ELECTROMAGNETIC WAVE PROPAGATION THROUGH CLOSED METAL SYSTEMS

by

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THROUGH CLOSED METAL SYSTEMS

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ABSTRACT

A Faraday cage is an enclosure that shields electromagnetic fields from entering or exiting the cage. While metals with high electrical conductivity are expected to effectively demonstrate the operation of a Faraday cage, preliminary observations of a sealed cast iron cylinder allowing the transmission of Bluetooth signals between a smartphone and wireless earbuds across it suggested the need for further research into electromagnetic wave propagation through closed metal systems. This research utilized Bluetooth connectivity tests through sealed metal cylinders made of cast iron, aluminum, and stainless steel to analyze the working of Faraday cages, explore related material properties, and isolate possible reasons for the conflict in expected behavior when electromagnetic transmission is detected through such cages. The research methods included conducting Bluetooth connectivity tests with different cylinder orientations and analyzing the strength of the transmitted and received Bluetooth signal. The key findings of this study suggest that material properties, spatial orientation, and the strength of the electromagnetic source influence the transmission of electromagnetic waves through sealed metal cylinders. The implications of these findings suggest potential exceptions to a common electromagnetic phenomenon and provide insights for future research.

TABLE OF CONTENTS

INTRODUCTION

From everyday machines like microwave ovens to experiences like losing connectivity on a smartphone as one enters an elevator, the interactions between electromagnetic waves and electric conductors can manifest itself in different ways around us. Considering the wide reach and applicability of this interaction, it is important to re-examine the working of Faraday cages. Additionally, such research can expand our current knowledge of Faraday cages as well as bring vast applications in fields such as electromagnetic interference (EMI) shielding or signal transmission.

Background

Faraday cages are enclosures that block electric fields and electromagnetic waves [1]. First observed by Benjamin Franklin, the Faraday cage effect was experimented on by Michael Faraday, who placed a gold-leafed electrometer within a 12-foot cubed chamber and observed that the electrometer showed no signs of electricity or charge within the chamber despite charging the cube through an external means [2]. The concept of a Faraday cage was thus defined due to the shielding effect it produced in enclosures made of electrically conductive materials, such as metals. These previous experiments developed the modern understanding of Faraday cages as utilized in applications across various fields from electronics to medicine [2].

Electromagnetic (EM) fields consist of two components: the electric field and the magnetic field. When an EM field acts on a metal enclosure, the two components influence the system in different ways. An undisturbed metal enclosure has an even distribution of free electrons and latticed metal cations (Figure 1.a). However, when an external electric field is introduced to this system, the free electrons will move toward the positively charged end of the external electric field. This redistribution of charges, or electrostatic induction, results in the creation of a positively and negatively charged side of the metal enclosure that counters the applied electric field, resulting in a net zero charge on the inside of the Faraday cage (Figure 1.b).

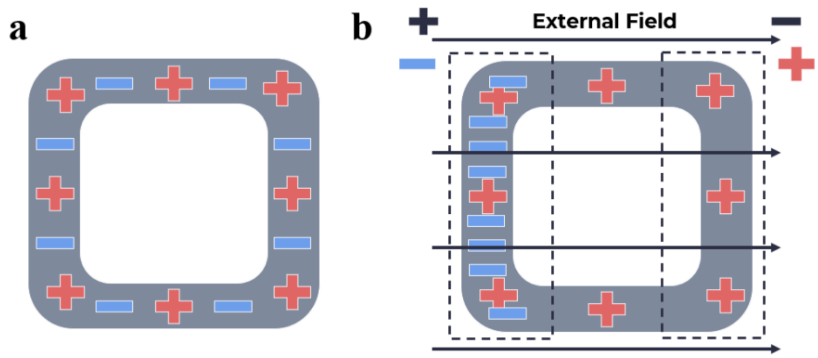

Figure 1: (a) Metal enclosure in electrostatic equilibrium with an even distribution of free electrons and metal cations. (b) Electrostatic induction in the metal enclosure under the influence of an external electric field

If the redistribution of charges facilitated the canceling effect of an applied electric field, the eddy currents generated by the flow of electrons create smaller magnetic fields that run opposite to the applied magnetic field and counteract it (Figure 2). These magnetic fields can thus redirect and significantly lower the net magnetic field acting on the Faraday cage.

