MIMO ANTENNA FOR 5G LAPTOPS

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Master's Thesis

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ABSTRACT

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The advancement of computers has become apparent in their abilities to perform intricate and complicated applications as well as their integration within modern life. The evolution of computer technology should be matched by evolution of data transfer, a key component that is responsible for the growth of technology in everyday life. As such, portable devices have become a necessity, and while the majority of these types of devices are mobile phones, laptops make up a formidable margin, as they are more powerful and capable of performing more advanced operations. It is therefore important to integrate state-of-the-art telecommunication technology inside laptops so that they are able to transfer and receive data at a high rate.

In this thesis, a 5G MIMO microstrip antenna is presented. The antenna's design is meant to fit inside a modern laptop and operate at frequencies above 3 GHz. The antenna's novelty is presented in it being circularly polarized through using a unique design. The antenna's circular polarization would be analyzed by studying its axial ratio. This is through studies of previous researches and multiple design alterations. The final design is a 35 × 9 mm^2 rectangular antenna with 5 dB gain.

Keywords: 5G MIMO, telecommunication technology, circularly polarization.

ÖZET

5G Dizüstü Bilgisayarlar için MIMO Anteni

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Bilgisayarların ilerlemesi, karmaşık ve karmaşık uygulamaları gerçekleştirme yeteneklerinde ve modern yaşamla bütünleşmelerinde belirgin hale geldi. Bilgisayar teknolojisinin evrimi, teknolojinin günlük yaşamdaki büyümesinden sorumlu olan kilit bir bileşen olan veri aktarımının evrimi ile eşleşmelidir. Hal böyle olunca, taşınabilir cihazlar bir zorunluluk haline geldi ve bu tür cihazların çoğu cep telefonu iken, dizüstü bilgisayarlar daha güçlü oldukları ve daha gelişmiş işlemleri yapabildikleri için müthiş bir marj oluşturuyor. Bu nedenle, yüksek hızda veri aktarabilmeleri ve alabilmeleri için en son telekomünikasyon teknolojisini dizüstü bilgisayarların içine entegre etmek önemlidir.

Bu tezde, bir 5G MIMO mikroşerit anten sunulmaktadır. Antenin tasarımı, modern bir dizüstü bilgisayarın içine sığacak ve 3 GHz'in üzerindeki frekanslarda çalışacak şekilde tasarlanmıştır. Antenin yeniliği, benzersiz bir tasarım kullanılarak dairesel olarak polarize edilmesinde sunulmaktadır. Antenin dairesel polarizasyonu, eksenel oranı incelenerek analiz edilecektir. Bu, önceki araştırmaların çalışmaları ve çoklu tasarım değişiklikleri yoluyla gerçekleşir. Nihai tasarım, 5 dB kazançlı 35 × 9 mm2 dikdörtgen bir antendir.

Anahtar Kelimeler: 5G MIMO, telekomünikasyon teknolojisi, dairesel polarizasyon.

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List of Abbreviations

Abbreviation	Expansion
PEC	Perfect Electric Conductor
BW	Bandwidth
LTE	Long Term Evolution
IFA	Inverted-F antenna
CST	Computer-Simulation-Technology
dB	Decibel
dBic	Decibel isotropic
RF	Radio frequency
LP	Linear polarization
CP	Circular polarization
LAN	Local Area Network
WLAN	Wide LAN
GHz	Giga hertz
mm	milli meter
µm	Micro meter
MIMO	Multiple Input Multiple Output
AR	Axial Ratio
FR4	Flame Retardant Type-4

List of Symbols

Symbols	Meaning
Γ	Reflection Co-efficient
εr	Di-electric Permittivity
G	Antenna Gain
D	Antenna Directivity
$\varepsilon reff$	Effective Permittivity
ΔL	Effective length
C	Speed of light
ηo	Intrinsic Impedance
E	Electric field
H	Magnetic field
L	Inductance
C	Capacitance
ρ	Mass density
σ	Conductivity
E	Internal Electric field

Chapter 1

Introduction

This chapter discusses the fundamental knowledge of antennas and mobile networks needed to follow up with this project step by step.

1.1. Antenna

An antenna is an electrical component capable of both sending and catching electromagnetic waves that propagate through an environment. It is a device that can stand on both the receiving end and the transmitting end of a system. As such, there are two methods to operate an antenna. When acting as a transmitter, the transmitting system connected to the antenna sends specific predefined electric current to the antenna's terminal that cause the antenna to generate electromagnetic signals of specific frequencies that propagate through the air towards a potential receiver. As the receiver, the antenna absorbs certain electromagnetic waves that coincide with the antenna's frequency, which is inversely proportional to its size, and therefore its wavelength. The waves are then converted to electric current that is sent out to the system connected to the antenna (G-NiceRF, 2021).

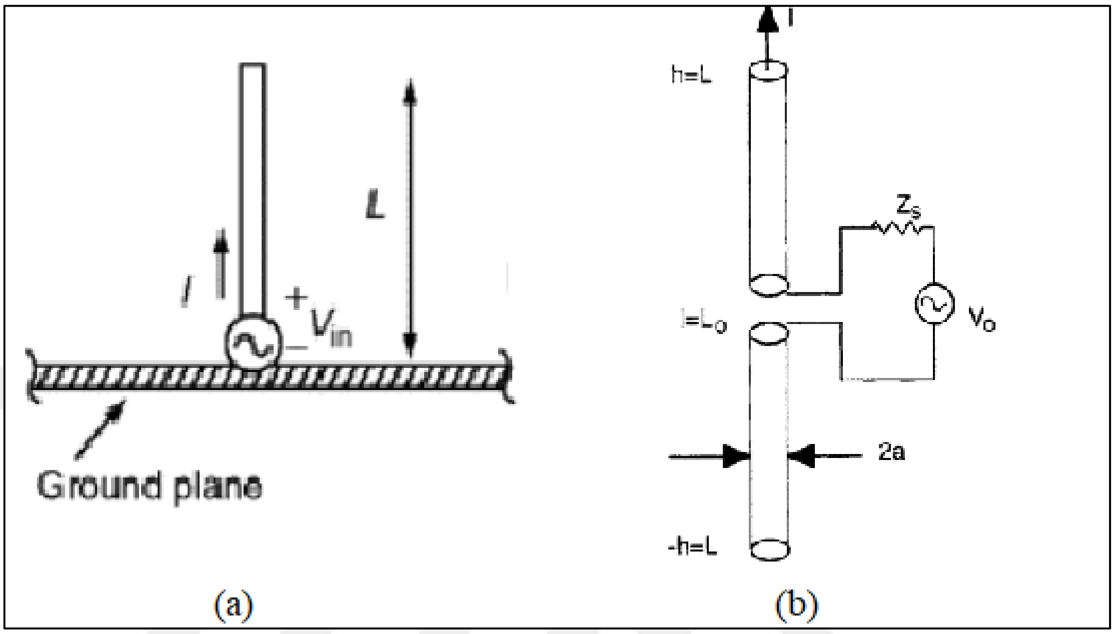
There are many types of antennas, each of which has its own field of application. The antennas that see the most use are: wire antenna, horn antenna, Reflector antenna, microstrip antenna, array antenna.

