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Designing card holders using Faraday cage principles to block hacking and protect data from theft.

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Abstract:
With the growing use of contactless payment methods, such as credit cards that allow users to make payments by simply swiping, security concerns have increased. One of the major issues is "card-not-present fraud," where criminals use NFC readers to steal money without the cardholder's knowledge. Since victims often do not realize the fraud until they check their transaction records, improving protective measures is essential. While many studies have explored payment security, few have considered the connection between Faraday Cage technology and cardholder protection. Our research integrates the Faraday Cage principles into card bag design to reduce the risk of data theft and unauthorized transactions. Two distinct experiments are demonstrated in this paper, which are using a specific electromagnetic wave transmitter and receiver to calculate the shielding effectiveness of Faraday Cages with various materials, and using pings received to display the relationship between sizes of mesh holes of the cage and their shielding effectiveness. This paper provides several dimensions for the producers of card bags to optimize the design of card bags based on Faraday Cage.

Keywords: NFC security, Faraday Cage, electromagnetic interference shielding, secure card holder design

1. Introduction

1.1 Research Background and Significance

Near-field communication (NFC) fraud has been a serious issue since more and more people began to use NFC cards. Criminals use skimmers or rogue NFC readers that emit the same electromagnetic signal as legitimate terminals, tricking the card into transmitting its data. "Card not present fraud" causes enormous property loss every year.

Card-not-present fraud increased rapidly between 2012 and 2016. In the United Kingdom, an increase could be seen in card not present fraud - from 750,200 reported cases in 2012 to 1,437,832 reported cases in 2016.

One way to reduce NFC fraud is to utilize the Faraday Cage theory in the design of card bags. This theory can cancel the external electromagnetic signals emitted by the readers by moving delocalized electrons.

The aim of this research is to determine the optimized design of card bags based on the Faraday Cage to shield external electromagnetic fields. The paper is focused on the sizes of the holes of the Faraday Cage and the optimized material to construct the card bag with the optimal capacity of shielding external electromagnetic fields.

Currently, there is little research related, because of the fact that the term NFC was created only a few years ago, the investigation and exploration of it is rare. This research combines Faraday Cage, NFC and information security together, to practically address real-life problems, which is different from all the previous studies.

The paper is organized into distinct sections. First, it introduces the background of the subjects and reviews relevant literature. Then, the paper explains the experiment and presents the results. Last, the paper concludes and provides directions for future research.

1.2 Faraday Cage

Based on Faraday Cage, which is a conductive closed surface that prevents the external electrostatic field from the space enclosed by the surface, as stated by Gauss's law. When an external electrical field contacts the outer surface of the cage, the electrons in the surface are forced to move to cancel out the field's effects within the cage, thus creating a zone shielded from external electric fields. It makes the entire surface to be with an equal potential and prevents potential changes inside the enclosure. If the wavelength λ of the wave emitted is larger compared to the typical sized d of the holes on the surface, then the field on the surface can be considered static and Gauss's law is applicable.

Faraday Cage is widely applied, for example, it is used in the protections of rooms and laboratories. Faraday Cage can be also applied to the design of card bags, which is used to prevent NFC Fraud by forcing the free electrons in the Faraday Cage when the electromagnetic signals are emitted by skimmers or rogue to cancel the effect generated.

1.3 Near Field Communication (NFC)

Near field communication (NFC) is a wireless technology operating in the short range of 4 to 10 centimeters for communication. NFC devices communicate through the magnetically induced signals, and energy is coupled between transceivers. An NFC device generates a radio frequency in 13.56 MHz spectrum and is limited in short-range communication distance. Within close proximity, information can be exchanged between these transceivers by magnetic induction. So it is suitable for transmission of short information and messages. Also, due to the data rates supported, which are 106 Kbps, 212 Kbps and 424 Kbps, NFC can transmit data in a small time interval (Timalsina, Bhusal, and Moh, 2012).

NFC is applied in many fields. It can be used as an identity card at school or office to unlock doors based on its Card Emulation mode. Also, it can be used to exchange data, such as Bluetooth pairing. The application of NFC has become wider and it is used in card fraud due to its information transmission property.