A sealed enclosure made of a solid metallic screen is expected to behave as a Faraday cage whose shielding effectiveness increases with the frequency of the electromagnetic wave applied [3]. Bluetooth is a short-range high frequency radio wave that operates at around 2.4 GHz. Metal enclosures under an external Bluetooth influence should thus not allow for transmission across the enclosure owing to the Faraday cage effect.

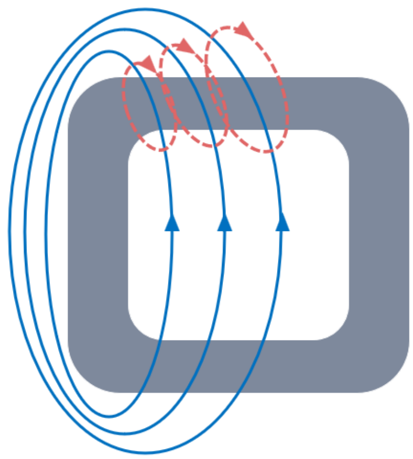

Figure 2: Faraday cage affected by an external magnetic field (blue), which is counteracted by the magnetic fields (red) produced around the eddy currents caused by the flow of electrons.

However, when a Bluetooth headset was connected to a phone and the latter was placed within a sealed cast iron cylinder, a Bluetooth connection between the two was detected through the music that continued to play from the headset despite the phone technically being placed within a Faraday cage. This transmission of Bluetooth signals through a Faraday cage brings to question the working of Faraday cages and the need to further investigate this conflict in expected behavior.

An additional consideration of the skin depth can aid with the current understanding of Faraday cages. The skin depth of a material is the distance from the surface of a metal that an external field penetrates before exponentially decaying. Thus, a thicker Faraday cage made of a material with a lower skin depth can prove to be more effective in shielding electromagnetic waves. The skin depth of a material can be calculated as shown:

$$Skin\ Depth = \sqrt{\frac{\rho}{\pi f \mu_r \mu_o}} \tag{1}$$

In equation 1, ρ is the resistivity of the material, f is the frequency of the electromagnetic wave, μ_r is the relative permeability of the material, and μ_o is the permeability of free space, where $\mu_o = 4\pi * 10^{-7}$H/m. Ensuring that the Faraday cages have a thickness greater than the calculated skin depth can ensure attenuation of the applied external field.

The presence of moving charges and currents in a Faraday cage under the influence of an external electromagnetic field as shown in Figures 1 and 2 can also set up evanescent waves at the surface of the cage. These evanescent waves do not propagate like electromagnetic waves and oscillate closer to the surface of the material, so they could influence the readings of electromagnetic waves taken near the surface of a Faraday cage but would have no significant impact at larger distances from the surface.

There have been some observations on the inconsistency of Faraday cages as well as attempts to explain them. A mathematical study of the Faraday cage revealed that the redistribution of charges within a Faraday cage was not sufficient for a complete cancellation of fields, attributed to producing electrostatic induction in a surface of limited capacitance [1]. Another study claims that the possibility of resonance between the applied frequency and the natural frequency of the solid enclosure can result in the cage in the electromagnetic field amplifying the applied field instead of shielding it as expected [4]. This paper aims to consider metal properties as a means of understanding how Faraday cages work.

METHODS

Materials

The metal enclosures used in this research were metal cylinders made of cast iron, aluminum, and 316 stainless steel. This variety in the metals used allowed for observations of any metal properties or design considerations that were consequential to the working of Faraday cages. All three cages were 6mm thick, completely sealed with sealant, and inspected to have no breaks or openings. Additionally, the skin depths of each material at 2.4GHz were calculated using Equation 1 to ensure that the applied external field would attenuate close to the surface (Table 1).

Table 1. Calculated skin depths at 2.4GHz

Metal	Approximate Skin Depth (μm)
Cast iron	0.16
Aluminum	1.67
316 stainless steel	8.89

Using typical values, all metals were found to have an approximate skin depth much smaller than the 6mm thickness of the cylinder walls. Thus, an electromagnetic signal with frequency 2.4GHz can be expected to attenuate close to the surface of all metal cylinders used.

