HF RFID Reader Antenna with Loop Switch for Avoiding Magnetic Coupling

Won-Kyu Choi, Seung-Hwan Jeong, Chan-Won Park, Cheol-Sig Pyo, and Hae-Won Son

This paper studies the magnetic coupling between two adjacent loop antennas that are parallel to each other in a plane and presents a new practical method to avoid the resulting magnetic coupling interference. The study focuses on the high frequency radio-frequency identification (RFID) system for casino applications, where several loop antennas are closely built into a game table to monitor gaming chips. In this case, neighboring loop antennas may severely interfere with each other by magnetic coupling, which leads to the malfunction of the RFID system. In this paper, we present a practical loop antenna with a new loop switch circuit for avoiding magnetic coupling. The loop switch circuit is integrated with a matching circuit and automatically operated by using an interrogating signal from a reader. We verified the validity of the proposed design by showing that an RFID reader with the proposed antenna can exactly and separately read the gaming chips placed on the different betting zones of a game table.

Keywords: RFID, reader antenna, loop antenna, magnetic coupling, casino application.

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I. Introduction

Radio-frequency identification (RFID) is a rapidly developing technology that uses RF signals for the automatic identification of objects. This technology can be used not only for simple identification but also for the tracking and locating of individual objects. Recently, RFID has received a lot of attention as a possible solution for item-level tagging (ILT) applications, such as those used in libraries, medical areas, and casinos [1]–[3]. In this paper, we focus on high frequency (HF, 13.56 MHz) RFID reader antennas for casino applications. In a casino application, gaming chips with built-in RFID tags are placed on several betting zones of a game table, and an RFID reader should read the gaming chips separately, zone by zone. Circular loop antennas are installed under each betting zone to pick up signals from the gaming chips placed on their own zone. Figure 1 shows an example of a game table configured with several betting zones that are near each other. In this case, the loop antennas for the betting zones are also near to

Fig. 1. Example of casino game table configured with several betting zones.

each other, and they may interfere destructively due to the magnetic coupling that exists between them.

In this paper, we study the mutual interference between two adjacent circular loop antennas that are parallel to each other in the same plane. The antennas are used to read gaming chips on betting zones. The magnetic coupling between them adversely affects the reading performance of the RFID system. By means of the magnetic coupling, one antenna may read the wrong RFID tags on the other betting zone; thus, it may miscount the number of gaming chips on its own zone. Therefore, in the design of an RFID reader antenna for casino applications, it is very important, and challenging, to avoid magnetic coupling between antennas. In this paper, we discuss the mutual interference caused by the magnetic coupling between two circular loop antennas in detail and propose a new interference-avoidance technique using high-speed electrical relay switches. Some papers have dealt with the magnetic coupling in view of the mutual inductance between loops [4]–[5], but there are few reports on the avoidance of magnetic coupling in practical problems.

II. Magnetic Coupling between Loop Antennas

To simplify the analysis of magnetic coupling interference, we consider two single-turn circular loop antennas on the same plane (xy-plane of $z = 0$), as shown in Fig. 2. The antennas have a radius of 70 mm, and their centers are separated by a distance of $d_{AB} = 160$ mm. The strip width of the loop is 2 mm. The two antennas have the same dimensions and are denoted as Ant-A and Ant-B, respectively. They are individually matched to 50 Ω with a combination of series and shunt capacitors. Note that Ant-B has a loop switch that controls the current flow through the loop.

Figure 3 plots the simulated return losses of Ant-A with and without nearby Ant-B. The black solid line is the return loss

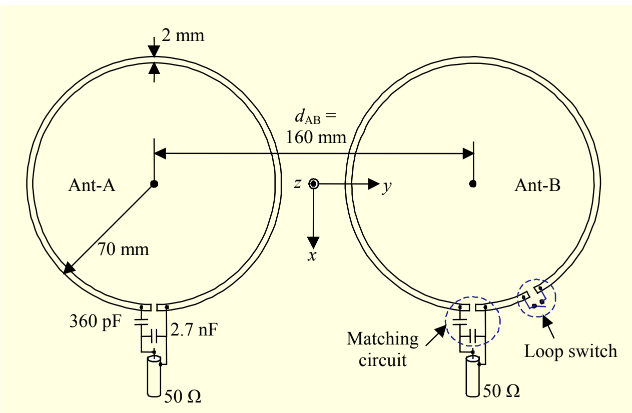

Fig. 2. Geometric arrangement of two circular loop antennas for magnetic coupling analysis.