1.4 Payment Card Reader

Payment Card Readers are tiny and portable, which are used to acquire the information of the cards and/or the money stored in the cards. In this circumstance, NFC contactless card readers are being discussed.

When the reader is close to the cards, the reader will emit radio-frequency signals, which provide power to the card. In turn, the card will send back the stored data to the reader via a process called load modulation, which means to provide the 13.56 MHz AC antenna current by a driver amplifier circuit.

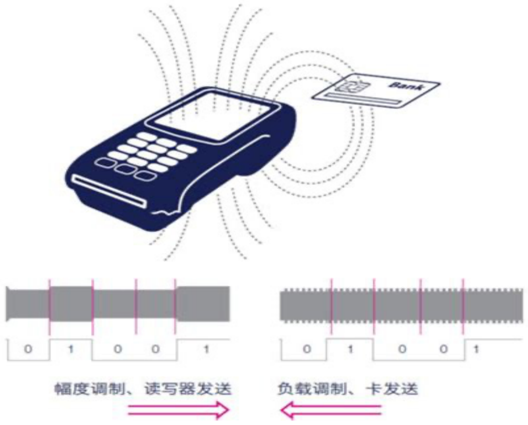

Figure 1: the electromagnetic field lines of a card reader when reading a card

Criminals use card readers to get the money and information from cards illegally.

Methods and Models

Equation 1

Arithmetic Mean Value Formula

$$x = \frac{1}{n}\left(x_1 + x_2 + \ldots + x_n\right) = \frac{1}{n}\sum_{i=1}^{n} x_i$$

Equation 2

Standard Deviation Formula

$$\sigma = \sqrt{\frac{1}{n} * \sum (x_i - \mu)^2}$$

Where,

σ represents standard deviation

μ represents arithmetic mean value

Equation 3

Shielding Effectiveness Formula (Pula, Sudarsan, Rallapalli, Narayan, Baskaradas, and Balasubramanian, 2019)

$$SE(dB) = 20log\left(\frac{E1}{E2}\right)$$

Where,

E1 represents the electric field outside the cage in V/m

E2 represents the electric field inside the cage in V/m

Equation 4

Electric Field Formulae (Pula, Sudarsan, Rallapalli, Narayan, Baskaradas, and Balasubramanian, 2019)

$$E1 = \sqrt{377 * 4\pi Pr / G\lambda^2} \quad \text{V/m}$$

$$E2 = \sqrt{377 * 8\pi Pr / G\lambda^2} \quad \text{V/m}$$

Where,

E1 represents electric field outside the cage

E2 represents electric field inside the cage

Pr represents received power

λ represents wavelength

G represents gain of the transmitted antenna

Equation 5

Distance between Transmitting Antenna Formula (Pula, Sudarsan, Rallapalli, Narayan, Baskaradas, and Balasubramanian, 2019)

$$d = \frac{2D^2}{\lambda}$$

Where,

d represents the distance between transmitting antenna

D represents the maximum length of antenna

λ represents wave length

Methodology and Experiment

2. Materials of the cage

2.1.1 Free Electron Density

This study uses a term called "Free electron density", which indicates the number of electrons per unit volume of a conductor. This term plays a crucial role in explaining the Shielding Effectiveness of Faraday Cage.

When the value of a material's free electron density is bigger, the distribution of electric charges across the cage's surface will be faster.

The data of free electron density of various materials is shown in Table 1.

Table 1. Free Electron Density of various materials

name	Free Electron Density (/10^22 cm^-3)
Copper	8.47
Aluminum	18.1
Silver	5.86
Gold	5.9
Indium	11.5

2.1.2 Theoretical Explanation of Free Electron Density

When an electromagnetic radiation is on the Cage's surface, the electrons in the material of the Faraday Cage will be forced to move. With more delocalized electrons inside the material of the surface of the Cage, the electrons are able to move more rapidly to generate the opposite current to cancel the external electromagnetic field.

According to Table 1, Aluminum theoretically will be the one with the highest shielding effectiveness compared to others in the table theoretically, because it has the biggest free electron density compared to others.

2.1.3 Electrical Conductivity

This study uses a term called "Electrical Conductivity", which means the ability of a material to conduct electrical current.