Connectivity Test

The first test utilized in this study focused on checking for Bluetooth connectivity between two elements separated by a Faraday cage made of different metals. To do so, a Bluetooth speaker was used to play music while connected to a smartphone. Unobstructed, the speaker and the phone had a general range of connectivity of up to 90 ft before they disconnected. By placing either the speaker or the phone within a metal cylinder, the set-up with maximum shielding was determined. This test showed that placing the phone within the metal cylinder showed more shielding in Bluetooth transmission than when the speaker was placed within the cylinder, which resulted in the former being chosen as the primary testing set-up (Figure 3).

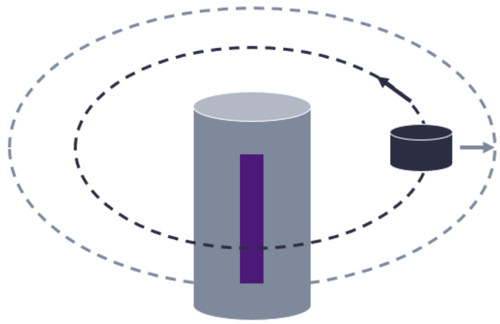

Figure 3: Schematic of Connectivity Test, with a phone placed within a metal cylinder and connected to an external Bluetooth speaker.

The connectivity test then primarily focused on checking the range of connectivity between the Bluetooth speaker and the smartphone when the latter was placed within the various metal cylinders. Additionally, the speaker would be moved around the metal cylinder to observe the directionality of signal transmission. Considering that the enclosed metal cylinders were Faraday cages, it was expected that none of the metal cages would allow significant Bluetooth signals transmit across their walls despite our previous observations of the cast iron cylinder allowing for such transmission. If Bluetooth transmission was observed across these metal cages, further exploration of signal strength could be undertaken.

RF Signal Strength Test

The RF Signal Strength Test quantified the strength of the Bluetooth signal that was transmitted out of the tested Faraday cage and compared the signal strengths detected through enclosures made of different metals. This test was designed as a follow-up to the Connectivity Test and to further explore material and design properties to not only understand the working of Faraday cages but also to investigate why certain Faraday cages did not function as expected.

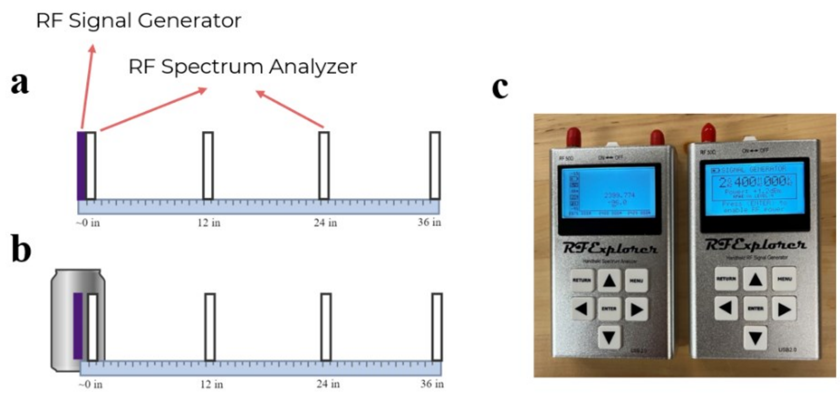

Figure 4: (a) Schematic of unobstructed RF Signal Strength Test. (b) Schematic of RF Signal Strength Test with the RF signal generator placed within a metal cylinder. (c) RF Handheld Spectrum Analyzer and RF Handheld Signal Generator set to send a 2.4GHz signal at +1.2 dBm.

This signal strength test utilized a Radio Frequency (RF) handheld signal generator and an RF handheld spectrum analyzer to send and receive a signal respectively (Figure 4.c). RF devices measure signal strength in dBm using a Received Signal Strength Indicator (RSSI), where the units of dBm are a logarithmic scale with reference to 1mW of power. The RF signal generator was set up to send a +1.2 dBm signal at 2.4 GHz, which would mimic transmitting a constant Bluetooth signal. The RF spectrum analyzer was then set to read isolated signals specifically sent from the RF signal generator by blocking the signals detected from ambient Bluetooth sources.

