Read/Write Mode Operating Distance Optimization for 13.56MHz Contactless IC Cards

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Abstract

Today, lots of electronical systems like the Automated Fare Collection, Automatic Vehicle Management, Passenger Information, On-Board Video Surveillance and Alternative Payment Systems use ISO/IEC 14443 Type A 13.56MHz contactless IC cards. Generally, these cards have read/write mode operation distance between 0 and 10cm from antenna of the system. Maximum card working distance is very important for performance of systems that assembled in field. In this study, different read/write mode operating distance optimization techniques has been discussed and applied to a bus payment system.

1. Introduction

ISO/IEC 14443 Type A contactless integrated circuit (IC) cards [1, 2, 3, 4] operating distance is very important and there are many different studies for improving operation distance. For example, in Wang B. et al. study, they showed that the current-carrying capacity can be increased from 5mA to 9mA with a new matching circuit [5]. In Druml N. et al. study, Adaptive Field Strength Scaling technique used for power optimization [6]. Gebhart M. et al. worked on operation times for different radio frequency (RF) card IC chip currents [7]. In Li W. et al. study, they worked on a near-field communication transceiver system with consideration of noise issues [8].

In this study, on a total solution have been discussed including the antenna design, noise and gain level adjustments, matching circuits and the antenna transmission power topics. There are many measurement results for each improvement steps of read/write level optimization for ISO/IEC 14443 Type A contactless IC cards.

An antenna was designed that mechanically suitable to bus payment system of İzmir, Turkey. In card reading block of the designed system, gain level and noise threshold level adjustment are very important. Especially, the noise level can be changed for different electronical systems. For improving the transferred RF power to contactless IC cards, supply of the system can be increased in component boundary levels.

2. System Overview

As can be seen in Fig. 1, there are six main parts of the system that named microcontroller, power supply, reader/writer IC, matching circuit, antenna and ISO/IEC 14443 Type A card.

The microcontroller and reader/writer IC are communicating via Universal Asynchronous Receiver Transmitter (UART) interface and all reading from contactless IC cards and writing to contactless IC card procedures has been managing from the microcontroller.

The power supply block of the system designed with an adjustable low drop-out regulator (LDO) instead of step-down converters. LDOs are more successful for noise isolation.

NXP CLRC663 contactless reader IC selected for the contactless reader/writer block. This IC does reading from contactless IC cards and writing to contactless IC cards procedures in the system.

When designing the printed circuit board (PCB) antenna, main target was reaching to maximum power transfer and maximum operation range. 50Ω matched antennas were used and antenna matching was done for 50Ω matched antennas topology.

The matching circuit is located between the reader/writer IC and antenna for adjustment of maximum power transfer.

In this study, ISO/IEC 14443 Type A cards has credit information of the bus payment system of İzmir City, Turkey. These cards includes RF antennas and ICs.

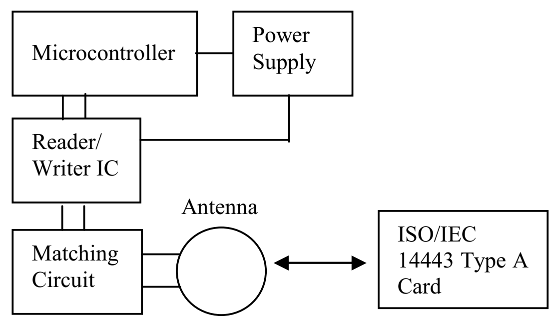


Fig. 1. System overview

3. Optimization Topics

For read/write mode operating distance optimization, the antenna design, the matching circuit design, the gain and noise threshold adjustment and the RF power transmission topics were studied.

3.1. Antenna Design

For RF card applications there are two main antenna design options that named directly matched antennas and 50Ω matched antennas. Directly matched antennas can be used in conditions that antennas without extension cables. These antennas are generally located at the same place with reader/writer ICs. 50Ω matched antennas can be used for long distances between the reader and the antenna using a coaxial cable. In the bus payment system of İzmir City, cable length can be up to 40cm. So, because of distance situation 50Ω matched antennas were selected for the antenna design.

The energy transmission between the reader/writer antenna and the contactless IC card is based on the transformer principle. At the reader/writer side, an antenna coil is required as well as a card coil implemented in contactless IC cards. Fig. 2 shows the basic principle and the equivalent electronic circuitry.

