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Transmission System for Wireless Charging in Three-Dimensional Space

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UNDER MY SUPERVISION BY

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TRANSMISSION SYSTEM FOR WIRELESS CHARGING IN THREE-DIMENSIONAL SPACE

By

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SENIOR DESIGN PROJECT REPORT

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Abstract

Current methods of wireless power transfer (WPT) limit the mobility and usage of a device when it is actively charging. Here, a three-dimensional wireless power transfer technique known as quasistatic cavity resonance (QSCR) is studied in arbitrary geometries and practical scenarios. Physical fabrications and simulations demonstrate the viability of QSCR along with techniques for lowering the resonant frequency to meet safety standards. Two methods of lowering the resonant frequencies are presented, one by changing the physical dimensions and the other by increasing the systems capacitance. It is shown that QSCR is a feasible option to wirelessly transfer power in a three-dimensional space.

Acknowledgements

We would like to thank Dr. Kurt Schab for his guidance and support throughout the duration of this project. His explanations — and several, patient reexplanations — helped us piece together the necessary understanding to carry out our work.

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1 Introduction

This project revolves around an over-the-air charging system meant to allow ubiquitous power transfer throughout a given space, which we refer to here as the "cavity." We will simulate multiple cavity geometries to understand the behavior of each system, which will ultimately allow for engineering design considerations. A power transfer analysis will be discussed along with the safety and ethical considerations of this project.

1.1 Objectives

The main goals of this project are to design, simulate, and verify the use of quasistatic cavity resonance (QSCR) to allow WPT inside of a three-dimensional space. The theory of resonant cavities will be examined in the context of both simple and complex geometries. This idea will then be explored in fabricated systems to verify simulated and analytic results. Furthermore, methods of tuning the resonant frequencies of a cavity to comply with safety regulations will be studied. More specifically, we will analyze the method of increasing cavity volume as well as the method of introducing a loading capacitance. Trends in the resonant frequencies and the Q-factor of each system will be studied under the loading capacitance implementation.

The technique of QSCR will be implemented in simulation using a rectangular cavity in which power is able to be transfer via permeating magnetic fields that are ultimately coupled to a receiver inside of the system. A power transfer analysis will be conducted to inspect trends in the data that can allow for design considerations between the possible power transfer efficiency and the tuning method.

1.2 Background

Current WPT options are limited in the way of mobility when charging devices. Presently, there exist two dimensional wireless charging options which require the user to forfeit his or her device to a charging pad until it is charged. These existing technologies use near-field magnetoquasistatic WPT, which causes the efficiency of power transfer to drop rapidly as the receiving device moves away from the source [3]. This is not ideal when one wants to be mobile with a mobile phone, for instance.

There are two previous methods used for three-dimensional WPT and each poses difficulties. If the source is omnidirectional, meaning that the fields radiate and couple when the device is close in any direction, the efficiency of power transfer decreases rapidly as the device is pulled away from the source. This is the case for charging pads that are on the market now. Another option that has been researched is the use of a unidirectional source. This can be problematic as the radiation source requires a continuous line of sight to the receiving device [4]. A system like this would need an active and more complicated mechanism to successfully track a device inside of a room. This is possible, but not practical for many devices at once.

Since the advent of these previous methods of WPT, there have been advances in three-dimensional WPT technology that allow for higher efficiency without a direct line of sight. We will use these new advancements to avoid the disadvantages of current two dimensional WPT, as well as create a solution for three-dimensional WPT.

1.3 Motivations

There are a few key motivations for this project that we see as a potential benefit to many people around the globe. One particularly important application could be for implanted medical devices. For instance, people who have pacemakers could use this technology as a way to circumvent standard, risky operational procedures. Pacemaker batteries tend to last 5 to 15 years, and require surgery to replace [5]. Instead of needing invasive surgery to replace the battery in their pacemakers, patients could instead simply walk into a doctor's office for a few hours and have the pacemaker recharged via wireless power transfer. This sort of procedure would eliminate the possibility of surgical complications and opens the door for a safer method.

Another application for three-dimensional WPT is in charging of wearable devices. A room that has wireless charging enabled can allow users to not worry about submitting their wearable devices to charging stations. Instead, they can continue to wear them and have them continuously charge. This is especially important for users who may deal with certain cognitive issues such as Alzheimer's disease. In such cases, the procedure of placing wearable devices such as hearing aids at a charging station and then having to remember to pick them up again later may be difficult.

We can also see an application in the manufacturing industry. Specifically, three-dimensional WPT can be used in a factory setting in which there are free roaming robots. Instead of having to pause work for charging purposes, a robot may continue its labor while being charged remotely. This would enable longer working time, thereby boosting factory efficiency.

2 Theory of Resonant Cavities

To achieve WPT inside of a given space, a technique known as quasistatic cavity resonance (QSCR) is studied. Previous literature on three-dimensional WPT [4, 6, 7] outlines a theoretical model for implementing QSCR, which is able to produce enough power to charge a device inside a room. The fabricated designs outlined in [2, 3, 8, 9] were used as the basis of this project and were expanded on to achieve the results outlined in this report. These papers demonstrated that it is possible to create a cavity that is able to wirelessly transfer power to a receiving device.

To conceptualize cavity resonance, we can turn to the analogous phenomenon seen in vibrations on a string. As shown in Fig. 1, there are various resonant modes that can be excited on a string of a given length. These modes are induced due to a set of initial conditions, such as plucking or bowing the string, which causes standing waves to form. In a similar fashion, electromagnetic cavities have a set of resonant modes associated with them. Just like how the length of a string defines what modes are possible, the three dimensions of a cavity are what define the possible resonate modes. There also needs to be a set of initial conditions which excite these modes. A coupling antenna can be used at a specified frequency to initiate a given resonant mode, creating standing waves in the system. The resonant modes we will be looking at can be divided into either transverse electric (TE) or transverse magnetic (TM) modes.

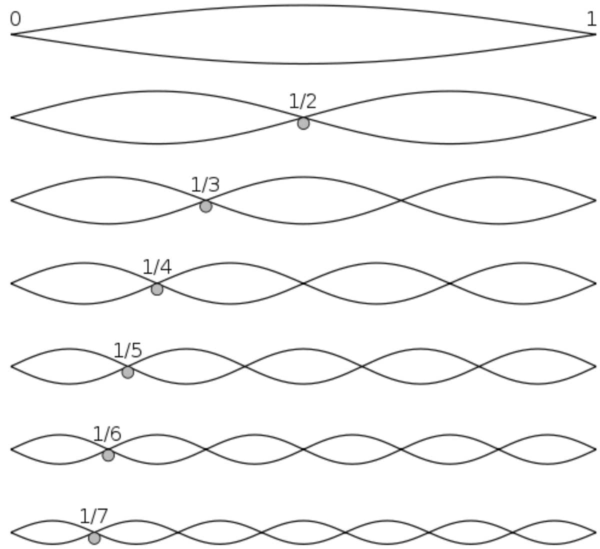


Figure 1: Resonant modes on a string of unit length [1].

2.1 Rectangular Cavity

First, we study a rectangular cavity to understand how QSCR behaves in a simple geometry. This case admits analytic solutions for the resonant frequencies, which can be used to verify simulation work and fabricated designs. From [10], we obtain the resonant frequencies

$$f_{mn\ell} = \frac{c}{2\pi\sqrt{\mu_r\epsilon_r}}\sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 + \left(\frac{\ell\pi}{d}\right)^2}, \tag{1}$$

where a, b, and d are the dimensions of a rectangular prism, m, n, and ℓ define the excited resonant cavity mode, and c, μ_r, and ϵ_r are known physical constants. If we input the prism dimensions and which mode we want to excite, the above equation will give us the corresponding resonant frequency.