1.1.1. Wire antenna

As the name suggests, the wire antenna is composed of wires. It could be single or multiple. This antenna's basic designs and inexpensive manufacturing have caused its popular use in multiple domains. It can be seen across many objects systems like on cars, ships, and buildings (Smith, 1988).

Monopole and dipole antennas fall within the wire antenna category. The monopole is composed of a single rod, with one end attached to the feedline and the other end to the ground plane. The dipole antenna on the other hand is composed of two rods of the same dimensions connected at one point of the transmitting/receiving system (Perez, 1998).

***Figure 0-1: (a) Monopole antenna** (Chen, 2005) **and (b) Dipole antenna** (Perez, 1998)*



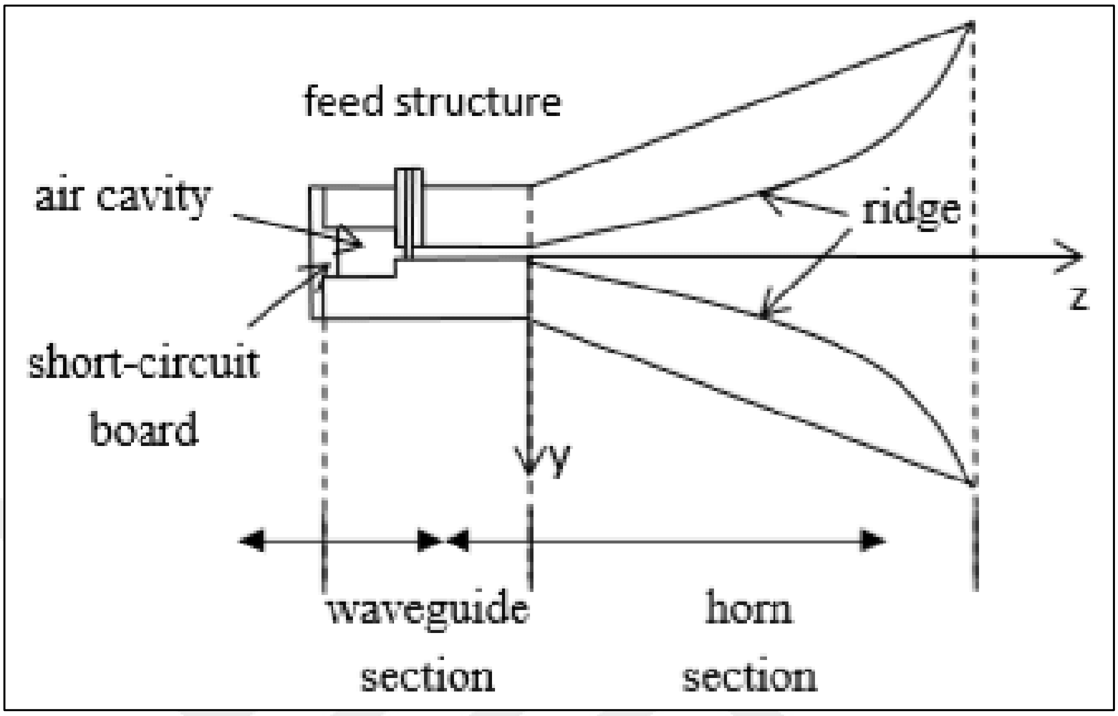
1.1.2.Horn antenna

The horn antenna is composed of a horn shaped metallic waveguide. Horn antennas operate at ultra-high frequencies (UHF) and microwave frequencies. Their key features include their wide bandwidth and their absence of resonant elements.

Using a waveguide without the antenna for receiving electromagnetic waves would cause a huge portion of the waves to reflect, resulting a big waste of energy. This is caused by the mismatch of impedance between the waveguide and free space. The addition of a horn, a tube that gradually decreases in width, provides progressive alteration to moderately adjust the impedance between the two fields.

The horn antenna's great efficiency and its microwave band propagation features make this antenna most prominent in terrestrial applications such as space crafts and satellite communications.

Figure 0-2: Structure of horn antenna (Xie & He, 2018)