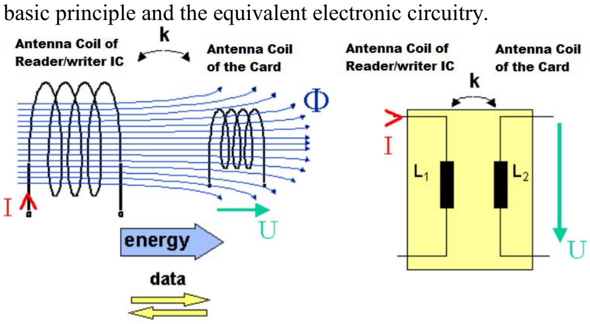


Fig. 2. Basic transformer principle of the energy transformation of the antenna system [9]

Left part of the Fig. 2 describes antennas and the energy transmission. The current I in the antenna coil of reader/writer IC generates a magnetic flux Φ. Parts of this flux Φ flow through the card coil and induce a voltage U in the card coil itself. This voltage U is rectified and the card IC is activated when the operating voltage is reached. The induced voltage will vary within the distance between the antenna coil of reader/writer IC and the card antenna. Due to that voltage variation, the achievable operating distance is limited by the transferred power. The right part of Fig. 2 shows the equivalent electrical circuitry.

In this study, the antenna shape was chosen as a circle because of the mechanical conditions. Diameter of antenna can vary from 6 to 12cm. When choosing optimum diameter Fig. 3 was used. Fig. 3 gives an approximation of the read/write distance for different antenna sizes. It shows that the best read/write distances (x(R)) can be achieved with antennas of about 20cm diameter (R=10cm).

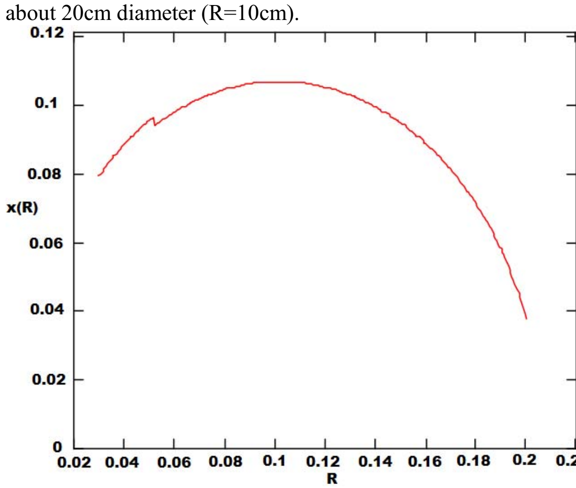


Fig. 3. Antenna radius versus operating distance [10]

At the designed antenna, diameter was chosen 12cm, because of size limitations of the bus payment project mechanics. Thus, based on Fig. 3, the operating distance should be around between 9cm and 10cm. The designed PCB antenna can be seen from Fig. 4.

Fig. 4. The designed PCB antenna

3.2. Matching Circuit Design

Matching 50Ω antennas is very important for maximum power transfer to the contactless IC cards. The whole read/write circuit contains an electromagnetic compatibility (EMC) circuit, a matching circuit and an antenna equivalent circuit. When designing the matching circuit, 3 different application notes were used [10, 11, 12].

The reader/writer antenna coil can be described with the series equivalent circuit that shown in Fig. 5.

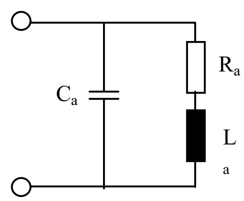


Fig. 5. The series antenna equivalent circuit

Component values can be found easily with an impedance analyzer or a network analyzer. However, for a first estimation of the inductance (L_a), resistance (R_a) and capacitance (C_a) of the antenna can be calculated with (1), (2) and (3).

$$L_a[nH] = 2I_1[cm]\left(ln\left(\frac{I_1}{D_1}\right) - K\right) N_1^{1.8} \quad (1)$$

I_1: Length of the conductor loop of one turn
D_1: Diameter of the wire or width of the PCB conductor
K: 1.07 for circular antennas, 1.47 for square antennas
N_1: Number of turns
ln: Natural logarithm function

$$R_a = 5R_{dc} \quad (2)$$

R_{dc}: DC resistance value of the antenna

$$C_a = \frac{1}{(2\pi f_{ra})^2 L_a} \quad (3)$$

f_{ra}= self-resonance frequency of the antenna

The quality factor of the antenna is calculated with (4).

$$Q_a = \frac{2\pi f_{ra} L_a}{R_a} \tag{4}$$

If the calculated value of Q_a is higher than the target value of 30, for each side an external damping resistor R_Q that can be calculated from (5) has to be inserted on each antenna side to reduce the quality factor to a value of 30 (±10%).

$$R_Q = 0.5\left(\frac{2\pi f_{ra} L_a}{30} - R_a\right) \tag{5}$$

The parallel equivalent circuit of the antenna together with the added external damping resistor R_Q can be seen from Fig. 6. L_{pa}, C_{pa} and R_{pa} can be calculated from (6), (7) and (8).