If our coupling antenna is driven at a resonant frequency, it will excite either a TE or TM mode, creating standing waves in the system. If the operating frequency is slightly above or below resonance, those waves will no longer be static. The magnetic fields will permeate the interior of the cavity and slowly rotate around the structure. If the operation frequency is low enough, it is considered to be in the "quasistatic" regime. Fig. 2 shows a possible magnetic field distribution inside of a QSCR enabled cavity.

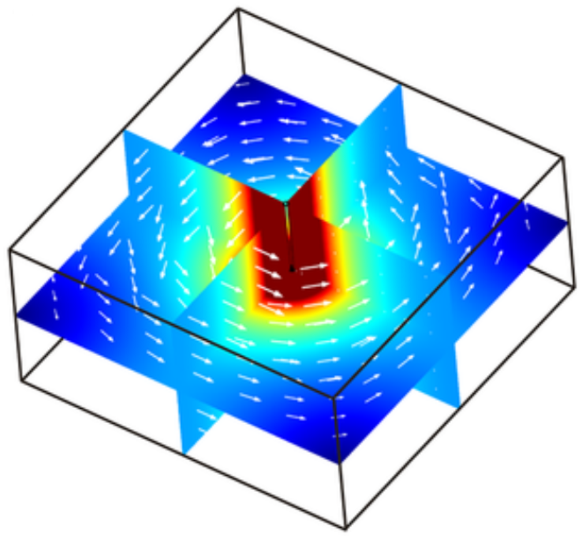


Figure 2: Example magnetic field distribution using QSCR in a rectangular cavity [2].

3 Controlling Resonant Frequencies

Power transfer efficiency is a function of field frequency — it is maximized when the fields in the cavity are oscillating at resonance. Therefore, any QSCR-compatible device would be designed to work at a resonant frequency of the cavity. However, care needs to be taken to ensure that the operation frequency is low enough to avoid damaging biological tissue. For this reason, controlling the resonant frequency is important; there are two methods of doing so. One involves changing the volume of the cavity and the other involves changing the system capacitance. These two methods will be elaborated on in Sections 3.1 and 3.2. To observe where on the frequency spectrum the resonances lie, we collect scattering parameter data. We specifically observed S_{11}, which gives us a measure of how much power from a magnetic field probe is returned to the probe at a given frequency. This probe is inserted at the top of the cavity and both couples and measures the magnetic fields. Mathematically,

S_{11} is defined as [11]

$$S_{11} = \frac{(Z_\mathrm{L}/Z_0) - 1}{(Z_\mathrm{L}/Z_0) + 1}, \tag{2}$$

where Z_L is the impedance of the cavity and Z_0 is the characteristic impedance of the probe. Note that S_{11} is exactly equal to the reflection coefficient Γ. When plotting the absolute value of this parameter in dB scale, the resonances show up as large dips in the trace, as can be seen in Fig. 4. That means our goal of lowering the resonant frequencies translates to shifting the frequencies at which these dips occur to the left.

In the process of changing the resonances of a cavity, we also affect the Q-factor. This parameter obeys the relation

$$Q \propto \frac{\text{energy stored}}{\text{power loss}}. \tag{3}$$

We would like the magnetic energy to stay within the cavity instead of being absorbed by the walls. In other words, we want high stored energy and low power loss, which means we would like the system to have a high Q-factor. This parameter is a function of frequency, and we observe how it varies for different cavities in subsequent sections of this report. Note that the Q-factor data presented should be considered only in terms of its trends rather than the numerical values. This is because the energy stored in the system is a normalized value dictated by HFSS and does not adhere to any given design specifications.

3.1 Volume-based Method

Eq. 1 predicts that one way to lower the resonant frequencies for a rectangular prism cavity is to simply make its dimensions larger. To verify this experimentally, we constructed two rectangular prism cavities of differing sizes and measured the scattering parameter S_{11} for both. These cavities were cardboard boxes wrapped in aluminum foil, with an incision made at the top of each to insert a magnetic probe. Our fabrication is shown in Fig. 3.

Fig. 4 shows our data, as measured by the probe. We found the five lowest resonances

(a) Small rectangular prism cavity (19.6 cm x 35.5 cm x 32.6 cm).

(b) Large rectangular prism cavity (45.7 cm x 45.7 cm x 61.0 cm).

Figure 3: (a) and (b) depict the physical builds of the rectangular prism cavities. The large cavity is approximately 5.6 times larger by volume than the small cavity.

for the small cavity and the six lowest resonances for the large cavity. We observed that even the lowest measured resonance for the small cavity occurs at a higher frequency than the highest measured resonance for the large cavity. Therefore, the empirical data confirmed our hypothesis based on Eq. 1 — a larger rectangular prism will lead to lower resonant frequencies. There is a slight discrepancy between the measured resonant frequencies and the analytic predictions due to the non-idealities present in the cavity construction. Eq. 1 assumes a rectangular prism made of a perfect electric conductor, meaning it is lossless. In the physical experiment, we introduce the probe into the cavity which causes a disruption to the idealized fields, and additionally, aluminum foil is a lossy material.

3.2 Capacitance-based Method

Although the volume-based method offers a way to lower the resonant frequencies of a cavity, it is impractical as it requires expanding a physical space. We wish to use a method that is able to work with existing structures (e.g., car chassis, airplane cabins, office spaces, warehouses). This can be done via an alternative method which involves placing a loading capacitor within the cavity. By raising the system capacitance, we can lower the resonant frequencies of the structure [2]. We implemented this idea in simulation by inserting a pillar-

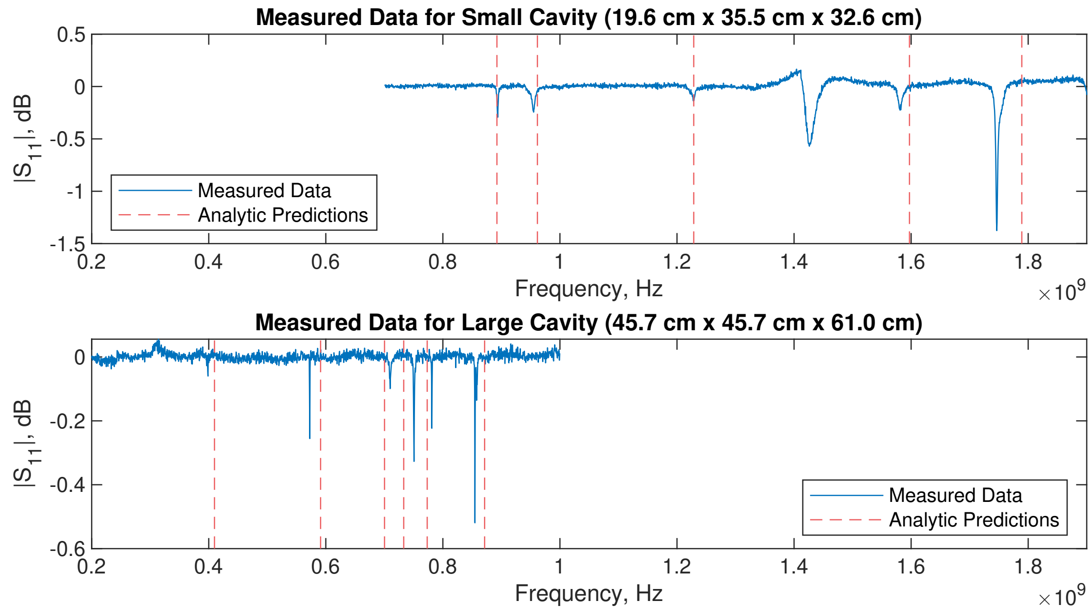


Figure 4: (Top) Measured S_{11} data for the small rectangular prism. The dip at just above 1.4 GHz is due to the self resonance of the probe, which is why it does not line up with a predicted resonance according to Eq. 1. (Bottom) Measured S_{11} data for the large rectangular prism.

like structure composed of two copper cylinders with a gap in between to make space for the capacitor, as seen in Fig. 5. We can examine the field distribution at various capacitance values to understand how they change with respect to system capacitance. Fig. 6 depicts the magnetic field distribution in the cavity when the variable capacitor was set to 0.2 nF. It is seen that the fields produced permeate the cavity with a relatively constant pattern. This result supports what was reported in the relevant literature.