1.1.3.Microstrip antenna

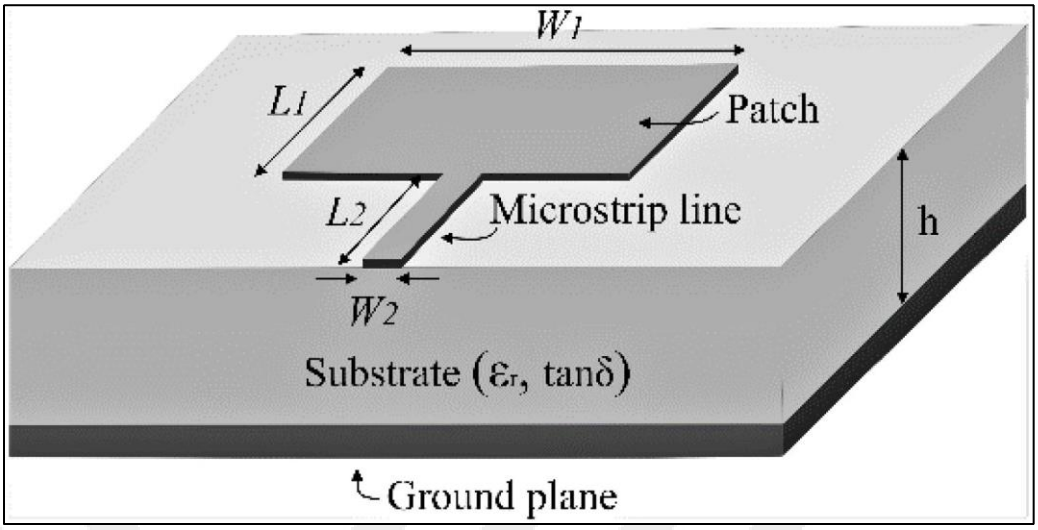
The microstrip antenna gets its name from its shape, a small and thin surface. This antenna boasts of a small and planar size that be easily mounted on flat surfaces. Coupled with its ability to transmit and receive at microwave frequency, this antenna has seen use in cars, satellite systems and mobile phones (Patil & C, 2019).

The microstrip antenna consists of three primary layers:

- Ground plane: on the bottom part of the antenna, it can be composed of any type of substance, but usually is composed of copper.
- Dielectric substrate: a layer with week electric conductivity on the middle part of the antenna.
- Metal patch: which is found on the upper part of the antenna. It is comparatively smaller and usually thinner than the other layers.

The antenna's patch is a key component, which is why the name "patch antenna" can occasionally be used interchangeably. The antenna is fed by the rest of the radio system through a transmission line connected to the patch (Patil & C, 2019)..

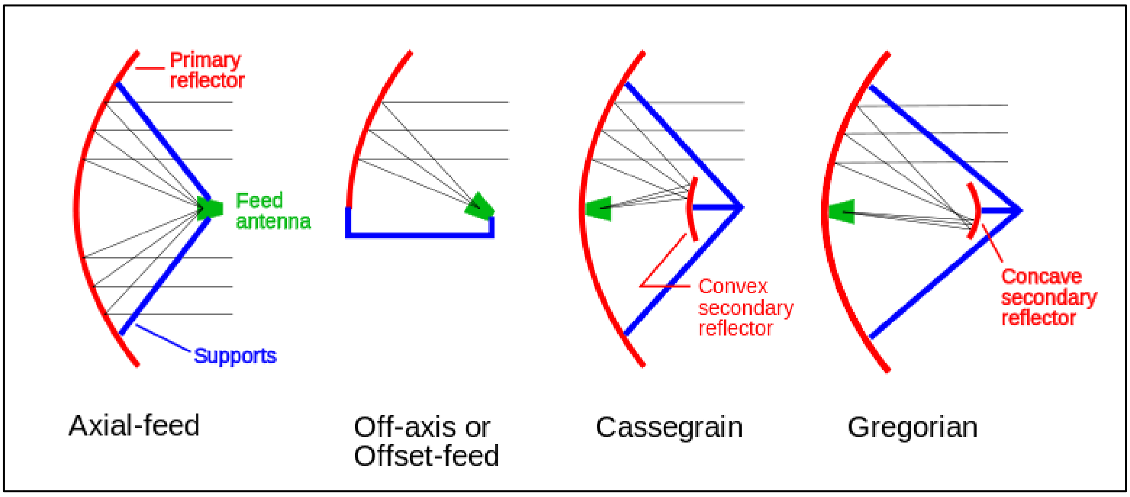
Figure 0-3: Structure of the Microstrip antenna (Da Silva, et al., 2019)



1.1.4.Reflector antenna

This antenna is equipped with a reflecting object that helps direct the waves into the system. It does so by altering the radiation pattern and increase the gain towards a specific direction. Reflector antennas can have many reflectors of many shapes and sizes, with the most prominent shape being the parabola, like in satellite antennas. These antennas are mostly found in spacecraft technology (Perez, 1998).

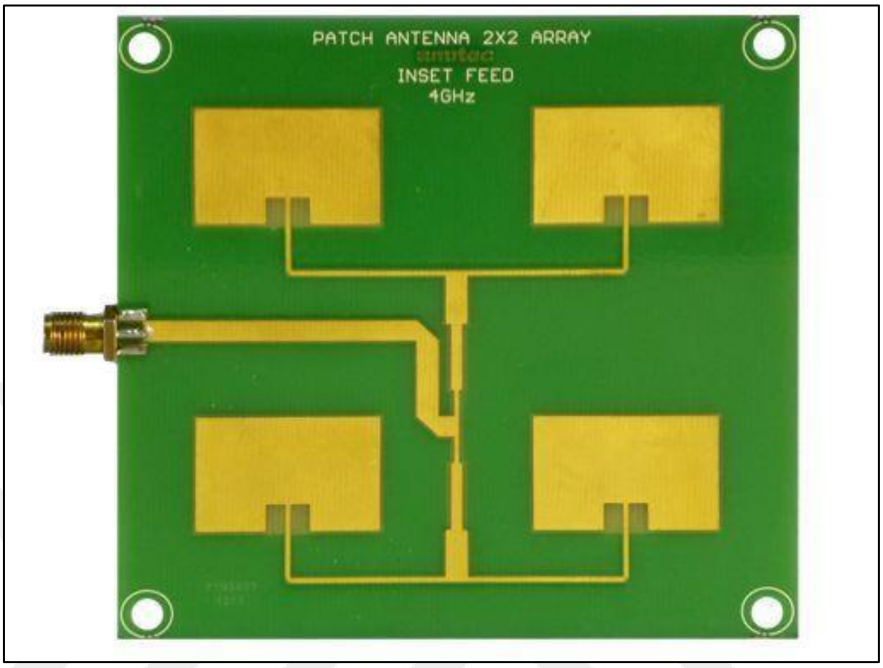
Figure 0-4: Types of reflector antennas



1.1.5.Array antenna

This type of antennas is a rather complex form composed of multiple simple antennas. It is most favored when there is a requirement for high gain while hold constraint in the radiation patterns. The array can be composed of any type of antennas in any kind of pattern (Hum, n.d.).

