Research Article

Design and Analysis of High-Performance Smart Card with HF/UHF Dual-Band RFID Tag and Memory Functions

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In this paper, we introduce a novel design of high-performance smart card with HF/UHF dual-band RFID tag to overcome frequency interference problem. Firstly, we have designed and tested a UHF RFID tag using a simulation software system. In the smart card hardware design stage, we connect a HF antenna and a UHF antenna and place them in one inlay sheet. Using a spectrum analyzer, we systematically adjust the antenna pattern to detect the optimal patterns that fit the impedance of the RFID chip. We evaluate the performance of the resulting smart card with standard RFID testers. The experiments show that our proposed RFID tag outperforms other dual-band RFID tags and maintains itself in a reasonable size. Moreover, we increase IC chip’s memory capacity to resolve security-related problems when RFID tags are used in a financial transaction. We firstly exploit an IC contact protruded from the card to add an additional memory, and we integrate functions of the RFID tag to use the equipped memory through the induced current of the contact. The implemented prototype of our proposal can accommodate an extended memory ranging from one gigabyte up to four gigabytes.

1. Introduction

Radio frequency identification (RFID) is one of the basic technologies for the realization and implementation of ubiquitous and pervasive computing. For the design of high-performance RFID technology, we primarily need to research and invest on technologies for the design of RFID antennas [1]. For the last several years, numerous studies have been conducted on the design and implementation of RFID. Especially, there have been intensive researches on the implementation of 13.56 MHz RFID antennas and on the commercialization of RFID tag products with different types and functions [2–4].

One of the popular commercial configurations in contemporary RFID card products is a financial IC chip. It is equipped with RFID and does not contain a USB-type memory. The IC chip is used for the authorization and authentication for secure financial transaction, and the separate USB-type memory can also be used for the memory function of public certificate, which is widely used in Republic of Korea. Another typical example of contemporary RFID card products is a transit card for public transportation. There have been various commercial RFID-based transit cards designed to maximize the functional usage and efficiency of USB memories inside the cards. Additionally, there have been observed remarkable changes in transit card development including the evolution to a general-purpose multifunctional card for the application to diverse domains. For instance, RFID cards are applied to the security of personal computers and business/enterprise-level security hub by utilizing the memories inside the cards.

1.1. HF/UHF Dual-Band RFID Tag. With this wide-spread use of UHF RFID tags, related studies are being conducted actively, and thus various patterns of UHF (900 MHz) RFID antenna are being designed [5]. The space at the center of a UHF RFID antenna is usually used for the contact with a chip through chip bonding. Furthermore, in antenna design, the size of antenna as well as its pattern can make a significant impact on the performance of RFID. Recently, dual-band RFID tags, which integrate two frequencies of HF/UHF on one sheet, are also widely studied [6–9]. One typical obstacle of the dual-band RFID tag is a mutual frequency interference

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phenomenon due to the fabrication of the HF antenna and the UHF antenna on the same sheet.

1.2. Memory Function. Also, RFID tags with low memory capacity can raise security issues due to the limited space for storing crucial information. The security of smart card can be greatly enhanced by adding large memory. For example, if a user can have a long password that can be encrypted in long bits, criminals will have much more difficulty in cracking the password. However, most RFID chips have only from one to four kilo-bytes memory, which are not suitable for storing encrypted passwords and public/private digital certificates used in electronic financial transaction.

Considering these backgrounds, in this paper, we present a novel design and implementation of a HF/UHF dual-band RFID tag that integrates internal card memory using an IC contact protruded from the RFID card in order to solve the above mentioned problems in the functions and security of card introduced by increasing the memory capacity of IC chip.

The remainder of this paper is organized as follows. In Section 2, we explain the design of dual-band RFID tag and IC chip embedded with memory function. In Section 3, we discuss empirical results of our proposed card prototype. In Section 4, we discuss related work. Finally, in Section 5, we summarize and conclude our research with future research directions.

2. Design of Dual-Band RFID Tag and IC Chip Embedded with Memory Function

In this section, we explain our design of memory-embedded dual-band RFID tag in general (Section 2.1), design of dual-band RFID tag (Section 2.2), and design of memory/IC chip (Section 2.3).