In order to understand the behavior of the resonant modes, the loading capacitance was swept from 0.01 nF to 1 nF. Fig. 7 shows the resulting trends of the four lowest order modes. As expected, increasing the capacitance produces lower resonant frequencies. Since we want to operate at the lowest possible resonant frequency, we only consider the lowest order mode for the remainder of this report. We also studied how the Q-factor was affected as a result of sweeping the loading capacitance. As seen in Fig. 8, the Q-factor also decreases monotonically as a function of capacitance. In the present work, we study the effect of increasing system capacitance for cavity geometries that do not admit analytic solutions for

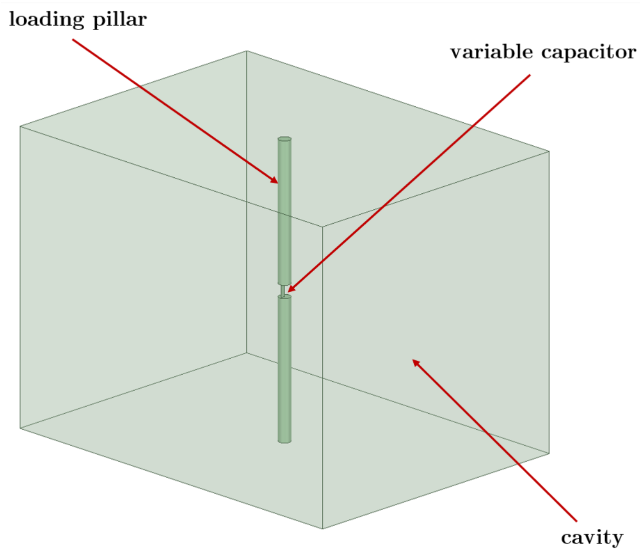
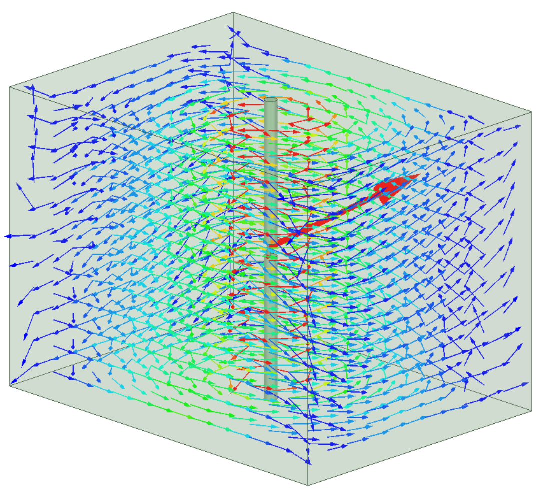
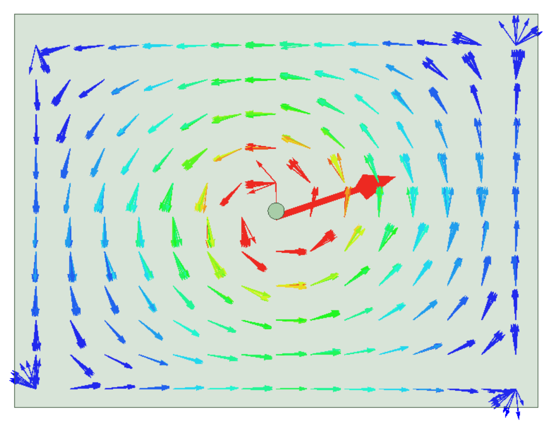


Figure 5: A loading pillar inserted in a rectangular prism cavity (45.7 cm x 45.7 cm x 61.0 cm). A loading capacitor is placed in a gap between two solid copper cylinders.

their resonances and Q-factors. We find that in those cases, we are still able to lower the resonant frequencies using this method, albeit at the cost of a lower Q-factor.



(a)



(b)

Figure 6: Rectangular prism cavity magnetic field distribution where (a) shows the dimetric view and (b) shows the top down view.

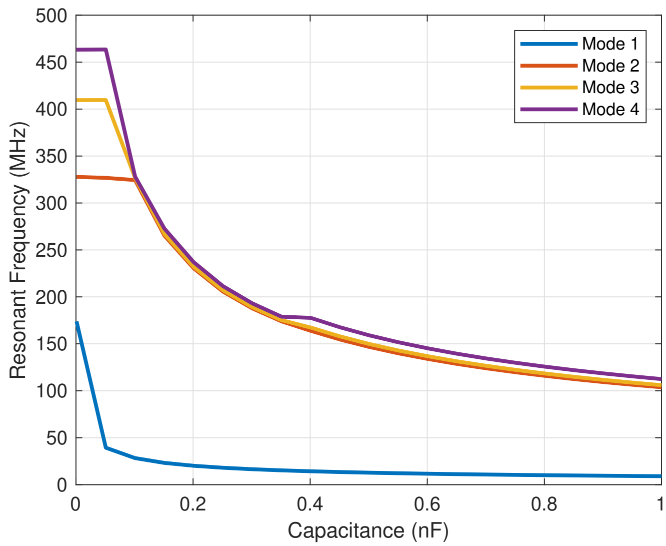


Figure 7: Four lowest order resonant modes of a rectangular prism cavity (45.7 cm x 45.7 cm x 61.0 cm) as a function of capacitance.

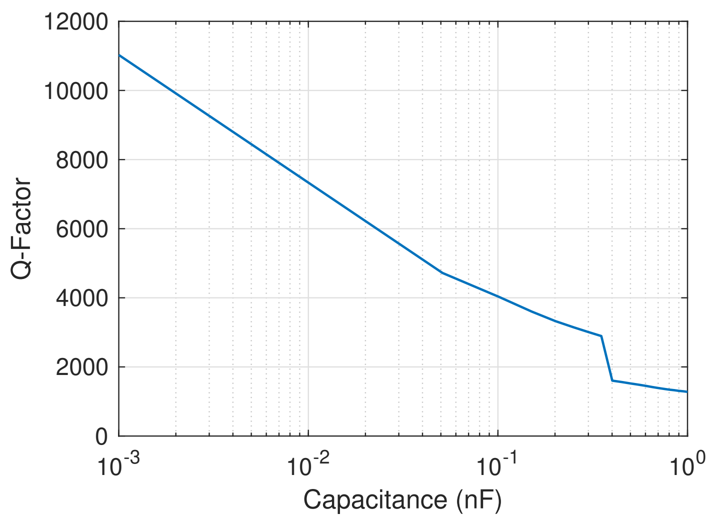


Figure 8: Q-factor of a rectangular prism cavity as a function of capacitance.

4 Power Transfer Analysis

To study how power can be delivered with a QSCR system, a power transfer analysis was carried out. This analysis was performed in HFSS for a rectangular cavity of dimensions 45.7 cm x 45.7 cm x 61.0 cm, the same as the large cavity that was constructed and tested in

Section 3.1. Much like the analysis of the Q-factor, all of the data presented in this section are normalized and do not show information about how much power is being delivered, but rather the trends that the system exhibits. This is important because it shows that power can be delivered to a load. Numerical outputs can be acknowledged if further work incorporated a matching network.