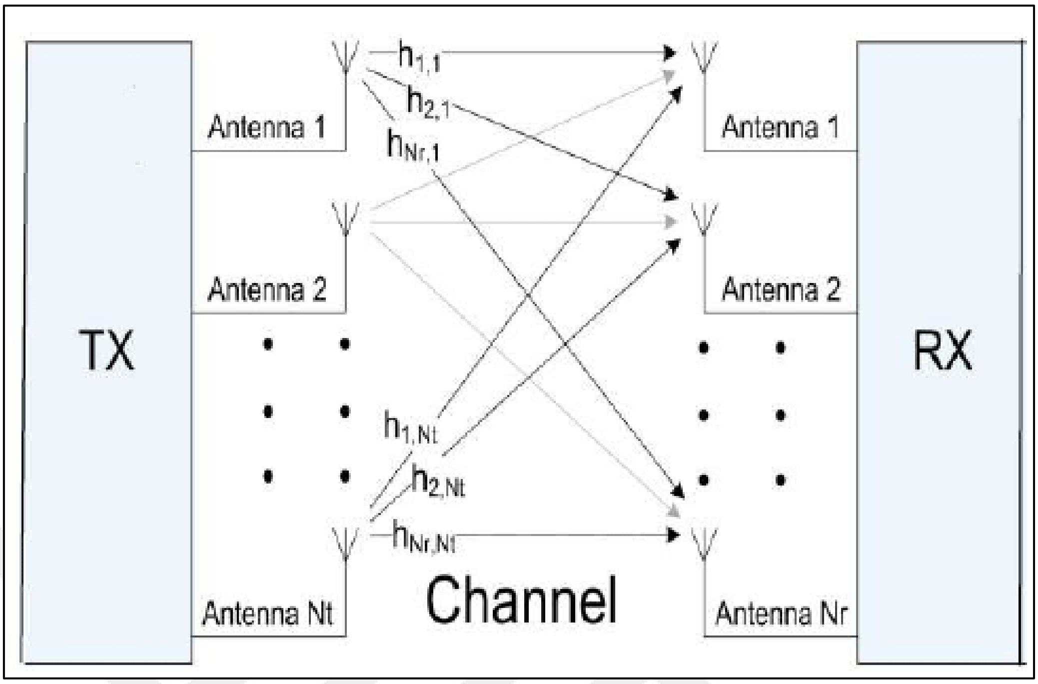
Figure 0-5: 2x2 microstrip patch array antenna



1.2. MIMO

MIMO, or Multiple Inputs Multiple Outputs, is a technological method that uses multiple transmitters and receivers for transferring large chunks of data at the same time. MIMO therefore exploits the multipath propagation found in the properties of systems that utilize multiple numbers of antennas instead of those of independent antennas (Epstein, 2009).

Figure 0-6: Structure of MIMO (Sinha, et al., 2013)

