OPTIMISING MATERIALS AND DESIGN FOR EFFECTIVE ELECTROMAGNETIC SHIELDING IN PHONE CASES

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Abstract

Electromagnetic (EM) shielding methods are often implemented to reduce the Electromagnetic Interference (EMI) between electronic devices for physical safety purposes. However, in recent years, the increased use of electronic gadgets has resulted in information theft. We aim to not only evaluate the material with the best shielding properties, but also an ideal corresponding protective design for a mobile phone to prevent eavesdropping of information in an electromagnetically noisy environment. Ultimately, the phone should be shielded effectively whilst the phone's essential functions remain operational, including maintaining connectivity to networks such as Wi-Fi and Bluetooth, as well as enabling the camera to function seamlessly. Using an iPhone 11 Pro Max as the test subject, aluminum proved to be the most effective shielding material. These were combined with a dust plug, wire mesh, camera slider, and cover to create a phone case that effectively shield EM waves.

Introduction

As advanced technologies continue to develop rapidly, sensitive data, such as banking information, identity details, and account passwords, can be compromised through EM waves emitted by everyday devices. This vulnerability can lead to identity theft, financial loss and unauthorised access to sensitive data, posing significant risks to individuals. Electronic devices generate and emit radio signals that often contain encoded information as a result of the electrical switching processes occurring in its digital circuitry. This can occur even when the emitted signal is suppressed in accordance with Electromagnetic Compatibility (EMC) standard [1]. An integrated circuit, which many are present in a modern day cell phone, processes data and can act as a EM wave leakage source[2]. Higher-frequency components (880MHz - 5GHz), consisting of LTE data, Bluetooth, and Wi-Fi, often propagate to device components that behave as an antenna[3], resulting in spatial radiation of the leakage[4], [5]. The leaked signals can then be easily received by foreign antennas, the wave pattern examined and decoded to derive the data in the original device.

The level of EM radiation generated by a device is heavily regulated by international EMC standards to ensure minimal EMI can occur. However, due to inherent limitations of standards, advanced eavesdropping techniques and cumulative emissions from multiple devices, leakage can occur even if the intensity of the EM radiation is less than the standard regulation value.

Currently, Faraday's Cages, formed by a continuous covering or mesh of conductive material, have been developed to confine EM waves and block EM fields within its walls. In today's efficiency-driven society, enclosing a device in a Faraday box while requiring it to function is impractical and cumbersome. As such, amongst a variety of conductive materials, we aim to investigate the material which displays the highest Shielding Effectiveness (SE) to strategically craft a Faraday's phone case. Openings in a case, such as gaps or holes, can weaken the shielding effectiveness because EM waves of certain frequencies can pass through these openings. Minimising these openings helps improve the shielding by reducing the paths through which EM waves can escape or enter. However, eliminating openings would block all electromagnetic waves, disrupting essential network connections for the phone. Hence, we would also be experimenting with different case designs to determine the most ideal combination of features and materials to effectively shield the phone. We aim to study the shielding of an iPhone 11 Pro Max to ensure optimal functionality in high EM environments and recommend a practical solution that meets shielding requirements without compromising performance.

Materials

For the front and back case of the phone, several materials, with varying levels of shielding effectiveness, were tested as shown in **Table 1.1** below.

Material	**Description**	**Link**
Black Copper Fabric	A cloth-like material made from a combination of Copper, Nickel, Carbon and RFID fabric	https://shorturl.at/kCQ4T
Copper Foil	A foil material made of Copper metal	https://shorturl.at/LTHox
Aluminium Foil	A foil material made of Aluminium metal	https://shorturl.at/YWAMT
Brass Foil	A foil material made of Brass metal	https://sg.shp.ee/ch1Je1W
Beryllium-Copper Bimetal Sheet	A sheet made of a combination of Beryllium and Copper metal	https://shorturl.at/8Bjlh
Graphene-Copper Bimetal Sheet	A sheet made of a combination of Graphene and Copper metal	https://sg.shp.ee/iRNYfwN
Zinc Sheet	A sheet made of Zinc metal	https://shorturl.at/iY8dL
Stainless Steel Sheet	A sheet made of Stainless Steel metal	Stainless Steel Plate
Silver-plated Fabric	A fabric made of Polyamide and Spandex plated with pure Silver	EM Shielding Silver Plated Fabric
RF Clear Film 1	A transparent sheet with shielding properties	RF Shielding Film - Redtec Industries
RF Clear Film 2	A transparent sheet with EM shielding properties attached to an adhesive layer	Clear RF Film