Table 2. Electrical Conductivity of various materials

name	Electrical Conductivity (S/m)
Copper	5.9*10^7
Aluminum	3.7*10^7
Silver	6.3*10^7
Gold	4.5*10^7
Indium	1.2*10^7
Brass	1.6*10^7

The bigger the value of the electrical conductivity of a material, the bigger the efficiency of the material to conduct electricity when there are lots of free electrons moving in the same direction.

2.1.4 Theoretical Explanation of Electrical Conductivity

Electrical conductivity is determined by not only the free electron density of a material, but also the purity, and the material's own features. Generally, the larger the free electron density of a metal, the higher the electrical conductivity of the metal. But there are also some exceptions that need to be discussed, such as copper, which has relatively high electrical conductivity but an intermediate value of free electron density.

Electrical conductivity and free electron density work in the same way in the construction of a Faraday Cage. The free electrons in the material of the Faraday Cage are free to move to cancel out the effects generated by an external electromagnetic field. The materials that have relatively high electrical conductivity can cancel out the electromagnetic field more effectively and rapidly.

2.2.1 Experiment

The experiment is cited from "Analysis of Shielding Effectiveness of a Faraday Cage for High Voltage Laboratory," by K.Pula, V. Sudarsan, D. Rallapalli, S. Narayan K.G., J. A. Baskaradas and M. Balasubramanian, released in 2019. This experiment explained the hypothesis of choosing materials, which indicates that the material with both high free electron density and electrical conductivity has high shielding effectiveness when applied in a Faraday Cage.

The signals of desired frequencies i.e. 1 MHz – 250 MHz are generated with the help of the Lab VIEW platform, a USRP N210 software-defined radio device, and transmitted using a test transmitter. The transmitter is kept at a distance while the receiver setup i.e. RF spectrum analyzer with antenna under test (AUT) is placed in the far field range which is calculated using Equation 5. The incoming electromagnetic wave which is generated by the test transmitter is received by AUT. For better results, the average of the signal strength values are taken for both inside and outside of the cage.

The absolute power at the point of interest inside and outside the cage is received. The power is converted into the electric field for comparison of practical and simulation results with Equation 4.

The amplitude of the incoming electromagnetic wave is set to 1 V/m, a point source Omni directional antenna is used to receive the signal strength inside the cage, and the SE is calculated using Equation 3.

The materials for building the Faraday Cage are changed, to investigate the effects of using different materials of Faraday Cage and the capacity of shielding electromagnetic field.

The Shielding Effectiveness (SE) of the cage is calculated by using Equation 3. The data is shown in Figure 2 below.

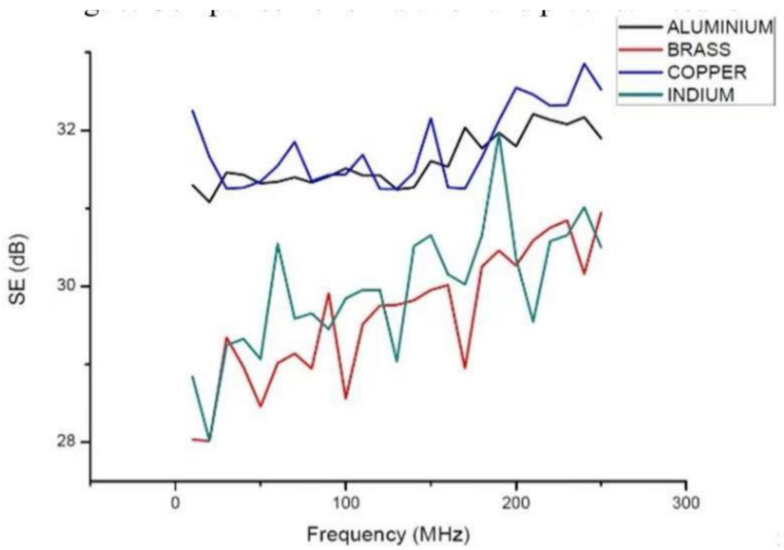

Figure 2: Comparison of SE(dB) simulation results for various materials. Cited from "Analysis of Shielding Effectiveness of a Faraday Cage for High Voltage Laboratory," (Pula, Sudarsan, Rallapalli, Narayan, Baskaradas, and Balasubramanian, 2019), Fig. 6(a).