An initial read for the test required the RF signal generator and spectrum analyzer to be placed next to each other with their antennae aligned to read the maximum strength of the signal transmitted between them. This read would allow for a determination of the signal loss in transmission in an unobstructed set-up (Figure 4.a). Then, the RF spectrum analyzer was moved 12 inches away from the signal generator, and the signal strength detected was noted. These steps were repeated with the signal generator moving 12 additional inches away, and an average of the values was tabulated. The test was then repeated with the RF signal generator placed within each of the three metal cylinders (Figure 4.b).

Bluefruit Spatial Test

In addition to the use of the RF handheld devices, an Adafruit Feather M4 Express with a Bluefruit Low Energy (LE) module was utilized as a data pipe to send Bluetooth signals from the Feather to a smartphone using Bluefruit connect, an IOS and Android mobile application. This repeat of the previous test using the Adafruit Feather would allow for further observation of the working of Faraday cages as well as checking for repeatability in the research.

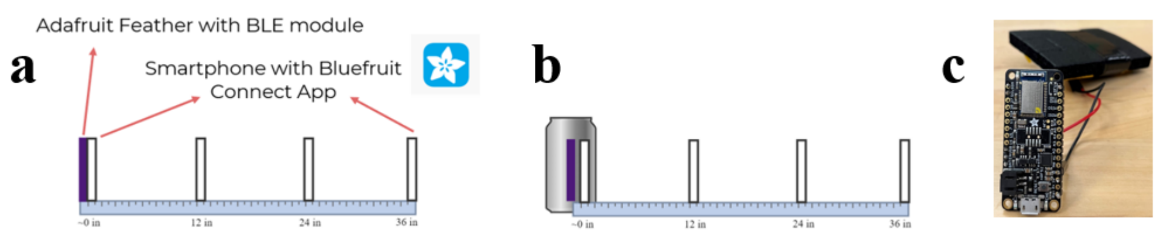

Figure 5: (a) Schematic of unobstructed Bluefruit Spatial Test. (b) Schematic of Bluefruit Spatial Test with the Adafruit Feather placed within a metal cylinder. (c) An Adafruit Feather M4 Express with a Bluefruit LE module connected to a 3.7V Li-Po Battery.

The Adafruit Feather's Bluefruit LE module needed to be activated to send signals to a smartphone, so an open-source code from Adafruit to have the Feather act as a Bluefruit controller was uploaded to it. The Feather was then connected to a 3.7 Lithium Polymer (Li-Po) battery (Figure 5.c) and tied together to create a Bluetooth emitter, the signal strength from which could be read in real-time on the mobile application.

An initial read of the signal strength of the Bluetooth transmission between the Bluetooth emitter and the phone when placed right next to each other was noted, with later readings taken as the phone was moved away in 12-inch increases (Figure 5.a). These steps were repeated with the Bluetooth emitter placed within each of the three metal cylinders, and the average values of the signal strength detected by the phone at each position were noted.

RESULTS

Connectivity Test

The first test provided expectations for the rest of the tests used in this research. For instance, the initial observation of the cast iron cylinder suggested that the enclosure would allow for the transmission of Bluetooth signals across it, but we did not expect the same for the aluminum or the stainless steel cylinders owing to their increased electrical conductivity properties. Additionally, if the three metal enclosures used allowed for Bluetooth transmission across, then the metal enclosures could be considered to not act as ideal Faraday cages.

However, a successful Bluetooth connection was observed through the speaker when the phone was placed within all three metal cylinders. A basic estimate of the range of connectivity between the phone and the speaker was noted, as detailed in Table 2.

Table 2. Range of Bluetooth connectivity between a phone and a speaker placed within a metal enclosure

Metal Enclosure	**Range of Connectivity (in)**
Cast iron	32
Aluminum	20
316 stainless steel	30

The cast iron enclosure thus seemed to show the least shielding due to the larger range of connectivity it allowed for, with the aluminum enclosure showing the most signal shielding.