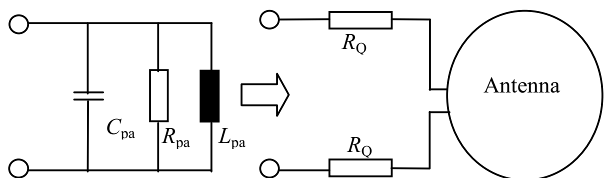


Fig. 6. The parallel equivalent circuit of the antenna

$$L_{pa} \cong L_a \tag{6}$$

$$C_{pa} \cong C_a \tag{7}$$

$$R_{pa} \cong \frac{(2\pi f_{ra} L_a)^2}{R_a + 2R_Q} \tag{8}$$

The read/write circuit contains CLRC663 contactless reader IC, the EMC circuit, the matching circuit and the antenna equivalent circuit can be seen from Fig. 7.

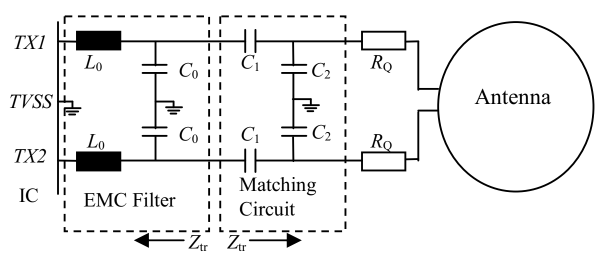


Fig. 7. The read/write circuit

The EMC filter circuit was used for filtering of the signal and the impedance transformation block. The main properties of the impedance transformation are decreasing the amplitude rise time after a modulation phase, increasing the receiving bandwidth. f_{r0} variable was selected 21MHz and calculation of C_0 can be seen from (9). 1uH value selected for L_0 and 68pF value selected for C_0 in the EMC circuit.

$$C_0 = \frac{1}{(2\pi f_{r0})^2 L_0} \tag{9}$$

The EMC filter and the matching circuit must transform the antenna impedance to the required transmit matching resistance $Z_{match}(f)$ at the operating frequency of f=13.56MHz. The measured $Z_{match}(f)$ can be remodeled in an equivalent circuit loading each TX pin of CLRC663 contactless reader IC with $R_{match}/2$. When cutting the circuitry after the EMC filter the precondition $R_{match}/2$ needs to be introduced to calculate the remaining components. The series (C_1) and parallel (C_2) capacitances can be calculated from following equations.

$$Z_{tr} = R_{tr} + jX_{tr} \tag{10}$$

$$Z_{tr}^{*} = R_{tr} + jX_{tr} \tag{11}$$

$$\omega = 2\pi \mathrm{f} \tag{12}$$

$$R_{tr} = \frac{R_{match}}{(1-\omega^2 L_0 C_0)^2 + \left(\omega \frac{R_{match}}{2} C_0\right)^2} \tag{13}$$

$$X_{tr} = 2\omega \frac{L_0(1-\omega^2 L_0 C_0) - \frac{C_0 R_{match}^2}{4}}{(1-\omega^2 L_0 C_0)^2 + \left(\omega \frac{C_0 R_{match}}{2}\right)^2} \tag{14}$$

$$C_1 \approx \frac{1}{\omega\left(\sqrt{\frac{R_{tr} R_{pa}}{4}} + \frac{X_{tr}}{2}\right)} \tag{15}$$

$$C_2 \approx \frac{1}{\omega^2 \frac{L_{pa}}{2}} - \frac{1}{\omega\sqrt{\frac{R_{tr} R_{pa}}{4}}} - 2C_{pa} \tag{16}$$

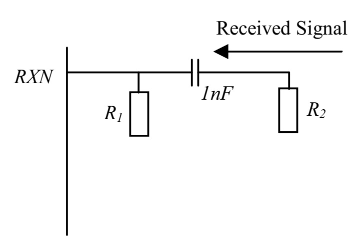
Finally, many different capacitor values were tried in experiments for fine tuning of the matching circuit. 68pF value selected for C_1 in the matching circuit based on the experiment results. C_2 capacitor is located on the antenna PCB and it includes fixed 82pF capacitor and 0-20pF adjustable capacitor. The adjustable capacitor was used for fine tune in the antenna matching procedure. Before test measurements, all antennas adjusted with this adjustable capacitor via an oscilloscope and 13.56MHz external source.

