicted. In contrast, the antenna gain for case 3 is less than 6 dBi, which is significantly different from the straight forward array theory derived from the image of the infinitesimal dipole. The vertical dipole above the imperfect finite-size ground plane causes the large back side lobe.

IV. Read Range Analysis

In RFID systems or any system using the back-scattering mechanism, transmission performance can be categorized in terms of sensitivity characteristics. That is, if the back-scattered power from the tag is the bottleneck of the overall system performance, the transmission distance can be defined by equation (6). However, if the RFID tag chip is the bottleneck of the overall system performance, the reading range can be defined as R_2 :

Fig. 9. Measured and calculated read ranges of 3 cases in the anechoic chamber.

$$R_1 = \frac{\lambda_0}{4\pi} \sqrt{G_{\text{reader}} G_{\text{tag}} \tau} \sqrt[4]{\frac{P_T}{P_{\min}}} \quad (6)$$

$$R_2 = \frac{\lambda_0}{4\pi} \sqrt{G_{\text{reader}} G_{\text{tag}} \tau} \sqrt{\frac{P_T}{P_{\min}}} \quad (7)$$

where λ_0 is the wavelength at 912 MHz; τ is the PTC of the antenna; G_{reader} and G_{tag} are the gain of the reader and the tag antennas, respectively; P_T is the standard transmission power at the reader; and $P_{\min}$ is the minimum transmission power to activate the tag at the reader at a distance of 1 m.

In realistic circumstances, the transceiver performance of a RFID tag chip is significantly inferior to a transceiver in a reader because the RFID tag chip has stringent size and performance limitations compared to the RFID reader system. That is why equation (7) is applicable in a real-world environment, and R_2 is chosen for transmission analysis in this work. There are 3 critical control variables, and they are the tag gain, the PTC, and the minimum required power at the tag antenna. An estimate of the read range can be obtained with controllable parameters. However, equation (7) cannot be applied when we measure the read range since these parameters are not measurable with conventional antenna measurement equipment. Measurement ports are not implemented in the tag, and moreover, the tag chip is directly connected to the antenna.

To measure the read range in an anechoic chamber environment, equation (7) should be modified to be represented with measurable quantities from the reader. One measurable variable is the sensitivity of the antenna at the reader side. By measuring the minimum power for the response of the tag at the reader side, the sensitivity can be derived with following equations [23]:

$$S_{\text{tag}} = \frac{P_{\min_tag}}{G_{\text{tag}} \tau} = \frac{P_{\min_reader}}{L_{\text{path}}} \quad (8)$$

$$R = \frac{\lambda}{4\pi} \sqrt{\frac{P_T G_{\text{reader}}}{S_{\text{tag}}}} = \frac{\lambda}{4\pi} \sqrt{\frac{P_T G_{\text{reader}} L_{\text{path}}}{P_{\min_reader}}} \quad (9)$$

where S_{tag} is the sensitivity of the tag antenna, R is the measured read range, L_{path} in equations (8) and (9) is the calibrated path loss at 1-m distance between the tag and the reader, P_T is 30 dBm, and G_{reader} is 6 dBi with linear polarization, so the EIRP is 36 dBm in this study.

With the derived parameters, such as the PTC and the realized gain, the read ranges for these 3 cases are calculated with equation (7) to predict the effect of a metal plane on tag performance. The estimated and measured read ranges are plotted in Fig. 9, and the estimated and measured results agree very well. Fig. 9 shows that read ranges for cases 1 and 2 of about 18 m and even 19 m are obtained for a 4-cm distance because the gain of the tag antenna increases over 8 dBi. Note that strong mu-

tual coupling between the antenna and the metal plane renders a lower PTC, resulting in a decreased read range.

These 3 cases reveal distinctive matching degradation characteristics with different metal plane configurations. Case 1 suffers significant matching degradation, resulting in a degraded PTC as the metal plane is 1 cm away, and the read range decreases to 9.3 m from 19.1 m. The PTC in case 2 decreased to 0.6 from 1, so the read range does not decrease as much as in case 1. Case 3 has a stable PTC, which is all more than 0.9, so the read range lies between only 13 m and 14.8 m.

V. Conclusion

The effects of an adjacent metal plane on RFID performances are derived and analyzed as a function of the degree of matching characteristics and gain variation. The most relevant 3 metal configurations are chosen to model the meandered slot RFID tag antenna in a real environment.

Cases 1 and 2 suffer matching degradation due to mutual impedance caused by electromagnetic coupling between the tag antenna and the metal plane face-to-face, so image radiation sources have an inverse direction that decreases the radiation resistance. Case 3 shows better matching characteristics, but the antenna gain enhancement is lower than in cases 1 and 2 because back lobe radiation occurred since the metal plane is located in the null direction of the original radiation pattern.

With the derived factors, the read range of the RFID tag system is predicted theoretically based on a modified Friis transmission equation. The read range is measured to confirm the validity of the prediction, and the results match the predicted values.

This research was supported by the MKE (The Ministry of Knowledge Economy), Korea, under the ITRC (Information Technology Research Center) support program supervised by the NIPA (National IT Industry Promotion Agency)" (NIPA-2012-H0301-12-1001).

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