2.1. Design of Memory-Embedded Smart Card in General. The purposes of this research are (1) to build a base to integrate two unique radio frequencies into a card, as a part of the development process of a RFID tag mounted with memory, (2) and to design and develop a dual-band RFID tag on which various security functions can be mounted using the memory. In order to make a RFID tag embedding a memory with these various functions, we need to explore the following design procedures.

(1) First of all, the antenna needs to be designed in consideration of various potential problems, which can be caused by memory mounting through the respective analysis of the frequency bands to be used. The smart card we propose is composed of HF (13.56 MHz) and UHF (900 MHz) RFID tags with IC chip and memories. That is, there is a RFID combination unit for RFID use, and there is a IC chip for financial transaction. The memory added is large enough to contain long passwords encrypted with very long bits and public/private certificates for digital signature.

(2) Once a memory-embedded dual-band RFID tag is designed, we use a performance evaluation program to simulate the performance of the RFID tag. If the result of the simulation is below the target level, we need to redesign the antenna (i.e., go to step 1). We will detail this procedure in the Section 2.2.

(3) After we successfully evaluate the performance of the designed memory-embedded dual-band RFID tag, we deploy the tag and other elements (IC chip, memory, etc.) on an empty space of a card. Firstly, the tag is fixed on an appropriate space of a card in consideration of other elements to be mounted including IC chip, internal memory, and controller.

(4) We design the controller to interconnect and interoperate the IC chip and the memory, so that the card can be interfaced from external media. After these steps, a prototype product is established through the evaluation of the design on a substrate.

As noted above, we embedded an IC chip and a controller to operate the memory, and there have been no problems caused by memory mounting. However, if we embed too big a memory chip, it is possible that the overall size of the smart card can increase.

2.2. Design of Dual-Band RFID Tag. There have been many researches to utilize heterogeneous RFIDs in one card [6-9]. However, there are fundamental differences between those previous researches and our research in terms of the structure of inlay and design procedure. In most of those previous researches, they embed each antenna on a different layer (or front side and back side of a layer) according to its frequency. In our research, we propose a RFID tag embedded with two different frequency bands on one layer to construct inlay. Also, for the previous researches of dual-band RFID tags stored in one inlay, our design usually outperforms the tags in terms of accuracy and size.

To understand the basic principle and to minimize the frequency interference and impedance mismatching among antennas, it is necessary to understand the product to which the antennas are to be applied.

Before the explanation, we would like to explain a few fundamental concepts for RFID tag design. In designing RFID tag, we bond antenna and RFID chip for actual functioning. Impedance is a measure of opposition to electric current in an electric circuit. Therefore, an impedance of RFID chip characterizes the RFID chip for its proper functioning and operation. For example, if the impedance level of a RFID chip is 50.0 Ω, we need to design the antenna to be attached to the RFID chip in order for the impedance level of the antenna to be 50 Ω for proper operation of the resulting RFID tag.

To begin with, we briefly summarize the design and optimization procedure discussed in this section as follows.

(1) We determine the shape, size, and position of the UHF antenna pattern to design a UHF RFID tag. We design and test the UHF RFID tag using
a simulation software system. Ansoft's HFSS is used for this purpose.

(2) We analyze Smith chart to fit the antenna to the impedance level of RFID chip. Please note that we use the simulation software for UHF antenna only, because there is no system that can simulate antennas with different frequency levels in one inlay-design.

(3) In the smart card hardware design stage, we connect a HF antenna and a UHF antenna and place them in one-inlay sheet to resolve the interference problem. Since we only have adjusted the UHF antenna to the RFID chip in the design stage using the simulation software, the combined antennas naturally will not fit to the impedance level of the RFID chip, which result in malfunction or no operation.

(4) To solve this impedance mismatching problem, we use a spectrum analyzer to systematically adjust the antenna pattern to detect the optimal patterns that fit the impedance of the RFID chip. We repeat this step for every pattern adjustment until we obtain an antennapattern that fits in the impedance level of the RFID chip. We consider a trade-off between size and recognition range of the antenna pattern during this adjustment.

(5) We evaluate the performance of the resulting smart card with standard RFID testers.