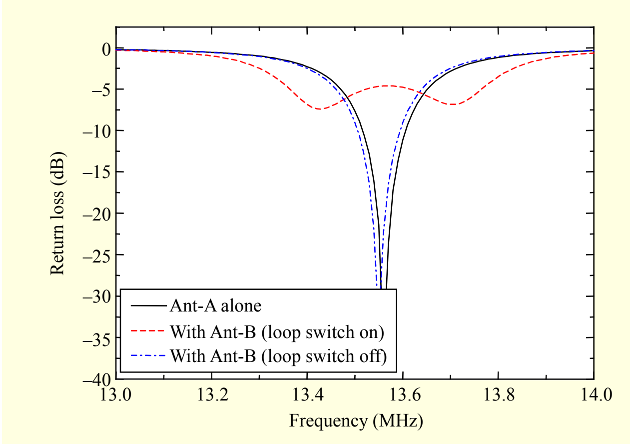

Fig. 3. Simulated return loss of Ant-A.

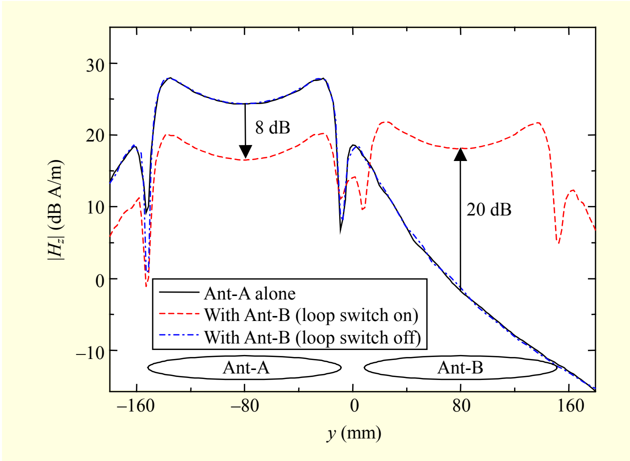

Fig. 4. Simulated H-field strength excited by Ant-A.

when Ant-A is alone, and the red dotted line is the return loss when Ant-B (with the loop switch on) is near to Ant-A. We can notice that the return loss of Ant-A is severely changed by the magnetic coupling with Ant-B. The frequency splitting phenomenon occurs, such as that in a wireless power transfer system, via magnetic resonance [6], and the maximum return loss is no longer obtained at the operating frequency of Ant-A (13.56 MHz). By turning off the loop switch of Ant-B, the magnetic coupling can be avoided. The blue dash-dot line in Fig. 3 shows the return loss of Ant-A when the loop switch of Ant-B is off, and it is almost identical to the black solid line. Therefore, we can notice that the loop switch can be used effectively to prevent the magnetic coupling interference between loop antennas.

Figure 4 shows the simulated magnetic field (H-field) strength excited by Ant-A, when the loop switch of Ant-B is on and off. The input power to Ant-A is 30 dBm. The normal component (H_z) of the H-field to the xy-plane is calculated along the straight path ($x = 0$, $-180 \leq y \leq 180$ mm, $z = 12$ mm)