2.2.2 Result Analysis

Figure 2 shows the results of the SE measured of various materials. Aluminum and Copper are the two metals that have high shielding effectiveness. According to Table 1, Aluminum has a free electron density of $1.81*10^{23}cm^{-3}$, which is the highest compared to the others in the table shown. Copper has a free electron density of $8.47*10^{22}cm^{-3}$, which is an intermediate value in Table 1. But it has a relatively high electrical conductivity shown in Table 2, which is $5.9*10^{7}S/m$.

Indium and Brass have lower shielding effectiveness than Copper and Aluminum. Indium has a free electron density of $11.5*10^{22}cm^{-3}$, which is bigger than Copper's, but smaller than Aluminum's. However, the shielding effectiveness of Indium is lower than the shielding effectiveness of Copper. The reason for this phenomenon may be attributed to the electrical conductivity of the metals shown in Table 2. The electrical conductivity of Indium is $1.2*10^{7}$ S/m, and the one of Copper is $5.9*10^{7}$ S/m. Copper has higher electrical conductivity than Indium, which means that Copper can conduct electrical current more effectively than Indium. Copper has higher shielding effectiveness than Indium.

For Brass, which is an alloy mainly made of copper, the data of its free electron density is few, but its electrical conductivity is $1.6*10^{7}S/m$, which is relatively low compared to others in Table 2. So, it has reasonably low shielding effectiveness in the results of the experiment shown in Figure 2.

3. Sizes of the mesh holes on the surface of the cage

3.1 Experiment Design

To find out the relationship between the sizes of the mesh holes on the surface of a Faraday Cage and the shielding capacity of the cage. An aluminum cage is made. WIFI is used to stimulate the electromagnetic field emitted by the card reader.

The size of mesh holes determines the range of frequencies it can restrict. The principle evolves that the cage allows the electromagnetic waves that have wavelengths shorter than the size of the mesh holes.

3.1.1 Aluminum cage

The Aluminum Cage is a cubic frame made of a box. The outer-lengths of the sides of the frame are all 20cm (±0.2cm). The inner-lengths of the sides of the frame are all 18cm (±0.2cm). The widths of the paper frame are 1cm (±0.1cm).

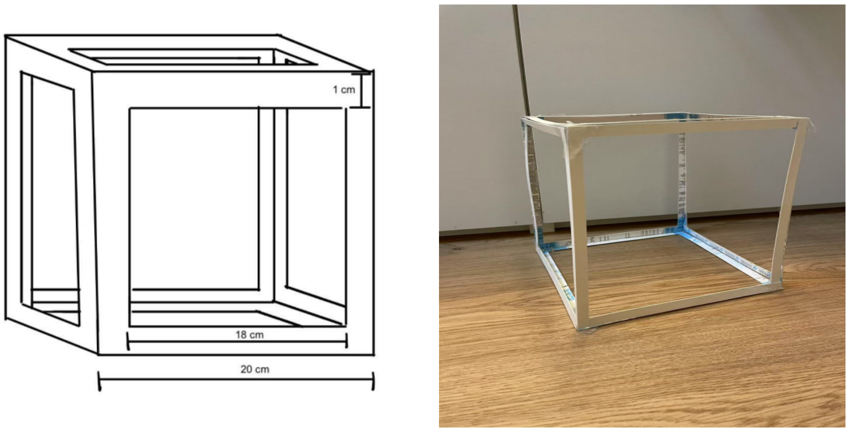

Figure 3 (a): The frame of the cubic Faraday Cage and its size. (b): The Faraday Cage made with box in reality.

The box-made Faraday Cage is wrapped with aluminum foil, with one layer. The thickness of the aluminum foil is 10µm.

3.1.2 Receiver

The receiver is iPhone 12 produced by Apple in 2020, which is placed at the central bottom of the Faraday Cage. An application called “Internet Speed Test Speedcheck” designed by “Etrality GmbH” is downloaded, used to the the speed of the internet in the Faraday Cage.