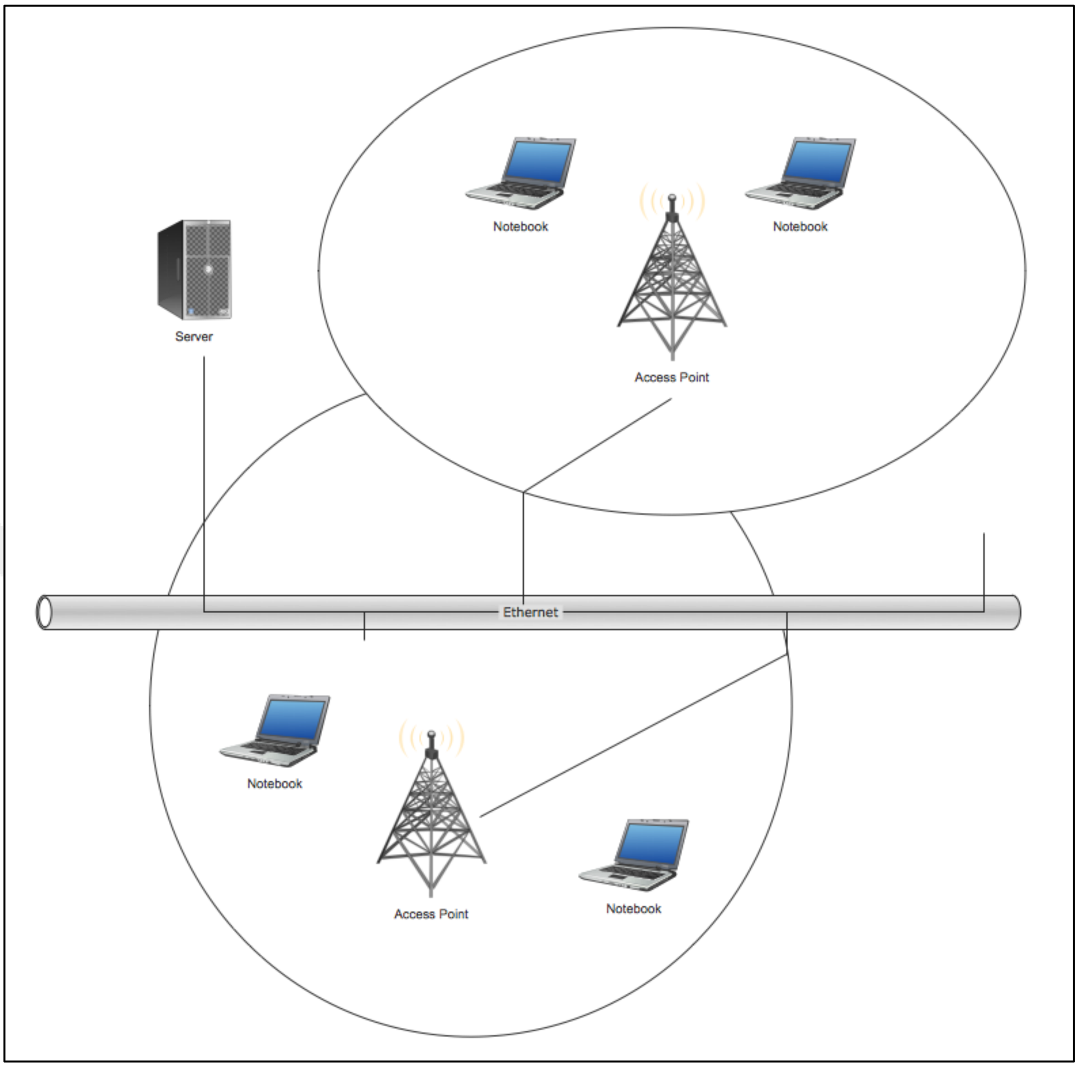


1.3. Wireless Networks

A network is a connection established between multiple devices. The application of networks saw wide use in companies by connecting their computers to establish a connection between their employees and speed up file transfer and communication. With the advent of the internet, a need to provide communication features to devices without the need for wires became an important need (Anon., 2020).

A wireless network is when any of its devices is able to connect to it and to other devices without the need for cables. An essential feature of a wireless network is that the end user's device is not connected to the network by wire (Zanjireh, et al., 2013).

Figure 0-7: Wireless network topology



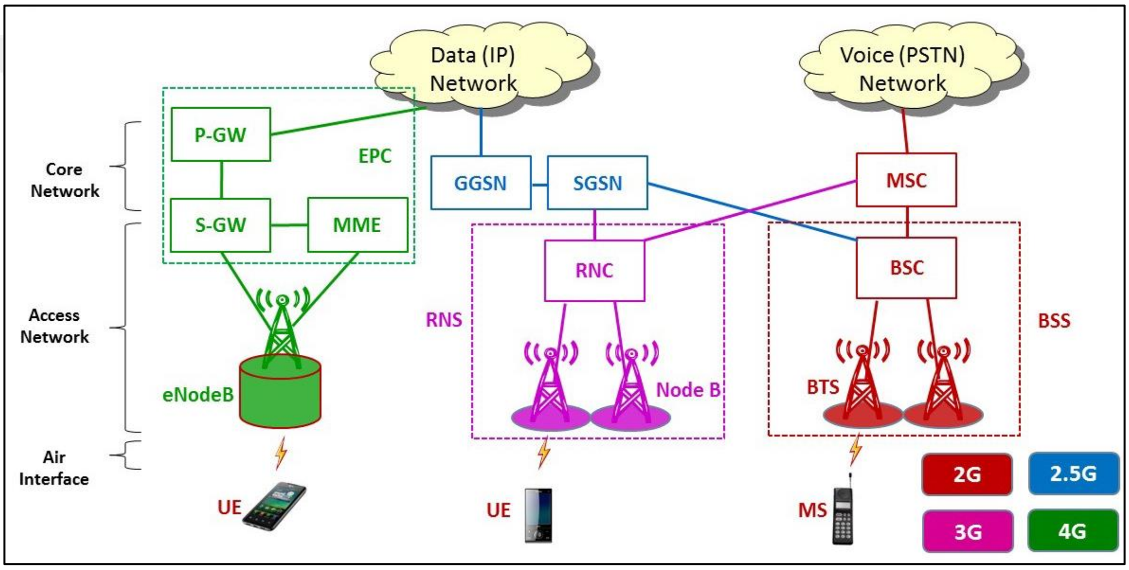
The necessity of utilizing a wireless network, motivated by the increasing use of mobile equipment like cellular phones and laptops, is a key factor for the implementation of antennas within these devices. The growing use of wireless networks has also prompted their continuous growth to keep up with user demands (Chai K, 2001).

The first use of mobile communication was the cellphone's 1G, which was an entirely analog function. 1G operated on the 800 MHz band, which needs substantially large antennas that further increase the size of already-bulky devices (Seo, 2013).

2G saw its inception in 1991, and it officially marked the massive switch from analog signals to digital, which added the use of encryption and support for mobile internet. 2G came associated with an official standard called GSM Telecommunications (Global

System Mobile) to construct a uniform architecture that makes it easier for mobile communication companies to handle their user base and provide better reception. Providing larger access was also heavily boosted with the introduction of roaming, which gives users access to other networks in case they were far away from the initial provider's network. 2G was later upgraded by adding a packet-switched domain in addition to the previously used circuit switched domain. This upgrade was labeled as 2G. The success of 2G is most apparent in the fact that it is still used by many data subscribers even though it has been succeeded by multiple other technologies (Avila, 2020).

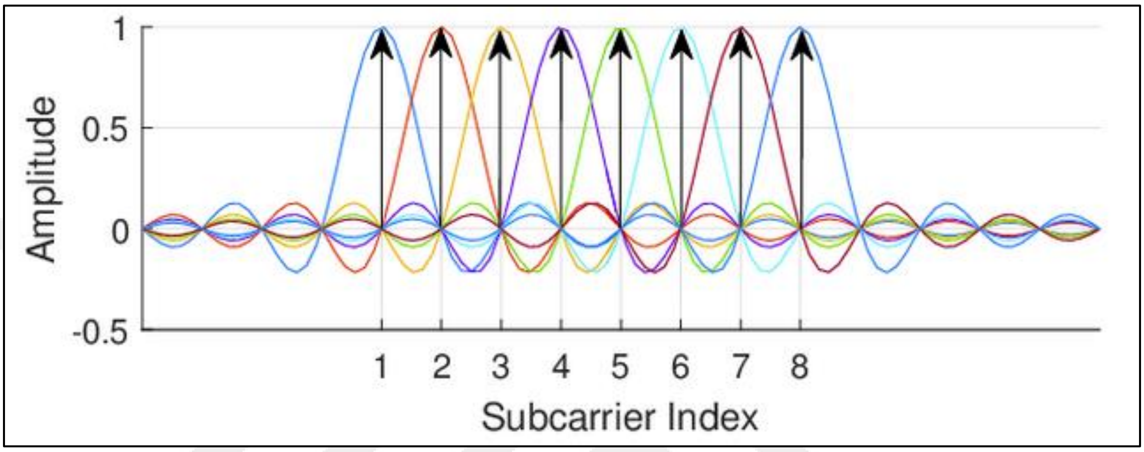
Figure 0-8: 2G, 3G and 4G architecture *(Ghandaily, n.d.)*



Out of research carried out by the International Telecommunication Union in the 1980s, came the base concept of what will be labeled and marketed as 3G in 2001. It was slowly constructed in parallel with the use of 1G and 2G and growth of the internet. By the time it was ready for use was when there was sufficient need for it to match the advancements in internet router bandwidths and the massive mobile network base of subscribers (Ghandaily, n.d.).