Table 1.1

Method

When creating a product mainly driven by practicality, many conditions need to be considered in its making. To determine the effectiveness of materials in making a shielding phone case, the SE and a few external factors were also considered. The factors are listed below:

1. **SE** — The most critical factor, which determines the material's ability to attenuate electromagnetic interference (EMI) from external sources.
2. **Material malleability** — The ability of the material to be pressed into the shape of a phone case, affecting the efficiency of the mass manufacturing process.
3. **Cost of material** — The cost of 100cm^2 material, affecting the affordability of the case.
4. **Mass** — The mass of 100cm^2 material, affecting the practicality of using it for convenient daily portability.

SE

To test out the SE of the different materials and designs, we proceeded with the set-ups described below. Then, a Spectrum Analyser (SA) was connected to the GTEM cell to process the data. This allowed us to plot graphs to compare the EM emissions leaked from the phone with different shielding design combinations.

SA Settings

Sweep time: 23.27s
Span frequency: 150MHz-400MHz
Resolution Bandwidth (RBW) & Video Bandwidth (VBW): 500Hz
Radio Frequency (RF) attenuation: 0dB
The ends of the cables connecting the spectrum analyser, GTEM cell, and the antenna were securely tightened to prevent inaccuracies due to poor connection.

Frequencies used to test potential materials used for the casing

The frequencies we intend for the iPhone to be able to connect to for basic functioning (LTE, Wi-Fi, and Bluetooth) lie within 880MHz to 5GHz. This prompted us to focus specifically on shielding the phone from emitting unnecessary EM waves of frequencies lower than 880 MHz. To fulfil this criterion, we first tested for emissions from an unshielded iPhone from 1MHz to 880MHz to locate problem areas. We deduced that the iPhone produces most of its unwanted frequencies within the range of 150MHz to 400MHz as shown in **Figure 2.1.**

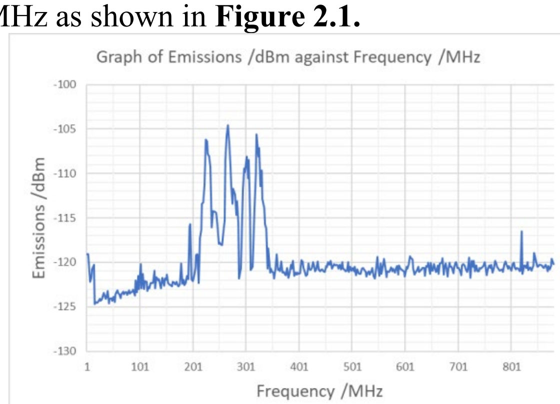

Figure 2.1 Graph of emissions/dBm against frequency/MHz showing that most emissions lie within 150MHz to 400MHz

Therefore, this frequency range was prioritized for our subsequent experiments to optimize shielding effectiveness.

Testing set-up

An antenna was placed in the GTEM cell, and a plastic-styrofoam set up as seen in **Figure 2.2** was used to ensure the phone is fixed at an upright position, 18 cm from the antenna, throughout our experiment. To induce the phone to emit EM signals, we activated the Wi-Fi and Bluetooth settings while playing a pre-downloaded video on the device at maximum volume.

Figure 2.2 Plastic-Styrofoam phone holder set up placed in GTEM Cell

In **Figure 2.3** and **Figure 2.4**, pouches of each material were made to fully encase the phone and the emissions from the phone within the frequency range of 150MHz to 400MHz were recorded.

Figure 2.3 Pouches made of respective experimental materials

Figure 2.4 iPhone placed in a pouch for testing

Double layer

Afterwards, we sought to find out the effect of increasing the number of layers of the material on the SE of the phone case. Firstly, we layered the inside of a prototype phone case with 1 layer of Aluminium foil and tested it for EM signal leakage with the GTEM cell using the set up previously mentioned in **Figure 2.2**.

For the second layer, we then added a layer of Aluminium foil to the outside of the phone case and tested it for emissions with the GTEM cell using the same set-up. This experiment is displayed in **Figure 2.5** and **Figure 2.6** below.

Figure 2.5

Figure 2.6

Weighing of materials

A lighter material is more practical and convenient for one to carry around on daily errands. Using an electronic weighing scale, we measured the mass of a $100cm^2$ section of each material.

Testing the physical design of the casing

After deducing that the best material is Aluminium, we used Aluminium to conduct further experiments to find out the best phone case design.