However, this test did not demonstrate the extent of shielding in terms of signal strength and merely estimated the range of connectivity between the phone and the speaker when the latter was placed within the tested Faraday cage.

RF Signal Strength Test

The RF Signal Strength Test addressed the limitations of the previous test by reading the strength of the transmitted signal across each of the metal enclosures and comparing these values with the strength of the unobstructed signal as well as with that of the transmitted signal through the other metal cylinders. The averages of the signal strength values were plotted on a graph to find trends in signal shielding (Figure 6).

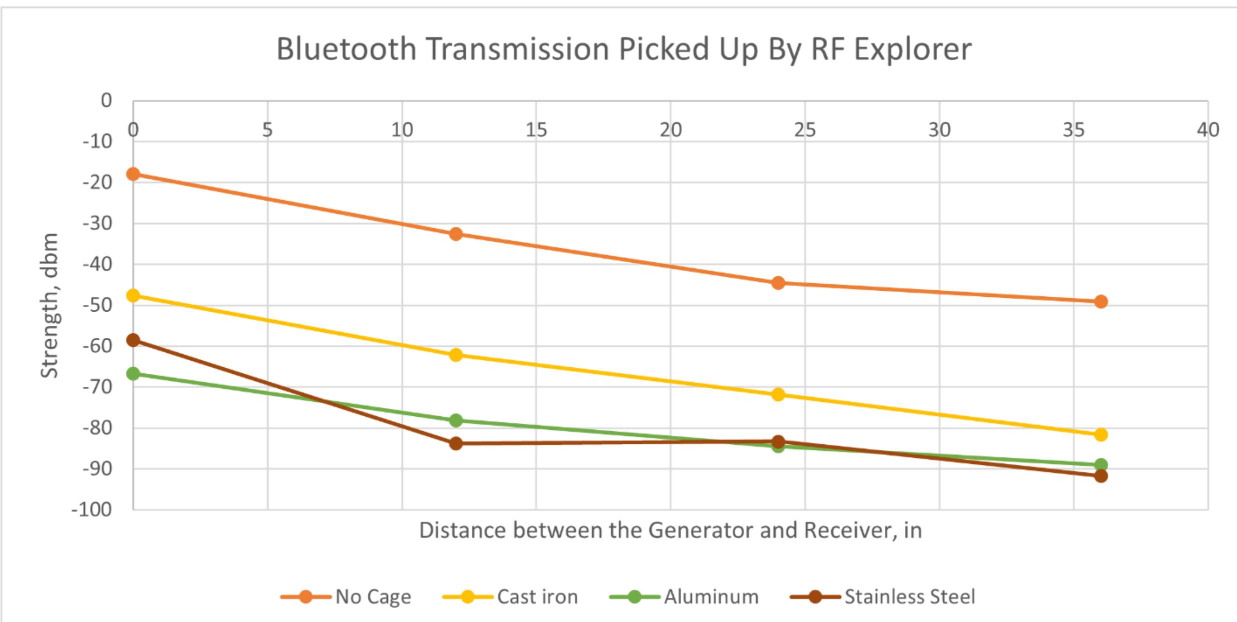

Figure 6: Strength of Bluetooth Signal Detected by the RF Spectrum Analyzer

The strength of a signal is expected to decrease with an increase in the distance from the source, which was a common trend with all values noted. The unobstructed signal strength data set starts with a -17.875 dBm reading when the RF spectrum analyzer is placed right next to the signal generator, indicating a loss of about 19 dBm in unimpeded transmission. There was about a 30 dBm difference between the unobstructed readings and the readings from the cast iron test, which seemed to show the least shielding in signal transmission.

The aluminum and stainless steel enclosures showed lower values in the strength of the transmitted signal. This observation is in line with the expectations derived from the ranges of Bluetooth connectivity detailed in the connectivity test. While the lower signal strengths detected suggest a greater shielding of the generated signal from the enclosed source, the two metal enclosures still allowed for electromagnetic transmission through their walls and were not very effective as Faraday Cages.

Bluefruit Spatial Test

The Bluefruit Spatial test was designed to check for repeatability using the Adafruit feather as a signal source instead. The averages of the strength of the signal transmitted to the phone were plotted on a graph to further analyze the data (Figure 7).