4.1 Methodology

To analyze the potential power delivery in this system, we constructed a probe that would couple the intended eigenmode and a receiver that would capture the available energy. This probe is a loop of wire, as shown in Fig. 9. It is driven at a given frequency and oriented to couple a chosen eigenmode. The receiver is constructed identically and aligned with the magnetic fields to receive maximal energy.

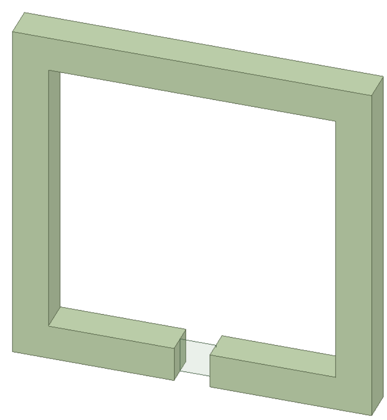


Figure 9: HFSS probe design to allow for eigenmode coupling. The receiver is designed identically.

The probe, which resides inside of the cavity, acts as a small magnetic source current, which then excites an eigenmode. This magnetic current is fictitious and does not exist within the system, but can be thought of as an analog to an electric current. This is used to study the magnetic fields produced in the cavity. Using the same analogy from Section 2 of resonant modes on a string, the cavity can be thought of as the string within which, at any moment in time, all possible eigenmodes can theoretically be excited. The probe, or the small magnetic source current, can be thought of as what is plucking the string in the correct location with the correct frequency to cause it to resonate.

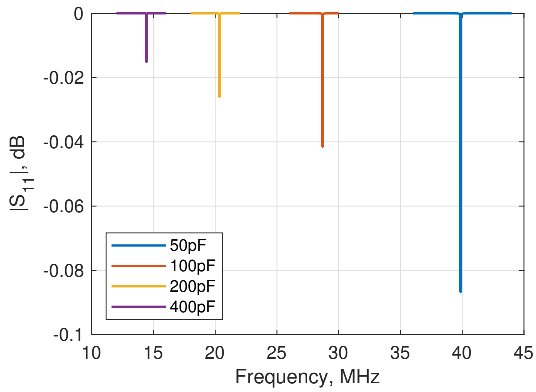
The frequency at which the probe is driven is determined by what operating frequency is needed, and thus by the capacitance needed to achieve that frequency. The location, on the other hand, can be determined by examining the following expression for the total magnetic field

$$\vec{H} = \sum_i \alpha_i \vec{H}_i \langle \vec{H}_i, \vec{M}_s \rangle, \tag{4}$$

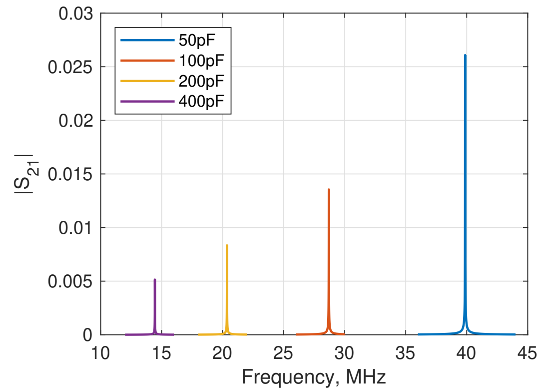
where α is a weighting coefficient for a given eigenmode, $\vec{H}_i$ is the magnetic field associated with the ith eigenmode, and $\vec{M}_s$ is the small magnetic source current, or the probe, that will be placed. This expression should be maximized in order to achieve the best possible coupling. Precise placement of the probe can achieve a maximum value indicated by the inner product of $\vec{H}_i$ and $\vec{M}_s$. If the probe is aligned with the magnetic field, this will maximize the inner product which in turn leads to the best possible coupling. This informs the decision as to where the best placement of the probe is; that is when the magnetic flux is maximized through the loop. The same is true of the receiver placement.

4.2 Simulated Results and Expected Outcomes

The probe and receiver shown in Fig. 9 were oriented such that a normal vector of the loop is parallel with the intended magnetic field that will be excited. With these two devices set in optimal locations, the power transfer from the created fields was examined by studying the scattering parameters of the probe and receiver. In particular, we observed S_{11} to analyze how much incident power was reflected back into the probe. We also examined the scattering parameter S_{21} to study at which frequencies power may be delivered to the receiver, if any. This is similar to S_{11} except that this scattering parameter measures the power that is transferred from the probe to the receiver instead of the power reflected back into the probe. We wanted to see how these scattering parameters varied with respect to system capacitance. The results of this experiment are shown in Fig. 10.



(a) Dips in the S_{11} data suggest that the power incident to the probe is leaving and not reflected back into the system at those frequencies. This indicates that power is able to be received within the system.



(b) Spikes in the S_{21} data suggest power is being received from the resonating magnetic fields inside of the cavity.

Figure 10: Power transfer analysis inside of a rectangular prism cavity (45.7 cm x 45.7 cm x 61.0 cm). Scattering parameters S_{11} and S_{21} are presented to study the reflection at the probe and the transmission to the receiver for various capacitance values.

These data show that power transfer is possible at the given design frequencies. They indicate the behavior of how varying the capacitance can affect the ability of the receiver to absorb power and the ability of the probe to couple the cavity. This is similar to the Q-factor trends studied in Section 3.2 for the same cavity dimensions. As the is capacitance increased, each resonant frequency is decreased, but so is the Q-factor. This is similar to the trends of the power transfer analysis; as the capacitance is increased, the amount of power transfer is decreased, as indicated by the fact that the nulls become shallower.

The quantitative outputs for this analysis show a very poor efficiency for the receiver. This is due to the fact that there is no matching network between the probe and the cavity. The design and implementation is left to future work on this project, but if a matching network were to be implemented, efficiencies up to 80% can be accomplished [8]. If we assume that a typical smartphone needs 2-6 W of power to charge, and the receiver is oriented such that the efficiency of the system drops to 20%, then the maximum input power needed for the system in the worst case is 30 W.

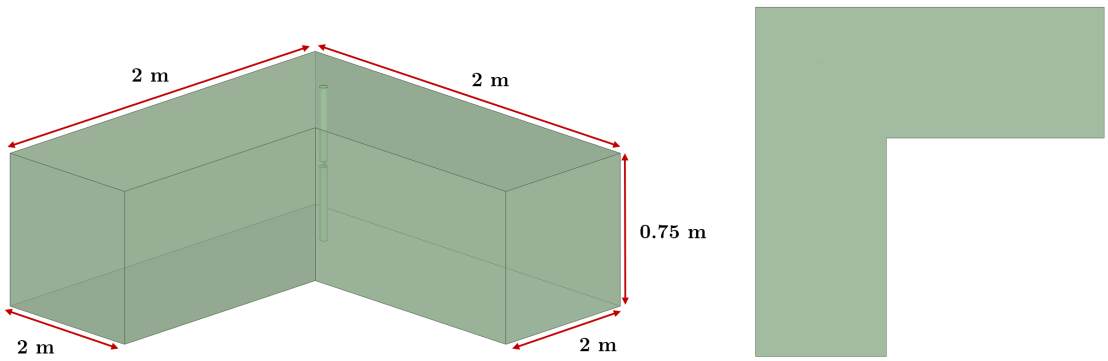
5 Arbitrary Geometries

The rectangular cavities studied in Sections 2.1 and 3 admit analytic solutions that can be used to compare against simulated and experimental data. However, many of the places where a QSCR system would be useful to implement are typically not perfect rectangular prisms. Extending the ideas in Section 3 to arbitrary shaped geometries is the natural step to move toward a practical implementation. This section will look at two cavity types; an L-shape and a studio apartment. These complex geometries lead to non-idealities that allow for the study of how the field distributions, resonant frequencies, and the Q-factor vary.