Reducing Aperture Sizes

We identified the charging port, speaker and camera lens as apertures which might affect the functionality of the phone if covered with opaque shielding materials. We explored methods to reduce overall aperture size while maintaining the functionality of these components:

- Back cameras
  Two initial ideas for covering the aperture were proposed. The first idea was to utilise a camera slider function allowing for the opening to be completely sealed by an effective shielding material whilst being easy to remove for camera use. The second idea was to attach a clear RF film over the camera opening. This enables users to take high-quality media while removing the large aperture created by the camera openings. During experimentation, the proposal of combining the two initial ideas was brought up and tested in **Figure 3.1** below.

Figure 3.1 Experimental casing with both camera slider and clear film cover

- Charging port
  We recognise that it is impractical for the phone case to completely cover the charging port opening, as it would make charging the phone extremely inconvenient. To address this, a dust plug, coated with the best shielding material deduced from our experiment, was used to cover the charging port.

- Speaker holes
  Additionally, we also covered the speaker holes with metal dust proof mesh. The mesh features smaller openings, which helps reduce the total aperture size while maintaining normal volume output, ensuring the phone's functionality is not compromised.

Figure 3.2 iPhone with shielded charging port dust plug and metal speaker cover mesh

Results

Testing potential materials used for the back face of casing

1. Comparison of SE

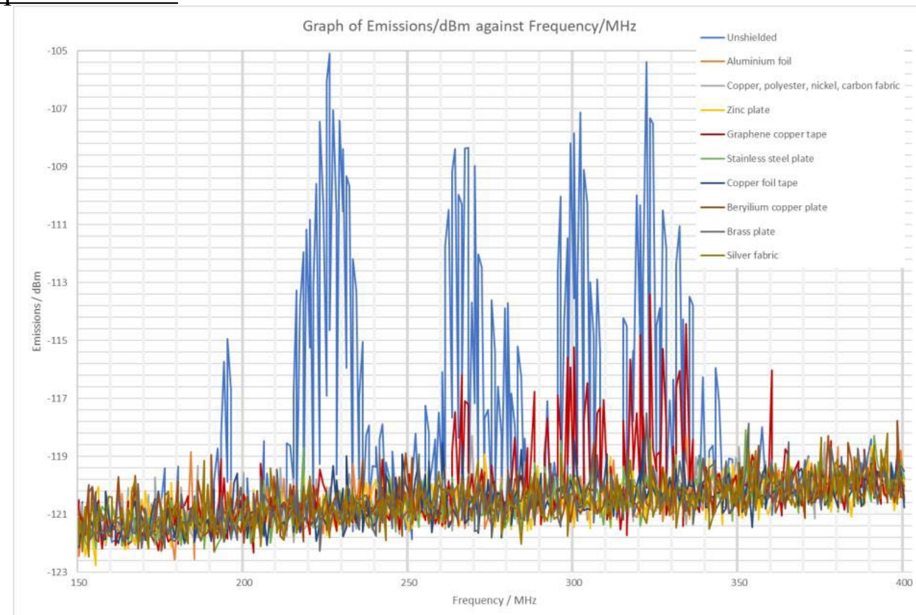

Figure 4.1 Graph of emissions/dBm against frequency/MHz of all materials for the back casing of the phone

From the graph above, the only outlier is the Graphene-Copper bimetal tape, which performed significantly poorer in shielding the emitted EM waves. Other materials, when used to completely wrap the phone, performed comparably well in shielding EM waves, effectively reducing emissions across most frequencies to a level close to the noise floor. Therefore, the external factors were evaluated to determine their suitability in coating a phone case.

Experiments conducted to deduce the effect of double layering the shielding material onto the phone case had produced the following results.