In 2010, 4G entered the market, bringing in a lot of advantages associated with its LTE and WiMAX standards, like standardizing the use of MIMO and switching focus towards IP telephony. This mobile technology operates at up to 6 GHz. Speed varies by region and company, but held an average of 30 Mbps. 4G also introduced the use of OFDM (orthogonal frequency division multiplexing). OFDM is a data encryption model that operates by splitting the signals to different narrowband frequency channels known as carriers. Using this method, multiple signals can be simultaneously sent over overlapping spectra. OFDM provided major benefits in resource utilization and simplifications of channel equalization. It also has tolerance towards narrow band co-channel interference and is adaptable to severe channel conditions (Doğan, et al., 2018).

Figure 0-9: OFDM sub-carriers *(Doğan, et al., 2018)*



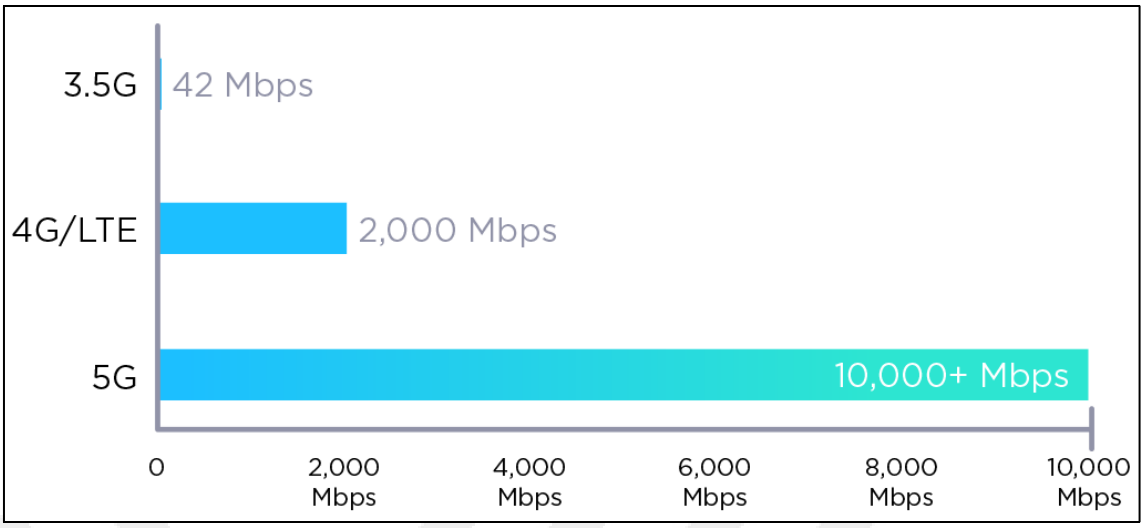
The fourth generation brought many new things and was sufficient for its time. However, the number of new people accessing mobile networks are growing at an exponential pace, which created a need to create a network that would able to comprehend a number of users manifold of the current population. In addition, other more intricate and speed-reliant technologies such as self-driving cars and tele-surgery need something that is more reliable and even faster than 4G. Thus, came the need to create 5G (Milanovic, 2018).

1.4. 5G

The fifth generation of wireless network technology entered the mobile market in 2019 by storm. 5G boasts of lower latency and higher bandwidth, which means higher stability and faster data transfer.

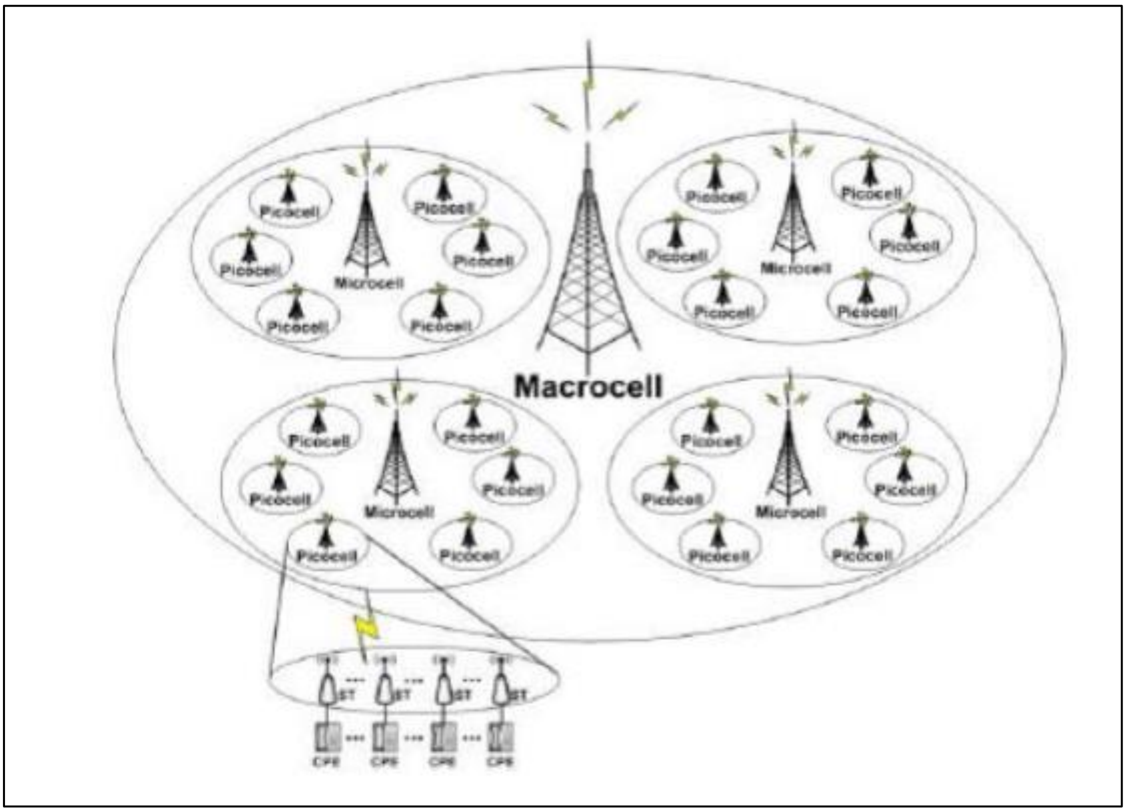
5G is able to operate at many bands of previous wireless technologies, using a feature called spectrum sharing. In addition to the newly introduced mmWave high band frequency, which is around 24 GHz (Segan, 2020).