5.1 L-Shaped Cavity

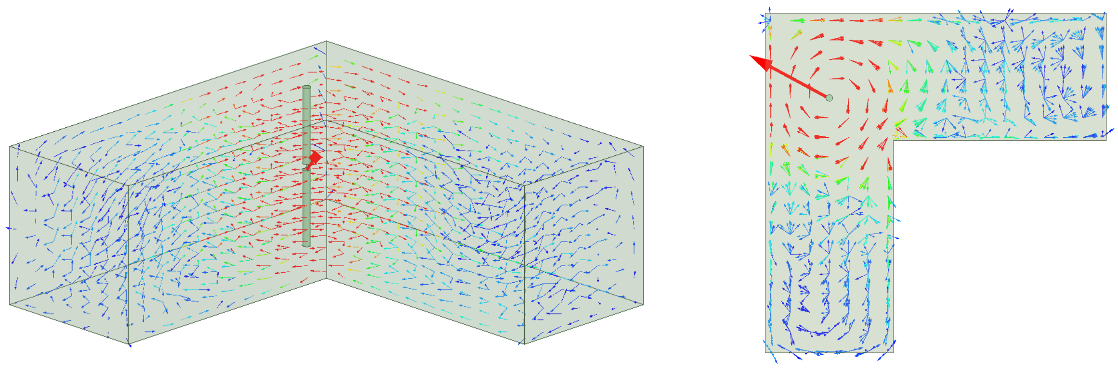
The first arbitrary geometry that we studied was the L-shaped cavity, as shown in Fig. 11. Due to the 90 degree bend, it is not immediately obvious how this cavity will behave when a QSCR system is implemented as this geometry does not have any analytic solutions for its resonances and Q-factor. First, we execute an eigenmode solver in HFSS to observe at what frequency the lowest resonant mode is excited. This gives us a sense of how much the frequency needs to be lowered to meet safety standards. This also allows for a visualization of the field distribution of the lowest resonant mode inside of the cavity as shown in Fig. 12. An explanation of where the probe and receiver should be placed for the highest efficiency is found in Section 4.

Much like the analysis of the rectangular prism in Section 3, the trends of the resonant frequency and Q-factor can be examined as a function of the loading capacitance. To understand how the placement of the loading pillar affects these parameters, two locations were studied. The effect of placing the pillar at the intersection of the two arms and at one end of the cavity is shown in Fig. 13. From these data, there appears to be a minimal effect on the resonance due to the different pole placements. However, when the pole is placed



(a) (b)

Figure 11: (a) Dimetric and (b) top view of the L-shaped cavity.

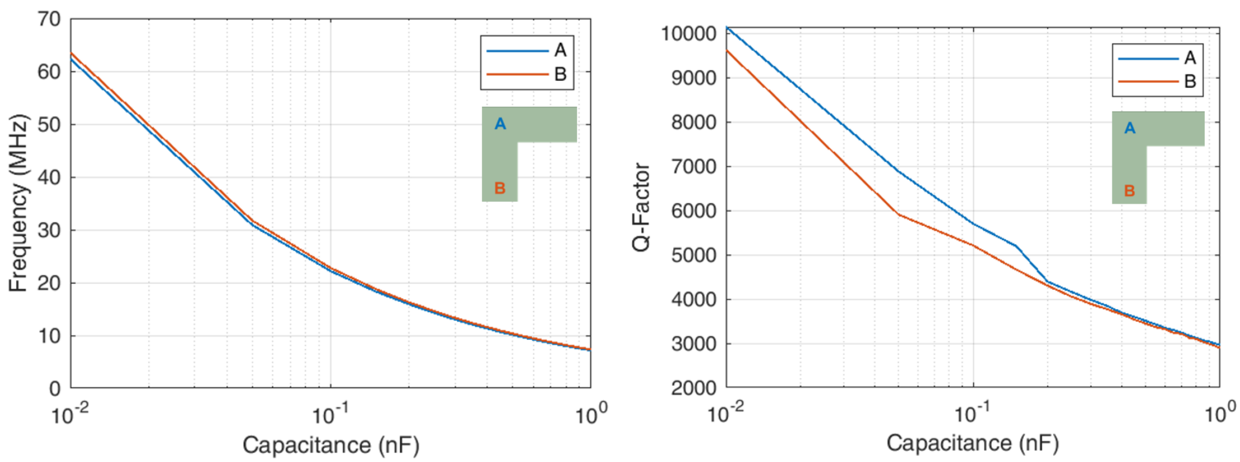


(a) (b)

Figure 12: (a) Dimetric and (b) top down view of the field distribution for the lowest order resonant mode inside of the L-shaped cavity.

at location A, the central location, the Q-factor seems to be higher. Again, these data are normalized and only allow for the examination of trends, rather than a quantitative output. These trends allow design choices to be made based on the studied cavity.

To solve the problem of the pole being placed in an obtrusive location, the pillar can be moved closer to a wall. We hypothesized that when this is done, there would be a greater deviation in the resonant frequencies and Q-factor due to increased interaction between the pillar and the cavity wall. When these experiments were run, the simulations did not converge so we were unable to confirm or reject this hypothesis. This has been left as future work, along with alternatives to the capacitive pillar.



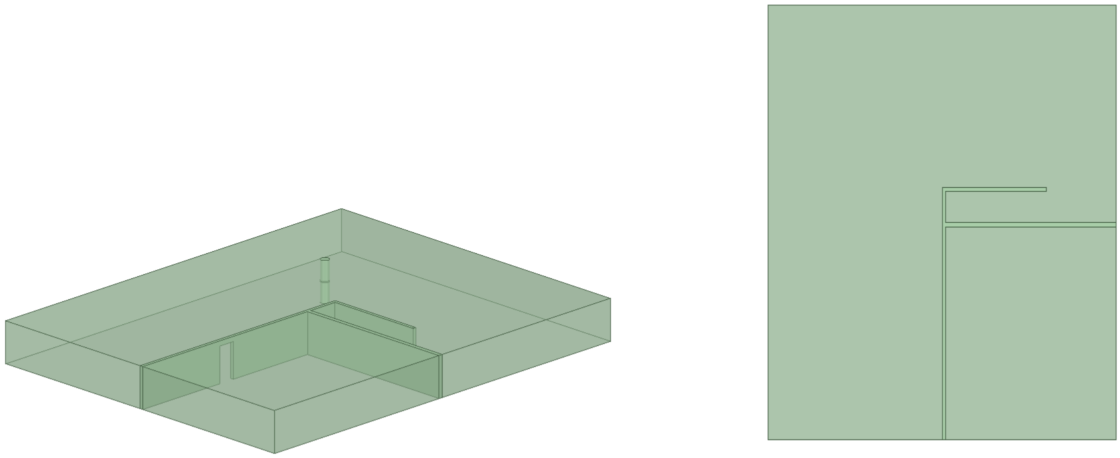
(a)

(b)

Figure 13: (a) Resonant frequency and (b) Q-factor as functions of capacitance for two pillar locations in the L-shaped cavity.