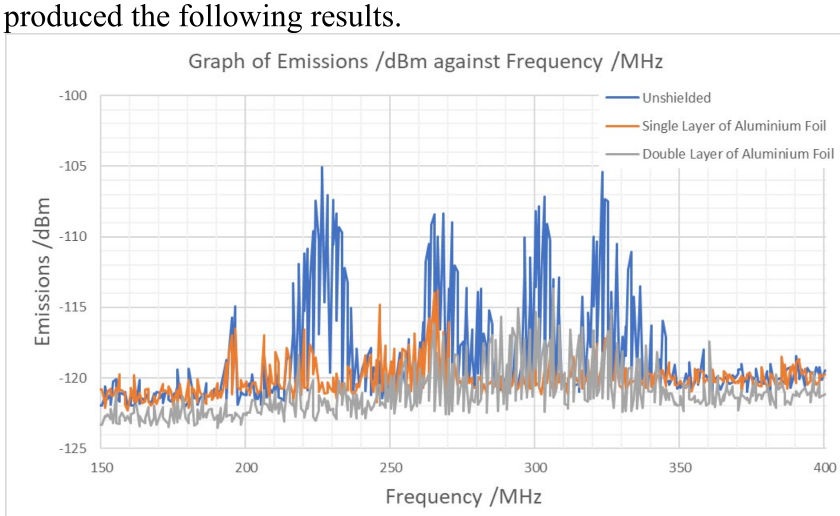

Figure 4.5 Graph of emissions/dBm against frequency/MHz of the iPhone with casing wrapped with 1 and 2 layers of Aluminium foil

Figure 4.5 above shows that the iPhone's emissions when its casing is wrapped with 2 layers of Aluminium foil is more effective below 260MHz as compared to when the casing is only wrapped with 1 layer of foil. This phenomenon observed could be due to the workmanship of the wrapping. Theoretically, it is expected that the 2 layered design will be able to lower the base level of emissions to a level significantly nearer to the noise floor even above 260MHz.

2. Comparison of Material Malleability

A few different textures were present amongst the materials bought (foil, sheet, plate and cloth). We found that the degree of hardness of certain materials posed a challenge in lining the phone case, requiring a significant amount of strength and effort to fully encase the iPhone. Hence, the basis of comparison of the malleability factor is the ability of the material to line a phone case. With this criterion in mind, the following ranking was determined:

Rank	Texture	Rationale	Material(s)
1	Foil	Easiest material to line the phone case due to their shapeable nature.	- Aluminium foil - Copper foil
2	Sheet	Folds easily but stays in place only to an extent.	- Graphene-Copper sheet
3	Cloth	Folds easily but does not adhere well or stay in place. Does not work well with adhesives.	- Black Copper fabric Silver-plated fabric
4	Plate	Least malleable and extremely stiff. Can have dangerously sharp edges.	- Zinc sheet - Brass sheet - Stainless Steel sheet - Beryllium-Copper sheet

Table 2.1

3. Comparison of Cost

Material	Aluminium	Black Copper fabric	Copper foil	Silver-plated fabric	Stainless steel	Zinc	Brass	Graphene-copper	Beryllium Copper
Price /100cm² ($)	0.01	0.03	0.22	0.47	0.59	0.72	0.82	0.89	2.45

Table 3.1

As seen from **Table 3.1**, for the same size of material, Aluminium foil and Black Copper fabric are significantly cheaper than the rest of the materials. This allows for these materials to make the most cost-effective EM shielding phone case.

4. Comparison of Weight

Material	Aluminium	Black Copper fabric	Copper foil	Silver-plated fabric	Stainless steel	Zinc	Brass	Graphene-copper	Beryllium Copper
Weight /100cm² (g)	0.40	0.79	1.61	1.88	7.77	5.23	7.56	3.49	7.85

Table 4.1

By weighing 100cm² squares of each material with an electronic weighing scale, it was deduced that the lightest materials were Aluminium foil and Black Copper fabric. This makes these materials most ideal in this aspect for making a phone case which is convenient to carry around.

Testing potential materials used for the front face of casing

1. Comparison of SE

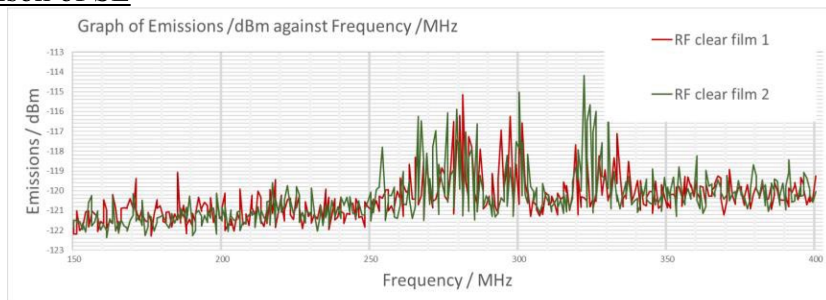

Figure 6.1 Graph of emissions/dBm against frequency/MHz for RF Clear Film 1 and RF Clear Film 2

2. Comparison of Cost and Weight

Film 1 was twice as heavy as Film 2, weighing 2.89g and 1.16g respectively /100cm² of material. However, Film 1 was 5 times cheaper than Film 2, selling at \$0.56 and \$5.30 respectively /100cm² of material.