Now, let us explain the procedure in more detail. As shown in Figure 1, we need to decide which size, shape, and position of the combined antenna (UHF and HF) to optimize the interaction with RFID chips. The width and height of the resulting dual RFID tag are 85.6 mm and 54.0 mm, respectively. To decide the positions that minimize the interference problem, we firstly estimate frequency functions of active power and reactive power to measure mutual interference of different frequency bands. From the obtained frequency functions, we identify amplitude and phase of frequency element of each sine wave.

After we identify the amplitude and phase of each frequency band, to optimize the electricity usage for each band, we solve the impedance mismatching problem by strategically changing antenna pattern, position, and shape for each band. However, if both antennas are not connected or both antennas are not designed with the consideration of their mutual interference, this trial-and-error based step-by-step change cannot completely solve the interference problem. For instance, in actual implementation, communication failure between the antenna and the reader can happen. And the failure can result in modification of reading speed and frequency priority, which affects the interaction between the antenna and the RFID reader.

To solve this interference problem, we propose and implement an inlay antenna design as shown in Figure 1 to effectively distribute active resonance current. Note that the proposed antenna works in integrated and connected mode, instead of independent modes. That is, as shown in Figure 1, we connect HF (13.56 MHz) antenna and UHF (900 MHz) antenna. This connection can cause impedance mismatching problem, which causes marginal performance degradation of HF (13.56 MHz) antenna; however overall performance turns out to be enhanced, as shown in Table 1 in Section 3. Note that the performance degradation of HF antenna due to its connection to UHF antenna does not affect actual real-world usage because the users of HF antenna equipped smart card usually touch their card to the reader.

As for the related work on RFID design technologies [10], there have been many researches conducted. In this research, we basically use an antenna pattern program (Ansoft's HFSS) and equipment to design and implement RFID tag antenna as shown in Figure 2. However, according to our knowledge, there are no antenna pattern tools available to assist generating antenna patterns for the antennas with different frequency bands on one sheet. That is why we have to adopt step-by-step trial-and-error based approach in this research. However, there are a few considerations to be maintained for the dual-band RFID tag design for smart card. Because the smart card should be portably used, the size of the card is strictly limited, and we know that if the antenna is bigger, its recognition range is farther. We consider this size versus recognition range trade-off during the antenna adjustment step.

From the structural diagram of the card in Figure 2(a), it can be seen that we stack a tag containing both antennas (HF and UHF) at the bottom, a PCB board containing IC chip and memory in the middle, and a controller with other components on the top of the card. Note that HF antenna and UHF antenna are on the same inlay, though we present them separately in Figures 2(b) and 2(c) for easier understanding for the readers.
Table 1: Performance evaluation results in terms of recognition range of dual-band RFID tag.

| Pattern | HF (13.56 MHz) | UHF (900 MHz) |
|---------|----------------|---------------|
|         | Test method    | Recognition range | Test method    | Recognition range |
| 1       | Mercury4       | 3.00 cm        | Mercury4       | 3.00 m          |
|         |                |                | Impinj         | 2.50 m          |
| 2       | Mercury4       | 3.00 cm        | Mercury4       | 3.10 m          |
|         |                |                | Impinj         | 4.00 m          |
| 3       | Mercury4       | 3.00 cm        | Mercury4       | 3.00 m          |
|         |                |                | Impinj         | 5.00 m          |
| 4       | Mercury4       | 3.00 cm        | Mercury4       | 2.20 m          |
|         |                |                | Impinj         | 3.80 m          |
| 5       | Mercury4       | 3.00 cm        | Mercury4       | 3.50 m          |
|         |                |                | Impinj         | 5.50 m          |

2.3. Design of Memory/IC Chip. After the installation of the antenna through the procedure explained above on the same card, a memory-embedded IC chip is additionally incorporated into a different inlay and stacked with the RFID antenna inlay into one hybrid smart card.

Figure 4 shows the layout of memory card and IC chip designed in this study. Note that the tag image on the left shows a front side of the tag, and the tag image on the right shows the rear side of the same tag. As we have noted, it is possible to make a dual-band RFID tag embedded with a complete memory function by fixing a memory card and an IC chip on PCB substrate.