3.3. Gain and Noise Threshold Adjustment

When improving the card reading/writing level, gain of the receiver circuit of CLRC663 contactless reader IC should be as high as possible. But, there is a threshold level for gain adjustments. Electronic systems have a noise level that covering all of the frequency spectrum.

CLRC663 contactless reader IC has some registers for controlling gain and noise threshold levels. Receiver block of CLRC663 contactless reader IC has a gain resistor divider circuit that can be seen in Fig. 8. This circuit can adjust input signal level of the receiver [13].

Different resistor values were tried when designing the receiver circuit. 1KΩ value selected for R_1 and 22KΩ value selected for R_2 resistors based on the experiment results.



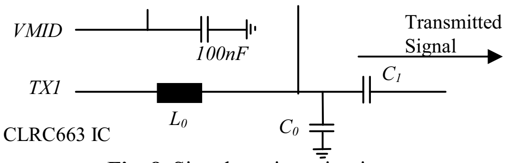


Fig. 8. Signal receiver circuit

The Sigout signal pin were used for an error output of CLRC663 contactless reader IC. When adjusting noise threshold from the RxThreshold register, minimum level of the input signal should be higher than the noise level in the system. If minimum level of the signal is lower than the noise level, an interrupt signal can be taken from the Sigout pin. So, when designing the system and adjusting the noise level, this pin was used in experiments.

After adjusting the noise level, the gain was adjusted from th e RxGain resister of CLRC663 contactless reader IC. Read/write mode operating distance levels can be seen from measurement results based on the gain register values that located in Table 1.

3.4. RF Transmission Power

The TxAmp register is responsible to amplitude of the transmitted RF antenna signal. And, maximum amplitude level was selected for maximum power transmitting to the antenna [13].

Supply voltage of CLRC663 contactless reader IC was changed from 4.85V to 5.05V by adjusting LDO output level. So, improvement level can be seen from measurement results that listed in Table 2.

4. Experiment Set-up and Test Results

First of all, a test program written in C language for an embedded Linux system. Kernel driver of CLRC663 contactless reader IC was modified for gain, noise threshold and amplitude of transmitted RF signal registers. The written C program does all the read/write procedure for testing read/write level of the contactless IC cards. Basic test set-up that used can be seen from Fig. 9.

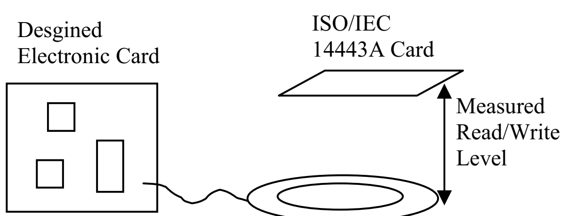


Fig. 9. Experiment test set-up

7 byte UID ISO/IEC 14443 Type A cards [14] were used in all tests. All measurements were done least two times for least 2 different antennas. Results of measurements were written as an arithmetic mean of all taken values. All components were calculated with equations where located in section 3.3. Before tests, R_1 and C_2 components was fixed. 1KΩ value selected for R_1. C_2 capacitor that located on the antenna fixed to 82pF and all test were done with this capacitor. The parallel capacitor that belong to C_2 was fixed too before test measurements. R_2 and C_1 components determined based on measurement results.

At first step, the noise level and the gain register values of CLRC663 contactless reader IC were determined. The Sigout pin were used for error monitor and the noise level register was fixed with this monitor pin. All measurement results can be seen from Table 1. Different noise level register values were tried with high gain levels. Minimum noise level with maximum gain register values were selected with R_1=1KΩ, R_2=15KΩ hardware (HW) specification and without the Sigout error signal. 0xAF value selected for the TxThreshold noise level register and 0x0F value selected for the RxGain gain register based on the experiment number 18 results.