3.1.3 Ping

The value of Ping is used to determine the communication latency between two networks. It is the time taken for data to travel between devices or across a network. Here, we use it to represent the shielding capacity of the Faraday Cage in this experiment. As we can expect, better shielding capacity will lead to longer Ping. The value of Ping is measured in milliseconds..

3.1.4 WIFI Router

The WIFI router is used to stimulate the NFC reader in this experiment. The frequency of the WIFI emitted is between 2.4GHz to 5GHz, with wavelength from 7cm to 13cm (Lohnes.K, 2017). The wavelength of WIFI determines the sizes of the mesh holes of the cage demonstrated. The size of the mesh holes of the cage should be smaller than the wavelength of the wave so that the wave emitted cannot go through the cage. So, the cage can manifest its shielding effectiveness.

3.2 Experiment

This experiment demonstrated five different conditions to determine the relationship between the holes on the Faraday Cage and the ping of the WIFI.

The router is placed 1m away from the Faraday Cage, keeping the distance between the router and Faraday Cage unchanged. A receiver is placed in the Faraday Cage with an unchanged position. The Internet Speed is tested once the receiver is placed properly in the cage. Every experiment is tested three times, to reduce inaccuracies. The arithmetic mean values and standard deviations are calculated for each experiment.

This experiment not only evaluates the relationship between the size of the mesh holes of the cage and its shielding effectiveness, but also the shielding effectiveness of the cage when the wavelength of the wave is smaller than the size of the mesh holes.

3.2.1 Accessible area: 18cm*18cm, without aluminum foil

This experiment serves as a control group, which is used to compare with the experiment with aluminum foil to acquire the effects of wrapping aluminum.

The pings are measured three times, the data is shown in Table 3.

Table 3. Pings of WIFI of box-made Faraday Cage with 18cm*18cm accessible area

test 1	test 2	test 3
76 ms	78 ms	50 ms

The arithmetic mean value of the pings tested of WIFI of a box-made Faraday Cage with 18cm*18cm accessible area is 68ms, calculated with Equation 1. The standard deviation of the ping is 68 ± 22ms, calculated with Equation 2. The data of the experiment shows that the WIFI is unstable, and the amplitude of variation is quite big. Which may influence the results of the experiments afterward.

3.2.2 Accessible area: 18cm*18cm, with aluminum foil

The Faraday Cage is wrapped with aluminum foil, compared to the experiment presented in 3.2.1. This experiment investigates the effects of covering aluminum foil of Faraday Cage, when the size of the mesh holes is bigger than the wavelength of the wave accesses.

The pings are measured three times, the data is shown in Table 4.

Table 4. Pings of WIFI of aluminum-wrapped Faraday Cage with 18cm*18cm accessible area

test 1	test 2	test 3
164 ms	106 ms	197 ms

The arithmetic mean value of the pings tested of WIFI of aluminum-wrapped Faraday Cage with 18cm*18cm accessible area is 155.7ms, calculated with Equation 1. The standard deviation of the ping is 155.7 ± 37.62ms, calculated with Equation 2.

The data of the experiment shows that the Faraday Cage has the shielding effectiveness of external electromagnetic waves, even though the wavelength of the electromagnetic wave is smaller than the size of the mesh holes on the surface of the cage.

3.2.3 Accessible area: 8cm*18cm, with aluminum foil

Based on the Faraday Cage shown in Figure 3, six more aluminum stripes with a width of 2cm (0.1cm) are added, with each surface one more stripe connected to the midpoints of the edges of the cage. The accessible area is separated into two identical areas, with an accessible area of 8cm*18cm, which is shown in Figure 4.