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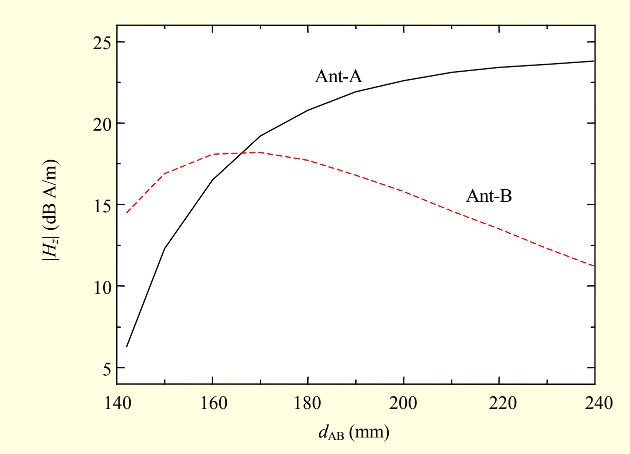

Fig. 5. Simulated H-field strength at each center of Ant-A and Ant-B vs. their separation distance (d_{AB}) when Ant-A is fed by an RF signal.

and plotted in the figure. The red dotted and blue dash-dot lines are the simulated H-field strengths when the loop switch is on and off, respectively. There are significant differences in both field distributions. When the loop switch is off, a strong H-field is generated above Ant-A, and it decays rapidly away from Ant-A. However, when the loop switch is turned on, the H-field strength over Ant-A is significantly reduced and that over Ant-B is highly increased due to magnetic coupling. This leads to the malfunction of an RFID system when they are used as reader antennas for betting zones. Assume that two betting zones (Zone-A and Zone-B) are subject to Ant-A and Ant-B, respectively. The decrease of the H-field strength over Ant-A may cause the missing of some of the betted gaming chips on Zone-A, and the increase of the H-field strength over Ant-B may cause the false detection of the betted gaming chips on Zone-B.

The black solid line in Fig. 4 shows the H-field strength when Ant-A is alone, and it is almost identical to the blue dash-dot line. This means that the loop switch effectively prevents the magnetic coupling between the antennas. In this paper, all the simulated results were obtained by using Ansys HFSS [7].

Figure 5 shows the simulated H-field strength (excited by Ant-A) at each center of Ant-A and Ant-B when their separation distance (d_{AB}) is varied from 142 mm to 240 mm. The input power to Ant-A is 30 dBm, and the loop switch of Ant-B is on. The fields are calculated at the points 12 mm above the *xy*-plane (that is, z = 12 mm). The H-field strength over Ant-B is greater than that over Ant-A when $d_{AB} < 166$ mm even though the RF signal is applied to Ant-A. This is due to the strong magnetic coupling between the two antennas. The magnetic coupling effect decreases with the increase of d_{AB}, and the H-field strength over Ant-A converges to the value that can be obtained with Ant-A alone. When the antennas get very close to each other, the field strengths over them drop off rapidly because they go out of resonance due to the strong magnetic coupling.

III. Design of an RFID Reader Antenna

1. Antenna Geometry

In the HF RFID application, loop antennas are of significant importance. They have to create strong H-fields in the near zone, without excessive far-field radiation. We have designed a six-turn circular loop antenna for RFID casino applications, particularly the betting zone. Figure 6 shows the schematic of the designed antenna. The antenna has an outer radius of 70 mm, and the strip width of the loop is 0.7 mm. The gap between the strips is also 0.7 mm.

The loop size of the antenna is determined to cover the entire area of the betting zone, which is a circular area on the game table with a radius of 57.5 mm in our target application. The

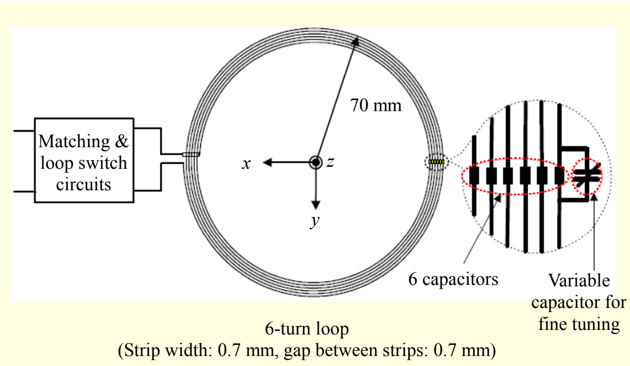

Fig. 6. Schematic of six-turn circular loop antenna for RFID casino applications.