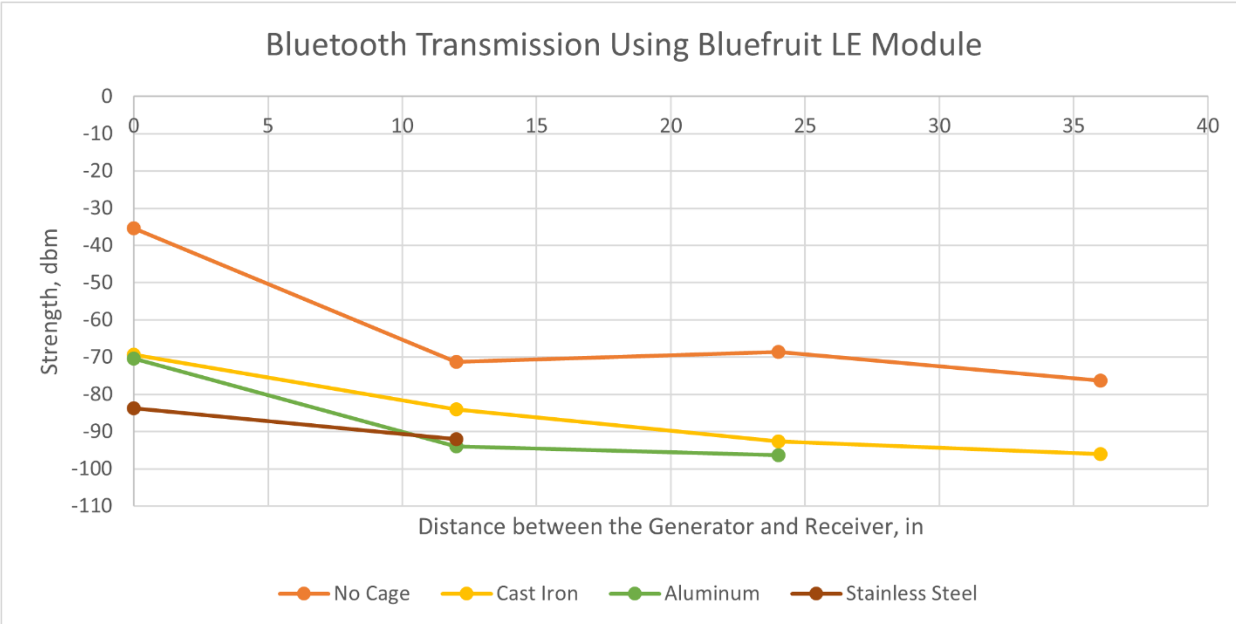

Figure 7: Strength of Bluetooth Signal Transmitted to the Bluefruit Connect App

The trends in data are similar to the results from the RF Signal Strength test, suggesting high repeatability with these tests. The Bluefruit LE module on the Adafruit Feather sends signals with a lower energy, which explains the lower values of signal strength overall. Due to this lower strength of the source signal, the readings taken with the Feather placed within the aluminum and the stainless steel enclosures and the phone positioned at 24 and 12 inches respectively were the last readings taken for each, after which the Feather disconnected from the phone. Thus, the cast iron enclosure again showed the least shielding, while the other two metal enclosures were more effective in shielding the generated Bluetooth signal from the enclosed source. However, this shielding could be attributed largely to the low energy Bluetooth signal generated or even the larger distance at which the receiver had to be placed to not detect signal transmission.

Shielding Effectiveness

The data from the RF Signal Strength test and the Bluefruit Spatial test can be used to gauge the shielding effectiveness of the cast iron, aluminum, and stainless steel enclosures. The IEEE standard for measuring the effectiveness of electromagnetic shielding enclosures [5] defines shielding effectiveness for high-range frequencies (300 MHz to 100 GHz) through the following equation:

$$SE = P_{without\ enclosure}(dBm) - P_{with\ enclosure}(dBm) \tag{2}$$

The average values of the calculated shielding effectiveness (SE) of each metal enclosure across both tests are displayed in Table 3.

Table 3. Shielding effectiveness displayed by the metal cylinders.