*Figure 0-10: **Max download speed for wireless technology*** *(Milanovic, 2018)*



The only disadvantage of the use of the high frequency mmWaves is that there small wavelength makes them incapable of propagating at long distances. Thus, wireless network companies have to rely on decreasing the size of their cells, by deploying more base stations at closer distances that represent micro cells. Multiple microcells combine to consist a bigger macro cell (Pearson, n.d.).

*Figure 0-11: **5G cell architecture*** *(Anon., 2016)*



Overall, 5G displays qualities that heavily surpass previous technologies. This explains the mass deployment of 5G across the globe as it became public. Table **0.1** outlines the differences in speed and latency between the mobile wireless technologies of 3G, 4G, and 5G (Milanovic, 2018).

Table 0.1: Comparison between 3G, 4G and 5G *(Milanovic, 2018)*

Generation	Maximum Download Speed	Typical Download Speed	Latency
3G	42Mbps	1.5Mbps	100ms
4G	300Mbps	30Mbps	50ms
5G	1-10Gbps	150Mbps	1ms

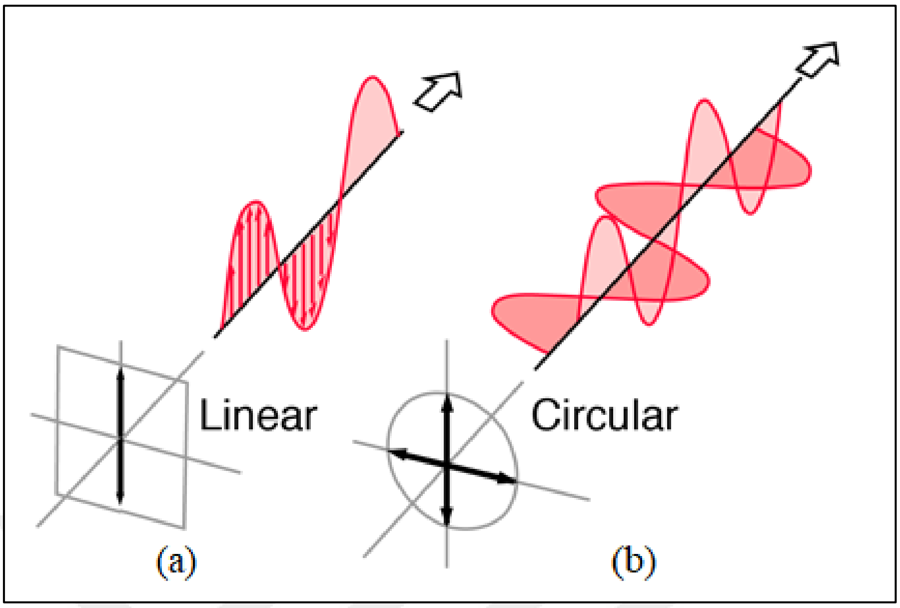
1.5. Circular Polarization

The electromagnetic wave takes on different types of polarizations. Polarization of the wave is basically the shape its single wavelength takes. The most common used polarization is the linear polarization; however, circular polarization also has its own advantage and uses.

1.5.1. Circular Polarization Explanation

When the electric field's x-axis and y-axis are in phase, linear polarization is attained. Contrarily, circular polarization happens when there is a phase difference of $\pi/2$ (90°) between the two axes. The circular polarized wave can be characterized depending on its direction, either right-handed (RHCP) or left-handed (LHCP), usually taken into perspective from the transmitting end (Schwartz, n.d.).

Figure 0-12: (a) Linearly polarized waves and (b) circularly polarized waves



While having slightly low cross-polarization, circularly polarized waves give higher probability of successful transmission link because of its difference in phase that makes it propagate in all fields. In addition, its circular characteristic gives it higher chance of bending and penetrating obstacles. These attributes make circular polarization ideal for long distance transmission like astronomical research and satellite communication systems, as well in FM radio [Mener, et al., 2016].