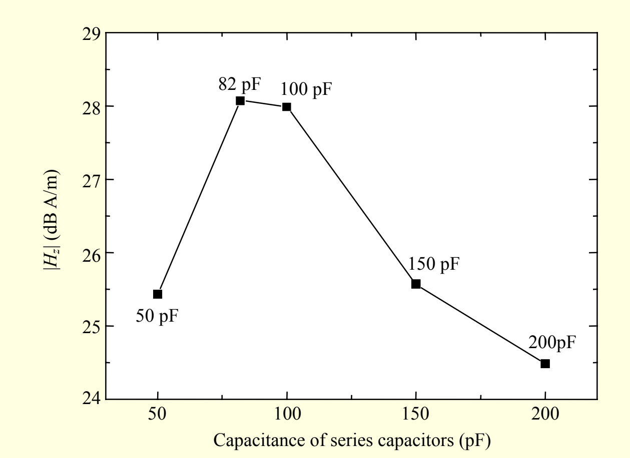

Fig. 7. Simulated H-field strength at center of loop depending on capacitance value of series capacitors.

number of loop turns is chosen empirically to yield an optimal performance for reading multiple tags stacked closely within the loop. In general, as the number of loop turns increases, the quality factor (Q) of the loop antenna increases, which means that the H-field strength is enhanced. However, a high-Q resonant reader antenna can be easily detuned by multiple resonant tags that are densely stacked within the loop, and its performance is often severely degraded. The interaction between a reader and numerous tag antennas is difficult to compute numerically or analytically. In this paper, the appropriate number of loop turns is determined by various experiments of reading multiple tags (stacked in various shapes) with different number of turns.

On the other hand, to enhance the H-field strength generated by the antenna, a capacitor is inserted between each turn of the loop. As depicted in Fig. 6, six capacitors are put in the six-turn loop, and their capacitance value is chosen such that the currents flowing in each turn of the loop are nearly equal in magnitude and phase. By keeping the current distribution uniform along the loop, the contributions from all the currents in the individual turns of the loop are added in phase and the H-field strength is enhanced within the loop. Figure 7 shows the variation of the simulated H-field strength at the center of the loop, depending on the capacitance value of the six capacitors. The input power to the antenna is 30 dBm, and the magnitude of the normal component (H_z) of the H-field is calculated and plotted in the figure. From the figure, we can find that the H-field strength reaches its maximum value when the capacitance is 82 pF.

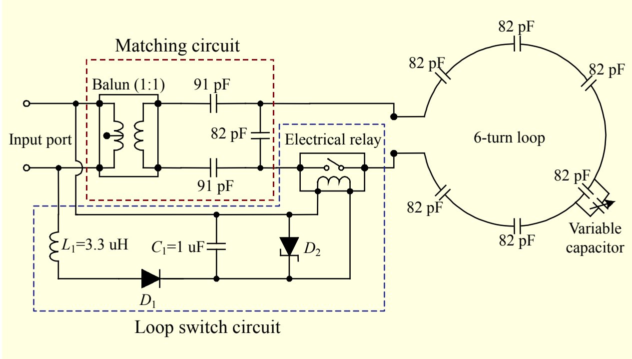

Fig. 8. Circuit diagram of proposed loop switch circuit.

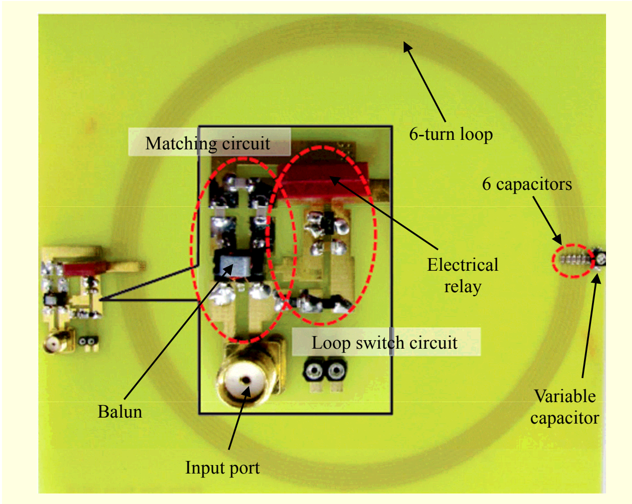

Fig. 9. Photograph of fabricated antenna.