Table 1. Adjusting noise threshold and gain registers

Exp. No	HW State	Noise Reg.	Gain Reg.	Gain Level	Level	Sigout Error
1	HW1[1]	0x4F	0x09	41dB	4cm	No
2	HW1[1]	0x1F	0x09	41dB	6cm	Yes
3	HW1[1]	0x29	0x09	41dB	5.5cm	No
4	HW1[1]	0x19	0x09	41dB	6cm	Yes
5	HW1[1]	0x3F	0x01	43dB	5.5cm	No
6	HW1[1]	0x2F	0x01	43dB	5.5cm	No
7	HW1[1]	0x3B	0x01	43dB	5.5cm	No
8	HW1[1]	0x3F	0x06	50dB	0cm	Yes
9	HW1[1]	0x4F	0x02	51dB	4.5cm	Yes
10	HW1[1]	0x29	0x02	51dB	0cm	Yes
11	HW1[1]	0x2F	0x02	51dB	0cm	Yes
12	HW1[1]	0x3F	0x02	51dB	0cm	Yes
13	HW1[1]	0xFF	0x02	51dB	4cm	No
14	HW1[1]	0xAF	0x02	51dB	4.5cm	No
15	HW1[1]	0x6F	0x02	51dB	5.5cm	No
16	HW1[1]	0x5F	0x02	51dB	5.5cm	No
17	HW1[1]	0x5F	0x0F	55dB	6cm	Yes
18	HW1[1]	0xAF	0x0F	55dB	6.5cm	No

[1] HW1: R_1=1KΩ, R_2=15KΩ, C_1= 100pF, C_2=82pF

After adjusting register values of CLRC663 contactless reader IC, the matching circuit components and the receiver circuit components were determined based on measurement results in Table 2. Experiments from 1 to 8 have different C_1 capacitor values and best result can be seen from the experiment number 4. So, 68pF value was selected for C_1 capacitor. The receiver circuit resistor was determined with the experiment number 8 and the read/write level reached to 10cm. Supply of CLRC663 contactless reader IC was changed from 4.85V to 5.05V with the experiment number 9 via adjusting LDO. Finally, the read/write level reached to 11cm at the end of the study.

Table 2. Adjusting the matching circuit, the signal receiver circuit and the supply voltage of CLRC663 contactless reader IC

Exp.	HW State	Noise	Gain	Gain	Level

No		Reg.	Reg.	Level	
1	HW2[2]	0xAF	0x0F	55dB	6,5cm
2	HW3[3]	0xAF	0x0F	55dB	6.5cm
3	HW4[4]	0xAF	0x0F	55dB	7.5cm
4	HW5[5]	0xAF	0x0F	55dB	8cm
5	HW6[6]	0xAF	0x0F	55dB	7.5cm
6	HW7[7]	0xAF	0x0F	55dB	7cm
7	HW8[8]	0xAF	0x0F	55dB	6.5cm
8	HW9[9]	0xAF	0x0F	55dB	10cm
9	HW9[9]+HW10[10]	0xAF	0x0F	55dB	11cm

[2] HW2: R_1=1KΩ, R_2=15KΩ, C_1= 130pF, C_2=82pF
[3] HW3: R_1=1KΩ, R_2=15KΩ, C_1= 100pF, C_2=82pF
[4] HW4: R_1=1KΩ, R_2=15KΩ, C_1= 82pF, C_2=82pF
[5] HW5: R_1=1KΩ, R_2=15KΩ, C_1= 68pF, C_2=82pF
[6] HW6: R_1=1KΩ, R_2=15KΩ, C_1= 47pF, C_2=82pF
[7] HW7: R_1=1KΩ, R_2=15KΩ, C_1= 33pF, C_2=82pF
[8] HW8: R_1=1KΩ, R_2=15KΩ, C_1= 27pF, C_2=82pF
[9] HW9: R_1=1KΩ, R_2=22KΩ, C_1= 68pF, C_2=82pF
[10] HW10: Supply of CLRC663 changed from 4,85V to 5,05V

After all of tests, the matching circuit and the receiver circuit component values were determined as R_1=1KΩ, R_2=22KΩ, C_1= 68pF, C_2=82pF. The noise (TxThreshold) and the gain (RxGain) register values was fixed as TxThreshold=0xAF and RxGain=0x0F. Final the read/write level of the card was measured 11cm.

5. Conclusions

In this study, the read/write mode operating distance optimization for 13.56MHz contactless IC cards has been done for bus payment system of İzmir, Turkey. An antenna, a matching circuit and a receiving circuit has been designed. System noise level and gain level determined for the reader/writer IC. For improving the read/write level of the contactless IC cards, the RF transmission power optimized. So, the read/write level improved from 4cm to 11cm by using all recommended optimization techniques.

6. Acknowledgment

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7. References

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