Metal Enclosure	RF Test (dBm)	Bluefruit Test (dBm)
Cast Iron	29.82	22.58
Aluminum	43.55	28.44
316 Stainless Steel	43.30	34.5

The SE values for the tests confirm previously mentioned trends, with aluminum and stainless steel demonstrating more shielding than cast iron. Stainless steel can be observed to have a significantly higher SE with the Bluefruit Spatial Test, but this value, alongside the SE for aluminum with the same test, does not account for the phone and the Feather disconnecting prematurely. This disconnection resulted in lesser data points recorded, which could lower the significance of the SE values calculated.

DISCUSSION

All three tests indicated that the metal enclosures overall allowed for the transmission of electromagnetic waves through them. To understand the reasons for this observation, some design considerations were evaluated. In the case of breaks or openings in the metal enclosures, the gaps would have to be less than $1/10^{th}$ the wavelength of Bluetooth signals [6]. Considering that the metal cylinders we used were sealed and were inspected to have no such gaps, this consideration can be disregarded.

Possible breaks in the continuity of the metal in the enclosure could have resulted in ineffective electrostatic induction. If one side or portion of the metal cylinders was discontinuous, that would mean that upon the influence of an external field, the free electrons would not redistribute evenly resulting in a partial canceling effect that leaves a non-zero field inside the Faraday cage, unlike shown in Figure 1.

Another consideration involves the electric conductivity of the metal used. A lower conductivity would mean that the metal would be more resistive and thus would slow the redistribution of electrons under the influence of an external electromagnetic field, also resulting in an ineffective canceling effect. Considering that the skin depth of a material is proportional to the square root of the material's resistivity (Equation 1), the skin depth values of the three metals can be related to their electrical conductivity.

With skin depth, the cancelling effect occurs at the surface of the Faraday cage, so increasing the thickness of the cage can help attenuate the external field before it can move from the surface to the interior of the cage in the case of partial canceling at the surface [6]. While the initial calculation of the skin depths of the three metals showed that they were much lower than the thickness of the cylinders used (Table 1), increasing the thickness of the cylinders could additionally extend the exponential decay and ensure attenuation. Thus, a metal with a higher conductivity and a lower skin depth can ensure a higher SE value and thus be used as a more effective Faraday cage. In the case of the metals used in this research, aluminum has the highest conductivity, and its ability to shield better than cast iron, for instance, can be supported by data from all three tests.

Additionally, the lowered magnetic field affecting a Faraday cage as a result of the influence of an external electromagnetic field (Figure 2) can require consideration of a metal's magnetic permeability as well. Metals like iron can have a higher permeability and shield more of the magnetic field, but this is more applicable with lower frequencies. With higher frequencies like with Bluetooth, however, iron's lower conductivity can make it less effective overall when used as a Faraday cage [7]. There can thus be different preferences when choosing a metal depending on the range of frequencies used in an application. In the case of Bluetooth signals, the lowered strength of the magnetic field that overall affects the Faraday cage shifts focus on choosing a metal with a higher conductivity over a metal with a higher permeability to ensure a high SE.

CONCLUSION

In this study, metal enclosures made of cast iron, aluminum, and stainless steel did not show the expected behavior of a Faraday cage when tested with short-range RF waves such as Bluetooth. A study of the signal strength transmitted across the metal enclosures allowed for a comparison of metal properties. Additionally, an understanding of shielding effectiveness and a comparison of SE values for the three metals supplemented the trends observed in the Bluetooth tests. Design considerations supported by the results collected in this research suggested that thicker Faraday cages with no breaks in continuity and made of metals with a high electrical conductivity could show higher shielding effectiveness against high-frequency electromagnetic fields like Bluetooth.

This study also raises questions about the effectiveness of these metal cylinders for shielding against other types of electromagnetic waves, such as microwaves. Working with a lower range of frequencies than used in this study could provide a different perspective to our understanding of Faraday cages as well as focus on the trade-off to be made between metals with a higher electric conductivity and those with a higher magnetic permeability. Further investigation of the observed inconsistencies in the behavior of these metal enclosures while under the influence of electromagnetic radiation can help us better understand electromagnetic shielding as well as throw light on new developments in this area of study.

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