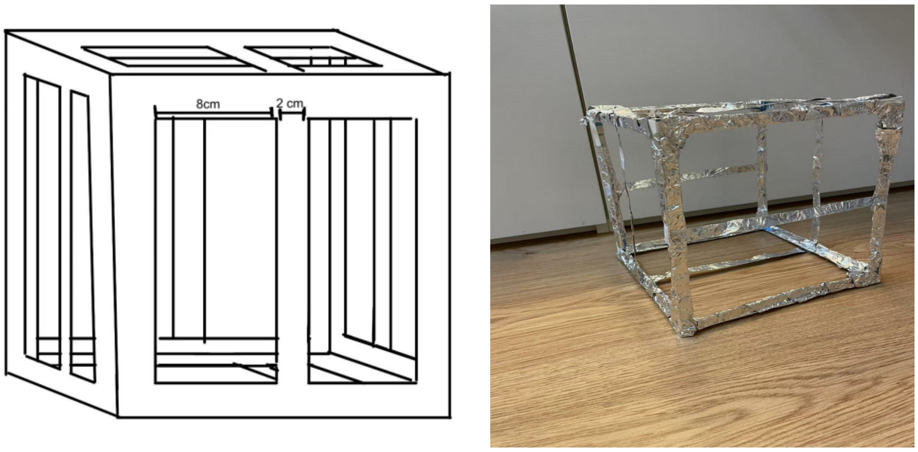

Figure 4 (a): model of the frame of the experiment presents in 3.2.3 and its size. (b): the Faraday Cage used in 3.2.3.

The accessible area of the cage is still bigger than the wavelength of WIFI. The pings are measured three times, and the data is shown in Table 5.

Table 5. Pings of WIFI of aluminum-wrapped Faraday Cage with 8cm*18cm accessible area

test 1	test 2	test 3
309 ms	201 ms	304 ms

The arithmetic mean value of the pings tested of WIFI of aluminum-wrapped Faraday Cage with 8cm*18cm accessible area is 271.3 ms, calculated with equation 1. The standard deviation is 271.3 ± 49.87ms, calculated with equation 2.

This data shows that with a smaller accessible area, the ping of the WIFI will increase, even though the accessible area is bigger than the wavelength.

3.2.4 Accessible area: 8cm*8cm, with aluminum foil

Based on the Faraday Cage shown in Figure 4, every surface of the cage is added with one more aluminum stripe, which perpendicularly intersects with the aluminum stripe added in 3.2.3 on the mid-points. The width of the aluminum stripes is 2cm (± 0.1cm). The model of the cage is shown in Figure 5.

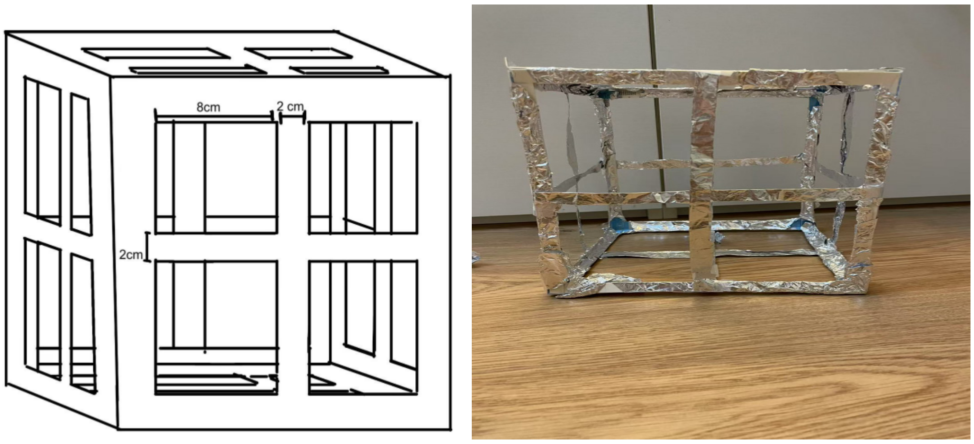

Figure 5 (a): model of the frame of the cage presents in 3.2.4 and its size. (b): Faraday Cage used in 3.2.4.

The accessible area of the electromagnetic wave is 8 cm*8 cm, which is in between the range of the wavelength, which is from 7cm to 13 cm. The ping is tested three times, as shown in Table 6.

Table 6. Pings of WIFI of aluminum-wrapped Faraday Cage with 8cm*8cm accessible area

test 1	test 2	test 3
597 ms	437 ms	471 ms

The arithmetic mean value of the pings tested of WIFI of aluminum-wrapped Faraday Cage with 8cm*8cm accessible area is 501.67ms, calculated by using Equation 1. The standard deviation is 501.67 ± 66.09ms, calculated with Equation 2.