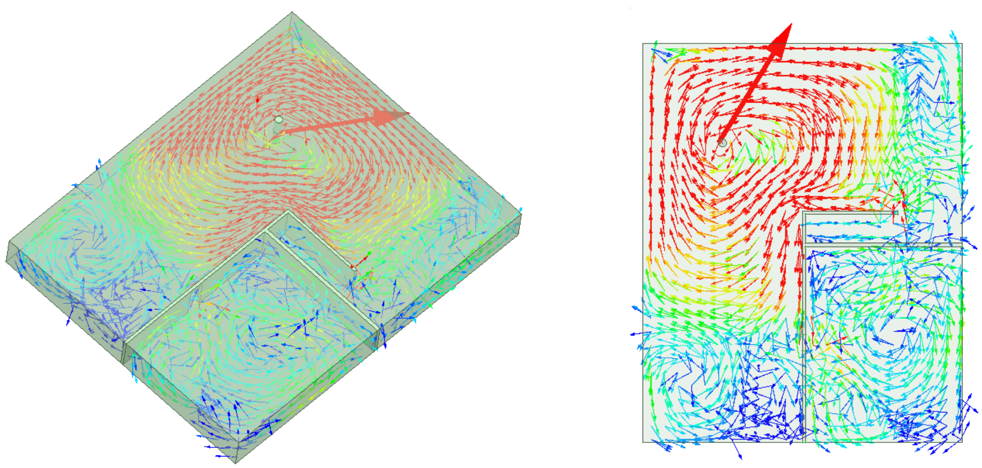
5.2 Studio Apartment Cavity

To study a cavity that only admits numerical solutions and represents a practical setting, we modeled a studio apartment, which is essentially the composition of an L-shaped cavity and two rectangular prism cavities, as shown in Fig. 14. In Fig. 15, we can see that the field distributions resemble those of the rectangular prism and L-shaped cavity as in Sections 3.2 and 5.1, but there is coupling between the different segments of the apartment due to the open doorways. We repeated the pillar location experiment done in 5.1. Fig. 16 shows that once again, moving the pillar had minimal effect on the resonant frequency. However, there is still a discrepancy between the two locations with respect to Q-factor. It should be noted that for this simulational experiment, we swept the capacitance from 0.1 nF to 1 nF instead of 0.01 nF to 1 nF. This is because HFSS was experiencing problems with convergence. This may be due to entries in the impedance matrix of the pillar blowing up for lower capacitance values.



(a) (b)

Figure 14: (a) Dimetric view and (b) top view of the studio apartment cavity (25 m x 20 m x 2.4 m).

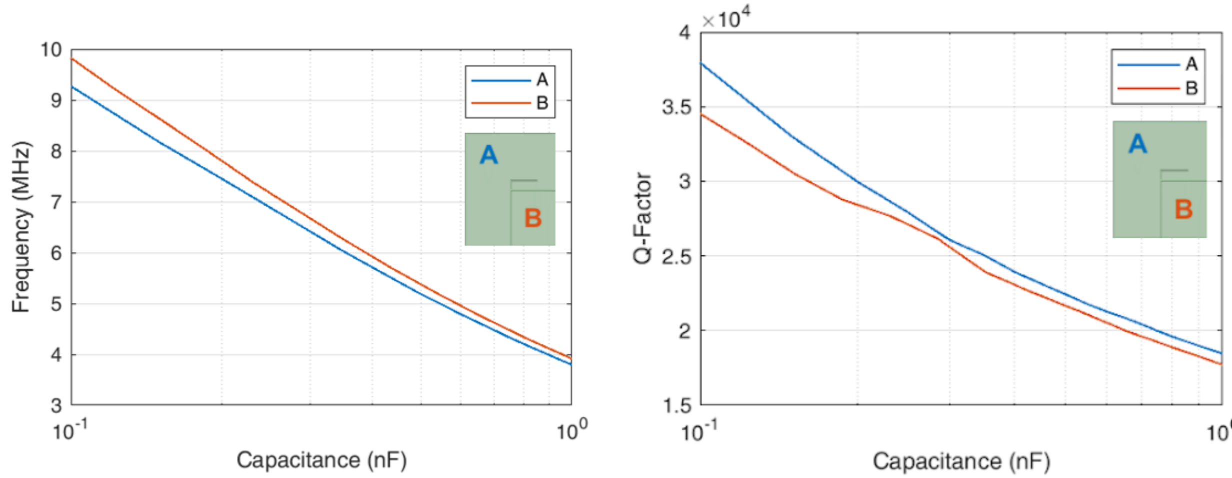


(a) (b)

Figure 15: Studio apartment cavity magnetic field distribution where (a) shows the dimetric view and (b) shows the top down view.

6 Safety Analysis

A quantitative safety analysis, much like the power analysis, was beyond the scope of this project. This analysis requires much more subtle and complex designs than the ones presented here. In the literature, however, it has been shown that these systems, when tuned to the correct frequency, are safe for human use [2,6]. This verification can be accomplished



(a)

(b)

Figure 16: (a) Resonant frequency and (b) Q-factor as functions of capacitance for two pillar locations in the studio apartment cavity.

by conducting a specific absorption rate (SAR) analysis, which measures the rate at which energy from a radio frequency (RF) electromagnetic field is absorbed by human tissue. It is commonly done when studying the biological effects of mobile phones and magnetic resonance imaging (MRI). Companies developing new RF technologies must comply with safety standards set by the Federal Communications Commission (FCC). As an example, the upper bound for a safe SAR for mobile telephones is determined to be 1.6 W/kg [12]. [2] has shown that it is possible to maintain a SAR below the rated FCC standard for various efficiencies and input powers in a QSCR cavity. Specifically, it is possible to safely transmit input powers up to 1.9 kW with efficiencies near 90%, which is equivalent to charging up to 320 standard USB powered devices.

The main method to achieve these safety standards is to lower the resonant frequency of the system. This can be understood by knowing that, in general, the lower the frequency of an RF signal, the less interaction it has with biological tissue. Higher frequencies lead to greater losses, or heat generation, in a material. In biological tissue, these losses are harmful and should be mitigated. In a microwave oven, energy is put into the system and lingers until it is absorbed by what is placed inside. A crucial difference between a microwave oven and a QSCR enabled cavity is that the former operates at 2.45 GHz, whereas the latter operates near 1 MHz. This lower operating frequency leads to significantly less interaction with biological tissue. A system such as a WiFi router, which is also regulated by the FCC, is able to operate at 2.4 GHz and 5 GHz because it does not allow energy to linger in a given space. It can be approximated by an isotropic radiator, which means that the signal radiates uniformly in all directions and the power decays rapidly as a function of distance. A person standing a few meters from the source will only experience a tiny fraction of the total power the system is outputting. This is the fundamental difference between resonance and radiating systems.

7 Professional Issues and Constraints

Due to the electromagnetic energy being coupled in the cavity, ethical considerations are especially pertinent for this project. We want to acknowledge that a QSCR enabled system should maintain safety for anyone inside of the cavity. Without careful consideration of the design parameters, it is possible to create a transmitting subsystem that will produce a power density high enough to cause harm to humans. We hope that such a product would provide convenience to the end user, but this objective needs to be accomplished in a meticulous way that does not compromise human health.

Furthermore, beyond taking safety concerns into account, we believe the intention behind our project is ethically justified. Our goal was to study QSCR in the hopes that eventually this technique may be applied to provide convenience. We envision that QSCR will enable people to get more use out of their portable electronic devices. Additionally, as mentioned earlier, this convenience may even provide a way to circumvent a potentially risky surgery or forgetfulness, as in the case of a patient with Alzheimer's using hearing aids.

As for a different context, a QSCR implementation may supplement the growing trend of automation in factory settings. Free roaming robots with QSCR compatibility would not have to stop for charging purposes. Therefore, this technique would allow manufacturers to produce more rapidly. This can help meet the demands of a growing world population which.

This is especially pertinent given the current circumstances regarding the coronavirus pandemic. A QSCR compatible facility could potentially work around the clock to manufacture face masks and ventilators that are desperately needed around the world.