Testing potential designs used for the casing

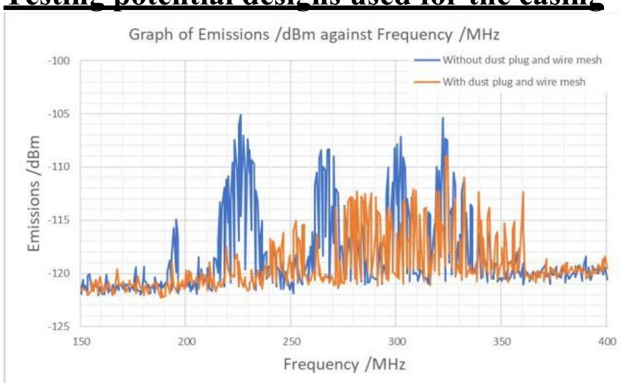

Figure 7.1 Graph for iPhone with and without dust plug and wire mesh

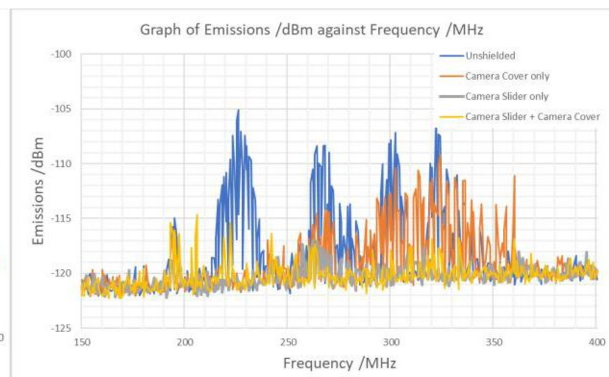

Figure 7.2 Graph for different phone case camera designs

From the results above in **Figure 7.1** and **Figure 7.2**, it can be observed that features like the shielded camera cover, camera slider, dust plug and metal speaker mesh all significantly impact the SE if the phone case, reducing the amount of leaked EM waves.

Overall results

Utilising our final prototype design, the overall EM wave shielding was shown below in **Figure 7.3**. A significant reduction in leaked waves can be observed. With the case on, the phone could still connect to Wi-Fi and Bluetooth connections.

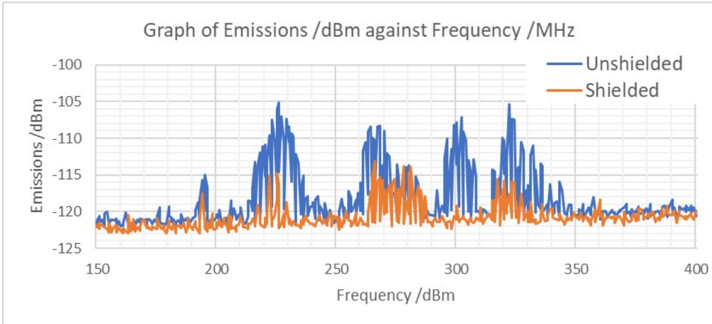

Figure 7.3 Graph of emissions/dBm against frequency/MHz for Unshielded Shielded iPhone

Discussion

Material of Back casing

Based on our results, most materials were able to shield the phone effectively, with the GTEM cell primarily logging the natural environmental noise. Aluminium foil, Copper-polyester-nickel-carbon fabric and Zinc plate could shield the phone best, resulting in relatively low emissions. The Graphene-Copper bimetal sheet demonstrated the poorest shielding performance, resulting in noticeable high spikes.

Although the SE of the different metal plates were comparable to high-performing shielding materials like Aluminium and Copper foil, these materials were not chosen for the final back casing of the phone case due to its high rigidity. This rigidity could lead to the formation of gaps or openings, making the casing more susceptible to EM wave interference.

Numerous materials like Black Copper fabric and Copper foil, performed excellently not only in terms of SE, but cost and weight as well. However, Aluminum foil ultimately was still the most cost-effective and lightweight option among the materials tested, whilst simultaneously possessing a relatively high SE. Meeting all the criteria considered, Aluminum foil is the optimal choice for lining the phone case. Multiple layers of shielding material increases the SE of the phone case, hence this design was adopted in our final phone case prototype.