3. Experimental Results

In order to solve the functional and security problems of the card by separating the IC chip and increasing its capacity, we add internal card memory using the IC contact protruded from the card and we integrate functions that can use the mounted memory through induced current in the contact. As a result, the memory in the card is expandable from one gigabyte up to four gigabytes, and the functions of 13.56 MHz, 900 MHz, and IC chip in the memory can be accessed easily.
Figure 3: Detected patterns of dual-band RFID tag antenna.

Figure 5 shows signal/response of UHF reader (Figures 5(a) and 5(b)). Note that, in the Figure 5(a), the response pulse (in red line) indicates a noise signal, but the response pulse (in red line) in the Figure 5(b) shows meaningful signals, which is 64 bit tag ID.

Testing results on the performance of the UHF (900 MHz) RFID tag antenna is generated using a simulation software (Ansoft's HFSS). The simulation software generates a Smith chart to analyze the design of the antenna. The red line shows the change of impedance level according to frequency. Each point on the red line (in white circle, square, and black circle) corresponds frequency in GHz and impedance in complex form. For example, the white circle indicates that the frequency is 0.5 GHz and the impedance is $52.09 - j300.3 \, \Omega$. Note that this software is used when we design the UHF antenna pattern in the beginning of the dual-band RFID tag design. After the performance of the designed antenna has been simulated using a performance evaluation program, if the result is below the target level, as we mentioned, we adjust the antenna design with size/recognition range trade-off. As for constructing a trial prototype product, we apply manufacturing technology based on the design of each function.

The RFID tag has been made in two types, and the prototype has been made through wiring and etching methods. Mostly etching method is preferred because of its relative convenience. Those methods have been chosen based on accuracy of antenna implementation and comparative evaluation of integration and assembly process.

Figure 6 shows experimental results of our proposed system including antenna reflection coefficient, standing wave ratio (SWR), Smith chart, and antenna radiation pattern measured by the performance evaluation system. Note that the blue oval in Figure 6(a) indicates the frequency bandwidth (about 109 MHz, which is 946 MHz minus 837 MHz) that the tag responds properly to. Also, the blue oval in Figure 6(b) indicates the frequency bandwidth (which is between 837 MHz and 947 MHz) that the tag responds properly to. The two blue ovals in Figures 6(a) and 6(b) approximately match the blue circle in Figure 6(c).

As in Figure 6, the bandwidth of the antenna reflection coefficient is 109 MHz with frequency between 837 MHz and 946 MHz, and the standing wave ratio is between 837 MHz and 947 MHz. From the Smith chart, it can be seen that there is a gain of around 7.9 dB at frequency 0.7–1.1 GHz.

In Table 1, we summarize the performance evaluation results in terms of the tag’s recognition range. Note that Mercury4 reader supports 13.56 MHZ and 900 MHZ, but Impinj reader supports 900 MHZ only.

As in Table 1, the recognition range of the 13.56 MHz RFID tag is around 3 cm, and that of the 900 MHz RFID tag was around 2.2 m and 5.5 m, showing relatively high performance. The recognition range of 13.56 MHz RFID tag in general is about 5 cm. From Table 1, performance degradation can be seen in our prototype in terms of 13.56 MHz RFID. This is due to the impedance mismatching problem caused by connecting two antennas with different frequency bands. However this performance degradation can be marginal, considering that, in regular usage, we usually approach a RFID tag to a reader as close as possible. As for 900 MHz tag, the recognition range is 5.5 m in antenna pattern 5. Since the usual recognition range of 900 MHz tag is between 3 m and 4 m, we can see some enhancement in 900 MHz RFID in antenna pattern 5. These results show the effectiveness and enhancement of our proposed design.

4. Related Work

In the seminal work of Pope et al. [12], they have proposed RFID systems with 13.56 MHz. According to Lewis [13] and
Mayer and Scholtz [9], 13.56 MHz RFID operates relatively slower than 900 MHz RFID, but 900 MHz RFID suffers more from environmental issues such as liquid and metal.