Despite the aforementioned benefits, we recognize that there are also potential ethical pitfalls in promoting this technology, even if it is implemented as intended with a safe operating frequency. Internet addiction is already a problem and QSCR may feed into it by enabling users to use their devices for longer. Also, some factories produce harmful byproducts and QSCR may exacerbate this issue by allowing them to output at a higher rate. Another concern is that as we envision it currently, most of the energy output in the cavity is not received for charging purposes, which is a waste of resources.

8 Future Work

There are a number of avenues through which this project may be explored further. For instance, note that only a small number of the endless possible geometries were analyzed in this project. Furthermore, an extensive safety analysis of these exact geometries was carried out in this project and has been left for future work. Alternative designs to lower the resonant frequency and the optimization of the resonate frequency and the Q-factor can also be studied. Lastly, fabrication of these cavities, along with a compatible receiver, can be manufactured to fully test this method of wireless power transfer.

8.1 Optimization

As was seen in Sections 3.2 and 5, there is a trade-off between achieving a specified resonant frequency and a high Q-factor, with slight variation due to placement of the loading pillar. The idea of optimizing these parameters to achieve the best possible combination has been left to future work. From what we have researched, there has been no work done in the optimization of these parameters. Given the complexity of the designs presented, this idea is a natural extension to further the engineering design considerations if this system were to be implemented. It would be interesting to know if the placement of the pillar in an arbitrary geometry can have a drastic effect on the reliability of wireless power transfer.

8.2 Extended Geometries

The geometries studied in this project were stepping stones toward more complex cavities that exhibit further complications. The geometries presented here are still limited and do not take into full consideration how practical spaces may be laid out. We can envision future work exploring how a leaky cavity, or a room with a hole or a window, will affect the power efficiency or the behavior of the field distribution. Other extensions of the work done here may be studies involving cavities with multiple layers (e.g. two story houses) or curved boundaries.

8.3 Fabrication

The original intention of this project was to fabricate a design and fit it with the loading pillar to demonstrate wireless power transfer. Due to the COVID-19 outbreak, the scope of this project was limited to simulation work in HFSS. We did, however, fabricate two cavities to show the fundamental concept that increasing the volume of a rectangular prism will decrease its resonant frequencies, but the next step of fitting the capacitive pole has been left to future work. To extend beyond a rectangular cavity, any of these geometries can be fabricated to determine the reliability of wireless power transfer using this method.

To successfully fabricate these cavities, a matching network must also be designed to match the impedance of the cavity to the impedance of the probe. This will allow for a complete power transfer analysis and in turn, a complete study of the safety considerations. This will also lend itself to studying the efficiency at multiple locations, and ultimately how many devices can be charged with a given input power.

8.4 Alternative Designs

As it stands, the placement of the capacitive pillar can be obtrusive when inserted in a room. Other designs implementations can be explored to lower the resonant frequency. A pole-independent method as seen in [7] provides an alternative. This method involves placing discrete capacitors in the corners of the rooms where the wall meets, rather than between a conductive pole in the center of the cavity. Further research and implementation of designing this type of QSCR system has been left to future work.

9 Conclusions

Methods to control the resonant frequencies of an electromagnetic cavity were studied. We experimentally verified that increasing the volume of a rectangular prism cavity resulted in lower resonant frequencies. Furthermore, in simulation, we found that raising system capacitance was also able to decrease the resonances for arbitrary geometries. A power transfer analysis performed for the rectangular prism cavity suggests that it may be possible to charge a device at a resonant frequency. To conclusively determine if power transfer is possible, further work should aim to include a matching network to study the efficiencies of these systems and how that affects wireless charging compatible devices. Also, a SAR analysis needs to be performed to ensure safety standards are met.

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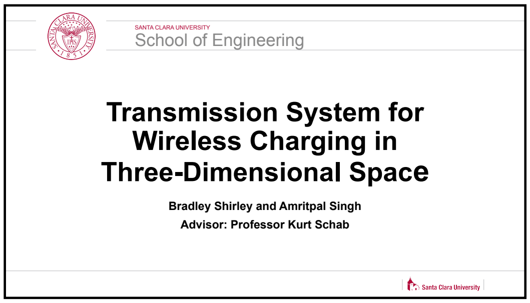
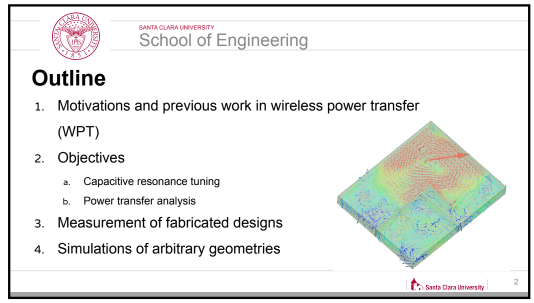
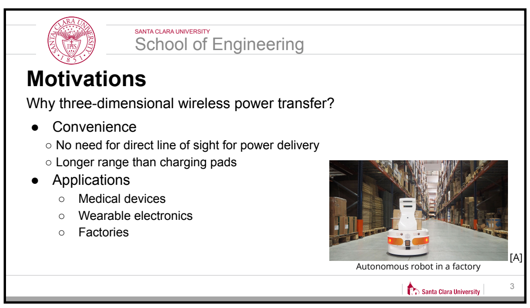
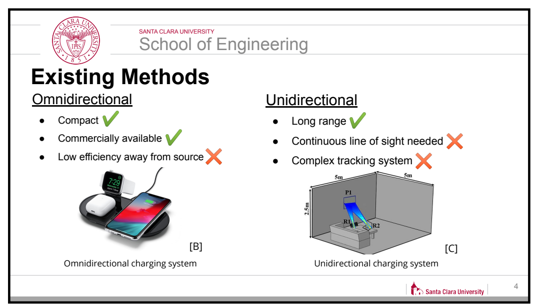
Appendices

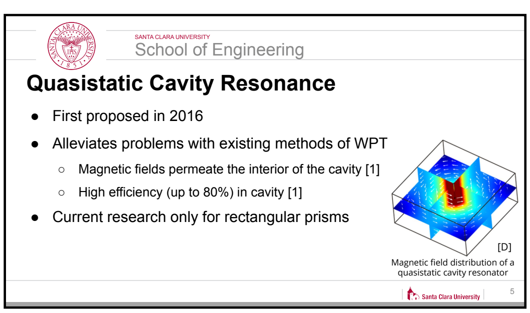
Appendix A: Senior Design Conference Slides as Presented

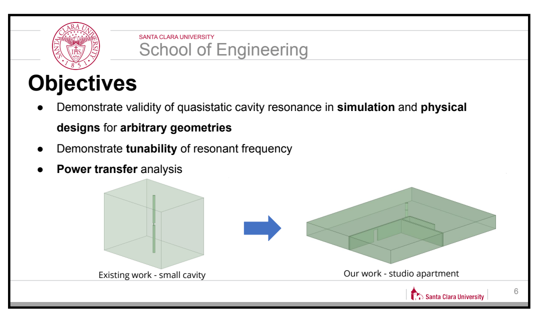










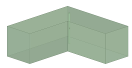


Design Process

- **Rectangular prisms**
  - Admit **analytic solutions**
  - Goal: corroborate analytic, experimental, and simulational resonant frequencies

$$f_{mn\ell} = \frac{c}{2\pi\sqrt{\mu_r \epsilon_r}}\sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 + \left(\frac{\ell\pi}{d}\right)^2}$$

- **Arbitrary geometry**
  - Non-analytic solutions
  - Can be studied via **simulation** and **experimentation**
  - Goal: study resonant frequencies and Q-factors

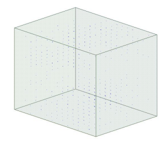


L-shaped geometry

Rectangular Prism Cavity

- **High-Frequency Structure Simulator (HFSS) simulations**
  - Intuition on the field distribution
  - Verification of simulation parameters
- **Research**
  - Compare with results from previous work [1]
  - Find eigenmode solutions for a given cavity

$$H_z = A_z \cos\left(\frac{m\pi x}{a}\right)\cos\left(\frac{n\pi y}{b}\right)\sin\left(\frac{p\pi z}{c}\right)$$



One eigenmode solution for a rectangular prism

Physical Experiment

Cavity A: 19.6 cm x 35.5 cm x 32.6 cm

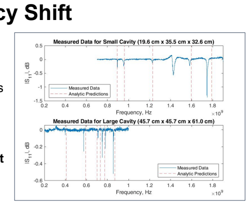
Cavity B: 45.7 cm x 45.7 cm x 61.0 cm

$$V_{\mathrm{a}} \approx 5.6 V_{\mathrm{B}}$$

Volume-based Frequency Shift

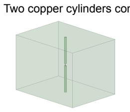
Do measured data agree with the analytic hypothesis?