Material of Front casing

The opaque materials tested for the back casing of the phone case generally performed better than the clear RF films used to cover the screen. This might be because opaque materials like Aluminum and the metal plates are made of more conductive materials, which are better at reflecting and absorbing EM waves emitted by the iPhone, compared to clear RF sheets made from less conductive materials which maintain their transparency, leading to a reduced SE.

From **Figure 6.1**, both clear films could reduce emissions detected by the antenna from the iPhone. Clear RF Film 1 may have a slightly better SE than Film 2, however the difference in emissions detected is almost negligible. In terms of weight, Film 1 performed worse than Film 2. However, Film 2 was more expensive than Film 1. After weighing the pros and cons of each film, Film 1 was deemed more suitable for covering the iPhone screen, as it offered the best balance of effective shielding, cost-efficiency, and is relatively lightweight.

Design of back casing

From **Figure 7.2**, the camera slider and camera cover alone both increased the level of shielding. When both features were combined, they complemented each other well and provided additional assurance in shielding EM waves from leaking through the camera holes. Along with the charger dust plug and speaker mesh, the most optimal shielding design was created.

Inaccuracies during testing

The iPhone 11 Pro Max we used throughout the testing uses a capacitive touch screen. When in use, the Clear RF Film interferes with the electrostatic field, normally provided by the finger, preventing the screen from detecting touch input. Hence, the touch screen is unable to function with the clear RF film covering the screen.

To address this limitation, further research on alternative solutions was conducted. The first solution is to use an iPhone compatible stylus instead of the user's finger to interact with the screen. An attempt on the theory was made with a Samsung S23 Ultra which also utilises a capacitive touch screen. It was found that even with the Clear RF Film applied, the screen remained functional with the model specialised stylus. This leads us to believe that on certain phone models, a stylus could be a solution to allow the screen to function even after applying the clear RF Film.

The second solution proposed is to apply the Clear RF Film on top of the screen in such a way to allow users to remove the film when needed. An experiment was conducted, as shown in **Figure 8.1** below, and it was deduced that the Clear RF Film is effective in reducing the emissions below 300MHz.

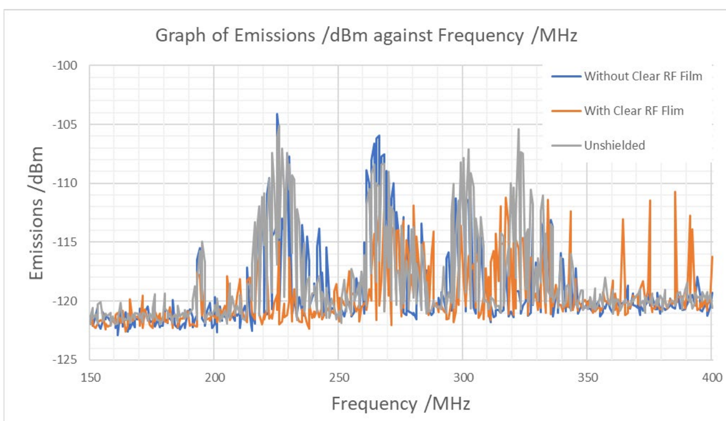

Figure 8.1 Graph of emissions/dBm against frequency/MHz for an iPhone with and without Clear a RF Film

Future research can be done on different phone models with different touch screen mechanisms (Capacitive, Resistive, Infrared Touch Screens etc.) and other types of Clear RF Films which could potentially enable touch input functionality while maintaining effective shielding.

Conclusion

After evaluating all the factors, the optimal design involved coating the phone case with 2 layers of Aluminium foil, in addition to a combination of covering the charging port and speaker holes, along with applying a camera slider over a clear RF film while using the same clear RF Film to cover the phone screen.

Future Works

In the future, it is worth exploring custom-designed phone casings to optimize shielding performance, instead of modifying commercial off-the-shelf (COTS) casings. Although there were attempts to 3D print the phone case during this research process, shown in **Figure 9.1** and **Figure 9.2**, future studies could focus in depth on 3D printing these casings using TPU material coated with Aluminium, or directly printing with a specialized filament if such materials are available.

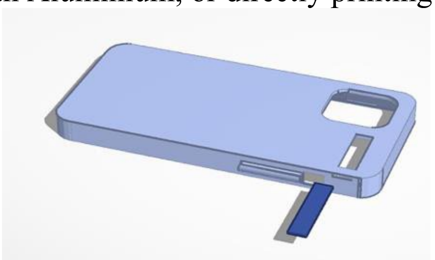

Figure 9.1 First phone case design for 3D printing

Figure 9.2 Second phone case design for 3D printing

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