This experiment shows that the wavelength of WIFI is probably smaller than 8cm, because the wave can still travel between the devices.

3.2.5 Accessible area: 3cm*3cm, with aluminum foil

Based on the Faraday Cage presents in Figure 5, the accessible area on the surface of the Faraday Cage is furthermore reduced to 3cm*3cm, with 4 more 2cm-wide aluminum stripes added each face of the cage, shown in

Figure 6.

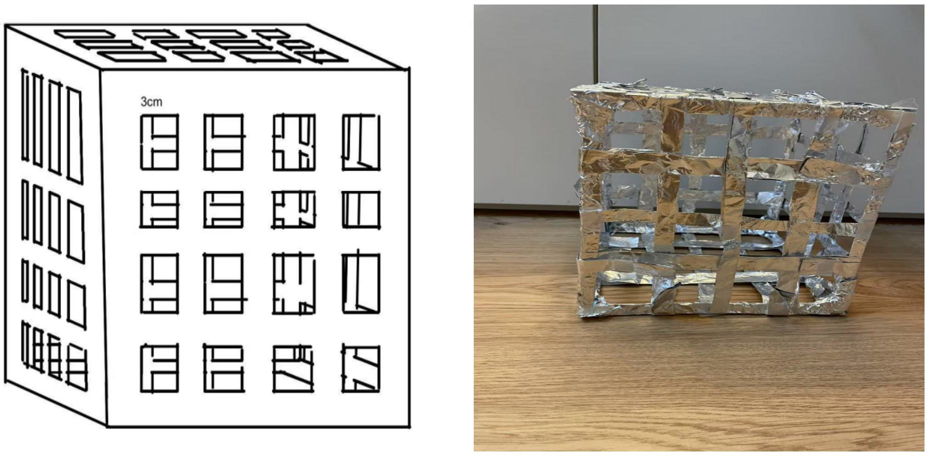

Figure 6 (a): model of the frame of the Faraday Cage presents in 3.2.5 and its size. (b): Faraday Cage used in 3.2.5.

The accessible area of the electromagnetic wave is 3cm*3cm, which is smaller than the size of its wavelength, which is at least 7cm. The ping is tested three times, and the results are shown in Table 7.

Table 7. Pings of WIFI of aluminum-wrapped Faraday Cage with 3cm*3cm accessible area

test 1	test 2	test 3
no response	no response	no response

This data set shows that the electromagnetic field cannot be transmitted when the accessible area on the surface of the cage is smaller than the wavelength of the electromagnetic wave. The electromagnetic field emitted cannot reach the receiver inside the cage.

4. Results

4.1 Results of Materials being chosen to demonstrate card bags

The material of the Faraday Cage should conduct the external electromagnetic field effectively and rapidly, which means that both its free electron density and electrical conductivity should not be too low. Copper, Aluminum and Silver are the three optimal options.

This study is about designing card bags, so the prices and the difficulty of obtaining the materials should also be considered. Aluminum is the optimal material for making card bags by considering its price, which is only one-third of the price of copper and 1/600 of the price of silver per unit mass.

4.2 Results of the sizes of the mesh holes of the card bags

The relationship between the pings measured and the conditions of the Faraday Cage is shown in Table 7. The higher the ping, the longer the time to transmit information, and furthermore, the higher the cage has higher shielding effectiveness.