2. Loop Switch Design

When two loop antennas with the same resonant frequency are placed close together, their resonant frequencies are seriously detuned by magnetic coupling. This magnetic coupling leads to severe impairment of the RFID system performance in casino applications, as mentioned before. To prevent the magnetic coupling between the two loops, the path of the induced current in one loop should be opened when the other loop is excited by an RFID reader, and vice versa. For this purpose, we have designed a new loop switch circuit that can be integrated with the matching circuit of the antenna. Figure 8 shows the circuit diagram of the loop antenna with the proposed loop switch and matching circuits.

The matching circuit is composed of a 1:1 balun transformer and three capacitors, and the loop switch circuit is made up of an electrical relay, inductor, capacitor, and two diodes. The electrical relay is switched between on and off states by the dc voltage, which is extracted from the interrogating RF power from the reader. A small fraction of the RF power is coupled through the high impedance inductor (L_1) and rectified to the dc voltage by the Schottky diode (D_1) and the capacitor (C_1). Consequently, the loop switch is turned on only when the antenna is fed by the RF signal from the RFID reader. Otherwise, the loop switch remains off. The Zener diode (D_2) is used to regulate the input operating voltage of the electrical relay to a safe level.

3. Fabrication of Antenna

Figure 9 shows a photograph of the fabricated loop antenna for casino applications, particularly the betting zone. The antenna was fabricated on an FR-4 substrate having a thickness of 1 mm. It is composed of a six-turn loop with six capacitors in series, and a matching and loop switch circuit. A variable capacitor of 50 pF (trimmer) is added to fine-tune the resonant frequency of the antenna, as shown in Figs. 8 and 9. The antenna is well matched to 50 Ω at 13.56 MHz by the matching circuit and the variable capacitor. A 1:1 RF transformer of CX2147 [8] is used as a balun in the matching

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circuit.

A Schottky diode of NSR0240HT1G [9], a Zener diode of LBZX84C6V2LT1G [10], and an electrical relay of 9012-05-10 [11] are used in the loop switch circuit. The 9012-05-10 is a high-speed switching relay manufactured by Coto Technology. The operate and release times of the relay are 0.35 ms and 0.1 ms, respectively, and its operating voltage is 3.75 V to 6.5 V. The relay can conduct a current up to 500 mA. A fast solid-state switch, such as a diode or transistor, may replace the relay, but it should be able to conduct a high resonant current (up to several hundred milliamperes) during its on-state and requires an additional bias supply.

IV. Measurements

In this section, we have verified the performance of coupling avoidance between two adjacent loop antennas with the proposed loop switch circuit. Two antennas are placed parallel to each other on the same plane (xy-plane of $z = 0$), as shown in Fig. 10. The two antennas are denoted as Ant-1 and Ant-2 and their centers are separated by a distance of $d_{12} = 160$ mm.

Figure 11 shows the measured return losses of Ant-1 when it is alone, and when it is near Ant-2 with the loop switch on and off. In this experiment, the loop switch of Ant-1 is always kept closed and that of Ant-2 is switched on and off, by applying separate dc operating voltages directly to their respective relays. The input port of Ant-2 is terminated by a 50 Ω load. The black solid line is the return loss when Ant-1 is alone. It is well matched to 50 Ω at 13.56 MHz. The red dotted line is the return loss of Ant-1 when Ant-2 (with the loop switch on) is near to Ant-1. The return loss is severely changed by magnetic coupling, as expected in the previous section. Ant-1 is no longer matched at 13.56 MHz, and the frequency splitting phenomenon occurs. The measured results in Fig. 11 show a similar tendency to the simulated results in Fig. 3. This