- Measure S_{11} to find resonant frequencies
  - Examine **dips** in **blue traces** to see if they **line up** with analytic **red traces**
- **Larger volume** leads to **lower resonant frequency** for each mode

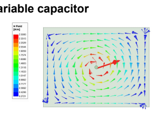


Rectangular Prism Cavity

- Increasing physical size may not be a viable option
- **Central pillar** houses loading capacitance
  - Two copper cylinders connected by a **variable capacitor**



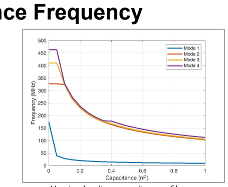
Rectangular cavity with loading capacitance (45.7 cm x 45.7 cm x 61.0 cm)



Top down view of magnetic field distribution

Controlling the Resonance Frequency

- A **loading capacitance** can **tune** the resonance frequencies
  - More feasible method to reach design frequency than changing cavity dimensions

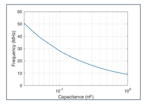


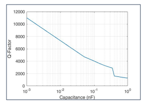
Varying loading capacitance of large cavity (45.7 cm x 45.7 cm x 61.0 cm)

Resonant Frequency and Q-factor

$$\text{Q-factor} \sim \frac{\text{energy stored}}{\text{power loss}}$$

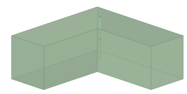
- Lowest order mode has the lowest resonant frequency
- **Trade-off** between Q-factor and desired frequency

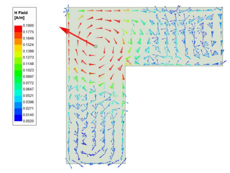




L-shaped Cavity

- Concave object
  - No analytic solutions
  - Field distribution is more complex



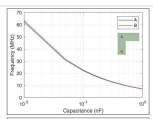


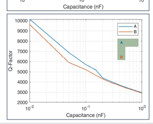
Field distribution in L-shaped cavity

L-shape Cavity Experiment

Does it matter where the pillar is?

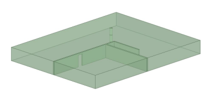
- These data suggest that pillar location has **minimal effect** on resonance and Q-factor
  - Edge case of the pillar being close to the wall may cause deviation

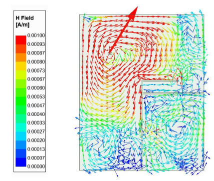




Studio Apartment Cavity

- **Practical scenario**
  - Cavity with multiple, divided rooms
  - Larger scale (25 m x 20 m x 2.4 m)



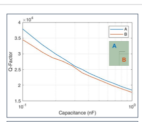


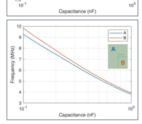
Field distribution in studio apartment

Studio Apartment Pillar Location

Does it matter where the pillar is?

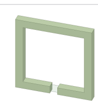
- Again, pillar location has **minimal effect** on resonant frequency
- Further complexities increase variation in Q-factor for lower capacitances
  - Nested cavities and sharp turns





Power Transfer

How can we create these fields?



HFSS model of probe

- Eigenmodes must first be excited
  - Probe will provide excitation
- Probe location will determine what eigenmodes are excited

$$\bar{H} = \sum_i \alpha_i \bar{H}_i \langle \bar{H}_i, \bar{M}_s \rangle$$

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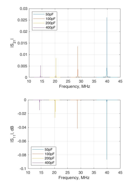
Power Transfer Analysis for Rectangular Prism

- S_{21} - Indication of how much **power** can be **delivered** to load
  - Want this be a **large positive number** at operating frequency
- S_{11} - Indication of **loss** in system
  - Want this to be a **large negative number** at operating frequency



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Power Transfer Hypothesis

- Analysis was done without a matching network
  - Causes poor power transfer
- Maximum possible efficiency of 80% [1]
- Maximum input power required to charge a single device is 30 W

Case	Efficiency (%)	Power needed (W)	Input Power (W)
1	80	2	2.5
2	80	6	7.5
3	20	2	10
4	20	6	30

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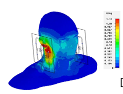
Specific Absorption Rate (SAR) Analysis

- SAR is a method to determine if an electromagnetic system is safe for human use
- The Federal Communications Commission mandates an **upper bound** of **1.6 W/kg**
- Involves simulating human tissue (phantom) inside the cavity



[E]

An example of a SAR analysis conducted on a human head phantom in the context of cell phone use.

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Future Work

- **SAR** analysis
- Find **optimal balance** between Q-factor and resonant frequency
- Study further functional non-idealities
  - Adding multiple windows
  - Construct more complex geometries (e.g. two story house)
- **Fabricate** described models
  - Implement in a room with compatible devices
- **Alternative implementation** of loading capacitance

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Summary

- **Physical designs** corroborate analytic predictions
- **Capacitive loading** is a viable technique for tuning the operation frequency in arbitrary geometries
- **Power transfer analysis** indicates transmission is possible at resonances

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Questions?

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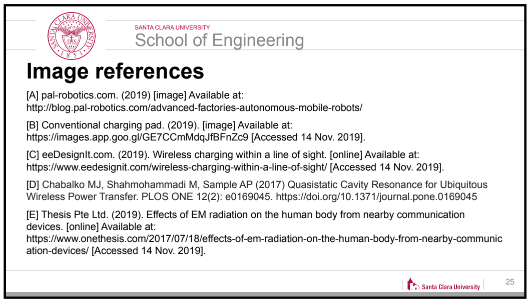
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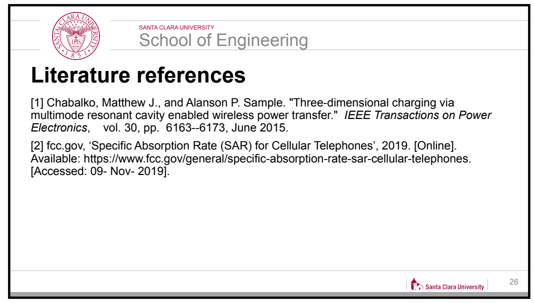
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Appendix B: Information on Equipment and Software used

The S_{11} and S_{21} data was collected using the N9923A FieldFox Handheld RF Vector Network Analyzer. More information may be found at:

https://www.keysight.com/en/pdx-x201782-pn-N9923A/fieldfox-handheld-rf-vector-network-analyzer-4-ghz-and-6-ghz?&cc=US&lc=eng

The magnetic field was coupled and measured by the TBPS01 EMC near field probe. More information may be found at:

https://www.tekbox.com/product/tekbox-tbps01-emc-near-field-probes/

All simulational work was carried out using High Frequency Structure Simulator (HFSS). More information may be found at:

https://www.ansys.com/products/electronics/ansys-hfss