Jeon et al. [6] have proposed dual-band slot coupled dipole antenna for 900 MHz (UHF band) and 2.45 GHz (microwave industrial, scientific, and medical band) RFID tag application. Note that their work has focused on dual-band RFID of HF and UHF application. Also they did not connect the RFID antennas due to high-frequency interference.

Leong et al. [7, 8] have proposed dual-band HF/UHF antenna design. In [7], they have simulated its functionality with Ansoft’s HFSS software; however they have not actually tested their design with RFID chip and antenna. In [8], they have implemented dual-band RFID tag in a single feed system with a UHF RFID C1G1 chip and a ‘Tag Talk First’ HF chip. While their antenna is designed as coil antenna, our proposed antenna is actually manufactured by etching method and is equipped with an IC chip, a controller and a memory for smartcard usage. They incorporated HF antenna on the front side of the RFID tag and UHF antenna on the back side of the RFID tag. In our work, we incorporated our proposed dual-band antenna on one side of the RFID tag as shown in Figure 1.

Mayer and Scholtz [9] have proposed dual-band HF/UHF antenna for RFID tags. Their antenna structure consists of a shorted loop slot antenna for the UHF band and a coil antenna for the HF band. Their antennas have experienced performance degradation of UHF RFID; however our antenna shows performance degradation in HF RFID. In our work, we have developed five different antenna patterns that can be applied directly for manufacturing dual-band HF/UHF antenna. They incorporated HF antenna and UHF antenna on one side; however, instead of connecting the two antennas, they installed HF antenna encompassing UHF antenna filled with four capacitors to solve frequency interference problems. We connected two antennas, and we solved

![RFID reader's response](image)

![RFID tag reading signal](image)

Figure 5: Signal and response of UHF reader (PowerRFID).
frequency interference problems by searching for optimal antenna patterns.

Hwang and Kang [14] proposed a conceptual design of dual-band RFID; however, they did not implement the design and test the effectiveness of their ideas. In our work, we not only enhance the design methodology but also have gone through extensive tests on the implemented cards to validate the effectiveness of our proposed approach.

Our proposed HF/UHF RFID tag antenna is constructed using etching method, and our proposed prototype has not only dual-band RFID but also memory functions. Table 2 shows the comparison results of our proposed dual-band RFID tag with the previous approaches by Leong et al. [8] and Mayer and Scholtz [9]. From Table 2, it can be seen that our proposed dual-band RFID tag significantly outperforms the previous approaches in terms of recognition range. That is, our proposed smartcard works in HF/UHF dual-band RFID.
and is equipped with an IC chip, a controller, and a memory and thus is directly applicable to industrial applications.

5. Conclusion

We introduce a novel design of high-performance smart card with HF/UHF dual-band RFID tag to overcome the frequency interference problem.

Firstly, we have designed and tested a UHF RFID tag using a simulation software system. In the smart card hardware design stage, we connect a HF antenna and a UHF antenna and place them in one-inlay sheet. Using a spectrum analyzer, we systematically adjust the antenna pattern to detect the optimal patterns that fit the impedance of the RFID chip. We evaluate the performance of the resulting smart card with standard RFID testers. The experiments show that our proposed RFID tag outperforms other dual-band RFID tags and maintains itself in a reasonable size.

Moreover, we increase IC chip’s memory capacity to resolve security-related problems when RFID tags are used in a financial transaction. We firstly exploit an IC contact protruded from the card to add an additional memory, and we integrate functions of the RFID tag to use the equipped memory through the induced current of the contact. The implemented prototype of our proposal can accommodate an extended memory ranging from one gigabyte up to four gigabytes.

By solving technological problems step by step in each stage until the prototype production and by evaluating the performance of the tag prototype in several environments where next-generation memory/IC chip cards can be used, we see high potential for the proposed tag’s commercial value in the smart card market.

We have conducted the design with the understanding of active power and reactive power resulting from spatial interference, which may happen in the integration of RFID tags, and in consideration of reading priority for frequency.

Furthermore, our proposal for utilizing memory has been required by major industrial manufacturers and recognized as a novel technology from the manufacturers. That is, we have applied and adapted our proposed technologies to industrial sectors during the period of this research with the RFID manufacturer’s technological cooperation.

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