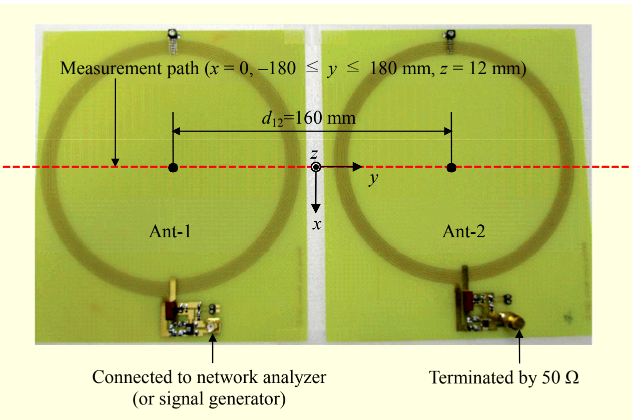

Fig. 10. Experimental setup for return loss and H-field strength measurements.

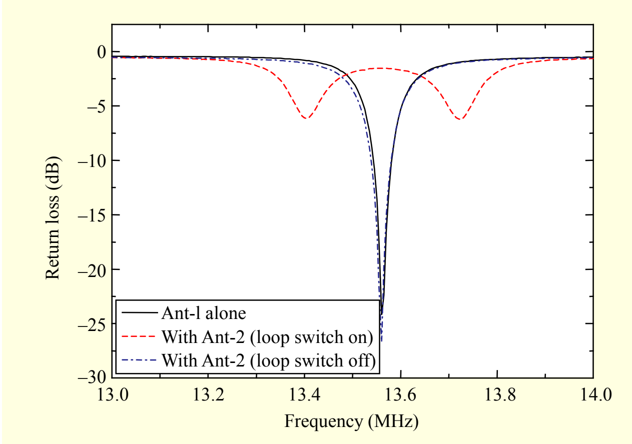

Fig. 11. Measured return loss of Ant-1.

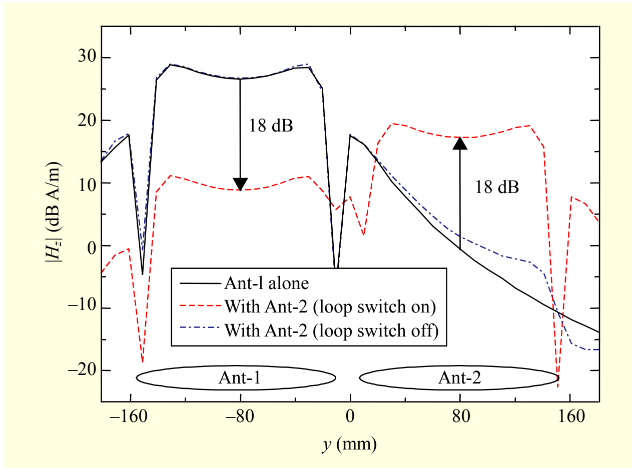

Fig. 12. Measured H-field strength excited by Ant-1.

magnetic coupling effect can be easily avoided by using the proposed loop switch circuit. By opening the electrical relay in Ant-2, the return loss of Ant-1 is no longer affected by Ant-2. The blue dash-dot line in Fig. 11 shows the return loss of Ant-1 when the electrical relay in Ant-2 is open, and it is almost identical to the black solid line.

Figure 12 shows the measured H-field strengths excited by Ant-1, when the loop switch of Ant-2 is opened and closed. The 13.56 MHz RF signal with a power of 30 dBm is applied to Ant-1. The magnitude of the normal component (H_z) of the H-field is measured by using an H-field probe (EM-6995) [12] along the straight path ($x = 0$, $-180 \le y \le 180$ mm, $z = 12$ mm), and plotted in the figure. In this experiment, the electrical relay in Ant-1 is automatically closed by the RF power applied to the antenna, and that of Ant-2 is controlled by a separate dc voltage source directly connected to the relay control terminals. When the RF signal of 30 dBm is fed to the input port of Ant-1, the measured dc voltage across the control terminals of the electrical relay is about 4.8 V, which is sufficient to operate the