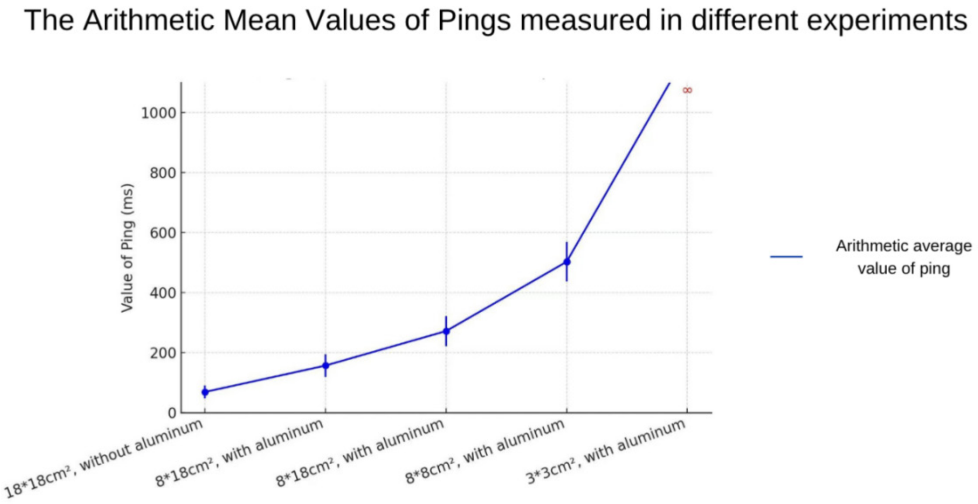

Table 7: the overall results of the arithmetic mean value of pings from different experiments

From the trend of the results shown in Table 7, adding aluminum creates a bigger shielding effectiveness than without aluminum. When the sizes of the mesh holes are reduced, the shielding effectiveness becomes bigger. Once the size of the mesh holes is so small that the wavelength of the wave is longer than the size of the mesh hole, the wave is unable to access the cage. All the electromagnetic fields are being canceled by the cage.

Based on the experiment result, to realize a better performance, the size of the mesh holes of the card bags should be smaller than the wavelength of the wave emitted by the NFC reader, which is 22.1m. This means that the size of holes of the card bags does not need to be designed carefully; once the diameter of the hole is smaller than 22.1m, it can shield the electromagnetic waves emitted by the NFC reader and prevent data theft and hacking.

Discussion

The simulation of using a WIFI router as an electromagnetic emitter provides us with easier ways to measure the shielding effectiveness of Faraday Cage, and also, the calculation of the shielding effectiveness of various materials provides valuable insights into understanding the shielding effectiveness related to the materials' own properties. Several key points emerge from the simulation results:

1) Accuracy

When using a WIFI router as the electromagnetic emitter, the instability of the electromagnetic waves being emitted leads to large-scale error, which enlarges the range of the pings. Future research could use a more stable electromagnetic wave generator to avoid large-scale errors and better present the results.

2) Limited Experiment Facilities

Only one kind of electromagnetic wave is tested in this paper, due to limited supplies of experiment facilities. Future research could change different electromagnetic field emitters to investigate the shielding effect of Faraday Cage on various electromagnetic fields with different properties, such as wavelengths.

3) Sizes of the mesh holes on the cage

The shielding effectiveness is not influenced by the size of the cage, so the scale of the cage can be small so that it would be easier to make; only the holes in the cage determine its shielding effectiveness.

This study helps improve the design of hard bags from two dimensions, which are the materials and the size of the holes of the card bags, to reduce data theft and hacking.

The optimal card bags that can prevent data theft possess some features shown below:

1. It is covered with conductive materials, such as metals. Aluminum is one of the best materials because it has both high electrical conductivity and free electron density.
2. The sizes of the holes on the surface of the conductive layer are smaller than the wavelength of the electromagnetic wave shielded. The smaller the holes, the higher shielding effectiveness of the card bag. If the costs of the raw materials are not considered, the card can be completely wrapped with the conductive layer, with no holes on it.

Conclusion

Data theft and “Card not present fraud” happen in many countries and places. We propose some ways which are

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using materials with both high free electron density and high electrical conductivity to make the card bags, and reducing the sizes of the holes on the card bags respectively, for the producers of card bags based on Faraday Cage to optimize their designs of card bags, which will prevent the criminals acquiring money from credit cards by using NFC readers. In other research, no one has mentioned the relationship between Faraday Cage and card bags yet. My research is mainly focused on the sizes of the mesh holes on the card bags and the materials chosen when making the card bags. Based on the results of the experiments, which are choosing the materials with high free electron density and high electrical conductivity in the production of card bags, and reducing the mesh holes on the bags, we think that a useful card bag is made of Aluminum and has as small mesh holes as possible (or no holes on the surface of the bag). Our research helps others prevent data theft and hacking and provides new ways for the producers to produce card bags, which helps them exploit the market.

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