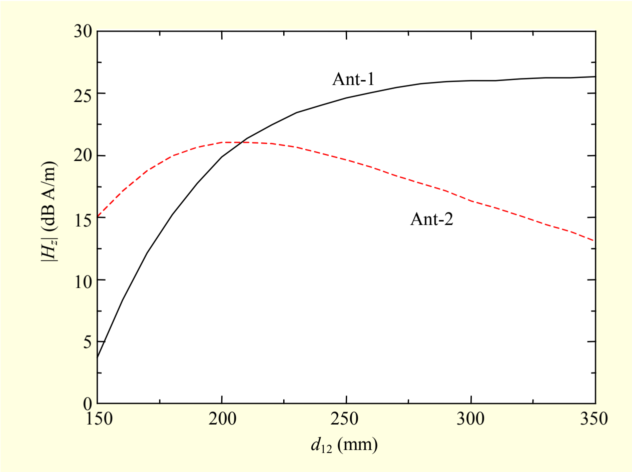

Fig. 13. Measured H-field strength at each center of Ant-1 and Ant-2 vs. their separation distance (d_{12}) when Ant-1 is fed by an RF signal.

relay.

In Fig. 12, the black solid line is the measured H-field strength, when Ant-1 is alone, without Ant-2. The red dotted and blue dash-dot lines are H-field strengths when the loop switch of Ant-2 is switched on and off, respectively. The measured H-field distribution is almost identical, when Ant-1 is alone, and when it is near to Ant-2 with the loop switch off. However, when the loop switch is turned on, the H-field distribution is seriously altered due to the magnetic coupling between the two antennas. The H-field strength over Ant-1 is significantly decreased by about 18 dB, and that over Ant-2 is highly increased by about 18 dB. This phenomenon is already expected from Fig. 4 and may lead to the malfunction of an RFID system. The results in Fig. 12 show the necessity of the loop switches for magnetic coupling avoidance and that the proposed loop switch circuit with an electrical relay works well for this purpose.

Figure 13 shows the measured H-field strength (excited by Ant-1) at each center of Ant-1 and Ant-2 when their separation distance (d_{12}) is varied from 150 mm to 350 mm. The input power to Ant-1 is 30 dBm, and the loop switch of Ant-2 is on. The measurement points are located 12 mm above the *xy*-plane (that is, $z = 12$ mm). The measured result shows a similar trend to the simulated one shown in Fig. 5. The H-field strength over Ant-2 is greater than that over Ant-1 when $d_{12} < 208$ mm even though the RF signal is applied to Ant-1. This is due to the strong magnetic coupling between the two antennas. The magnetic coupling effect decreases with the increase of d_{12}, and the H-field strength over Ant-1 converges to the value that is obtained with Ant-1 alone. When the antennas are very close to each other, the field strength over both antennas drops because the antennas go out of resonance due to the strong magnetic coupling. A higher coupling effect is observed in Fig. 13 than in Fig. 5 since the number of loop turns of Ant-1 (and Ant-2) is much more than that of Ant-A (and Ant-B).

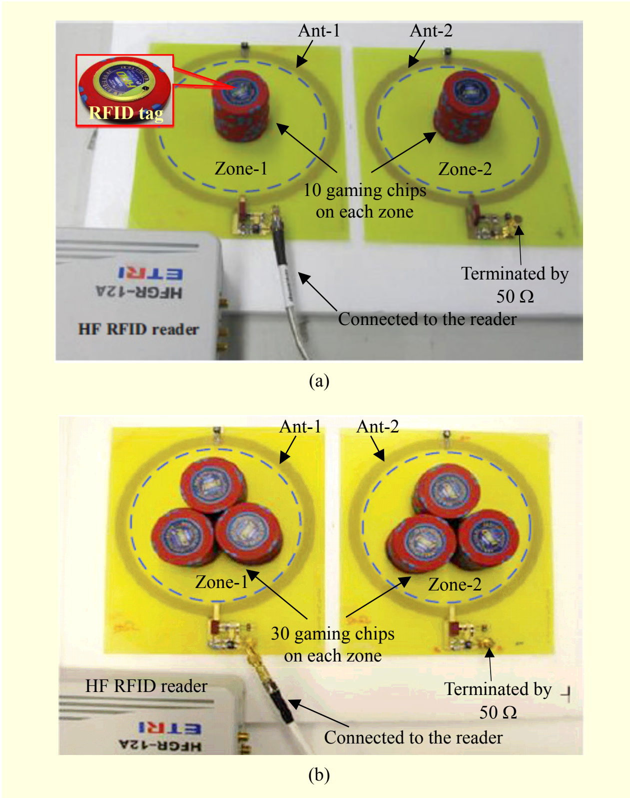

Fig. 14. Experimental setup for reading performance test of RFID reader with proposed antennas: (a) scenario 1 and (b) scenario 2.

Finally, we carried out an experiment to investigate how the magnetic coupling causes the malfunction of an RFID system and how useful the proposed loop switch circuit is for preventing the magnetic coupling between loop antennas. Figure 14 shows the experimental setup, which is composed of two loop antennas with the proposed loop switch circuit, multiple gaming chips with built-in RFID tags, and an RFID reader. The gaming chips have an RFID tag inside that we have designed with the tag IC of NXP ICODE ILT [13]. The reader has been developed by our group for HF RFID applications, which is compliant with the ISO/IEC 18000-3 Mode 3 standard [14]. The experiment was carried out under the assumption that two circular betting zones are separated by 160 mm (center to center). The betting zones are denoted as Zone-1 and Zone-2 in the figure, which are covered by Ant-1 and Ant-2, respectively.

The experiment was conducted in two scenarios. In scenario 1, 10 gaming chips are stacked at the center of each zone as shown in Fig. 14(a), and in scenario 2, 30 gaming chips are stacked in three columns of equal number, as shown in Fig. 14(b). Ant-1 is connected to the reader, and Ant-2 is

Table 1. Number of gaming chips detected by reader with Ant-1.

Loop switch state of Ant-2	Number of detected gaming chips			
	Scenario 1		Scenario 2	
	Zone-1	Zone-2	Zone-1	Zone-2
Off	10	0	30	0
On	3	8	20	28

terminated by a 50 Ω load. The transmitted power from the reader is 30 dBm, and a separate dc operating voltage is used to control the electrical relay in Ant-2.

Table 1 shows the number of gaming chips detected by the reader according to the two scenarios, when the loop switch of Ant-2 is switched on and off. When the loop switch is off, the reader detects all 10 and 30 gaming chips on Zone-1 by using Ant-1, and does not detect the gaming chips on Zone-2. However, when the loop switch of Ant-2 is switched on, the reader connected to Ant-1 wrongly detects the gaming chips on Zone-2. In scenario 1, the reader detects only 3 gaming chips on Zone-1 (that is, missing 7 gaming chips on Zone-1), and improperly detects 8 gaming chips on Zone-2 that should not be detected. In scenario 2, the reader detects only 20 gaming chips on Zone-1 (that is, missing 10 gaming chips on Zone-1), and improperly detects 28 gaming chips on Zone-2. This result is reasonable, taking into account the H-field distributions of Fig. 12. To avoid such a malfunction, the loop switch of Ant-2 should be turned off while reading the gaming chips on Zone-1.

V. Conclusion

This paper studies the magnetic coupling between two adjacent loop antennas and proposes a new practical method to avoid it. We designed an HF RFID loop antenna for casino applications, especially the betting zone. In this application, two neighboring loop antennas may suffer severe interfere from the resulting magnetic coupling, and this coupling can adversely affect the reading performance of the RFID system. To restrain the magnetic coupling, we proposed a simple loop switch circuit, in which a high-speed relay switch is controlled by the dc voltage that is partially coupled and rectified from the interrogating RF signal of the reader. We verified that the antenna with the proposed loop switch circuit works well, by showing that an RFID reader with the antenna can separately read the gaming chips placed on different betting zones. Our developed RFID system for casino applications can read more than 180 gaming chips, betted separately on six betting zones, in less than three seconds by using the proposed antenna.

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