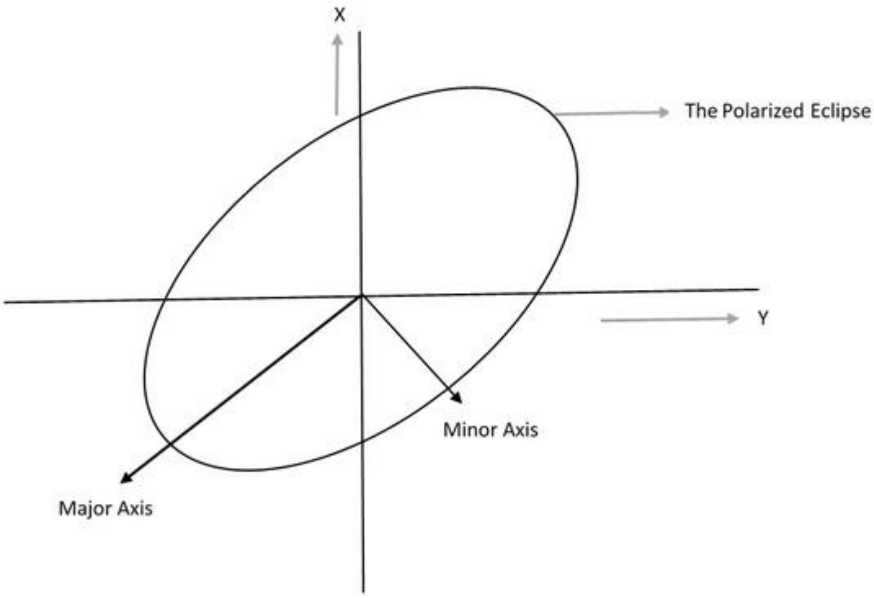
The popular types of antennas for producing circularly polarized waves are:

- Helical antenna: composed of conducting wires twisted around in the shape of a spiraling helix.
- Patch antenna: the patch antenna's waves depend on the shape of the patch applied, and therefore a circular patch antenna can produce circular waves.

1.5.2. Axial Ratio

The axial ratio is the method used to determine the perfection of the circular polarization of the antenna. It is defined as the ratio between the major axis and the minor axis of the produced wave's orthogonal components in the E-field. This is further illustrated in Figure 0-13 (Bevelacqua, 2008).

Figure 0-13: Representation of the major and minor axes of an ellipse (RF, 2021)



It can be therefore concluded from the figure that the linearly polarized wave has an infinite axial ratio (due to perpendicular components), and if it equals to one (0 dB), then it is perfectly circularly polarized. Anything between these two results is labeled as elliptical. However, since it is hard to obtain a perfect 0 dB axial ratio, modern standards allow room for error of up to 3 dB axial ratio for the wave polarization to be characterized as circular (RF, 2021).

1.5.3. Obtaining Circular Polarization

Since linear polarization is the polarization type used in most cases, there are times when it is necessary to convert these waves into circular polarization rather than producing them circularly polarized from the get-go. Such process requires the study of the effects of the wave's parameters in order to express the viability of the results. A set of rules have been founded to theoretically express the conversion from linear to circular polarization (Sofi, et al., 2019).

$$\vec{E}^t = \vec{E}_x^t + \vec{E}_x^t = E_0^t \, (T_x\hat{x} + T_y\hat{y})e^{-jkz} \tag{1}$$

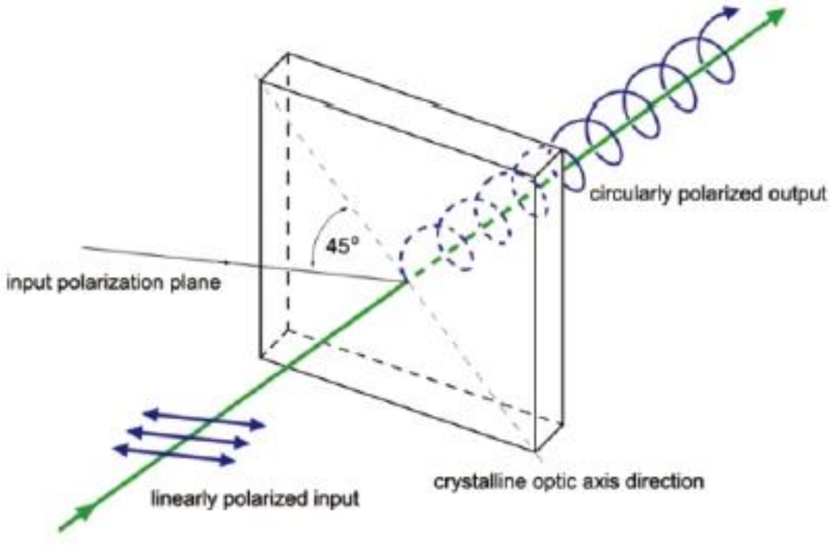
$$\begin{bmatrix} T_x \\ T_y \end{bmatrix} = \begin{bmatrix} |T_x|e^{-j\varphi_x} \\ |T_y|e^{-j\varphi_y} \end{bmatrix} \tag{2}$$

$$\Delta_\varphi = \varphi_x - \varphi_y \tag{3}$$

The transmitting wave is a superposition of two perpendicular elements of same magnitude. The amplitude represented through E^t_0 is found in equation (1). T_x and T_y are part of the transmission matrix T shown in equation (2), where $|T_x| = |T_y|$. The conversion process also requires an alteration of the phase of the wave, as expressed in equation (3). Where the phase change should be constant at $\Delta_\varphi = \pm 90°$ (Sofi, et al., 2019).

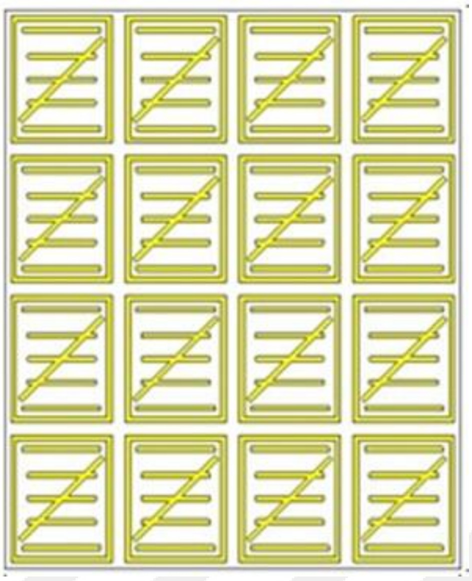
To achieve the desired circular polarization, there are multiple methods of the conversion of linear polarization, with the most common in practice being the implementation of a quarter-wave plate. A wave plate is an optical device designed generally for wave alteration and specifically for polarization switching. It is composed of birefringent crystals. The success rate of polarization conversion through the quarter-wave plate depends on the plate's crystal thickness, refraction index, and their correspondence with the wavelength. The closer the angle at the intersection between the wave and the wave plate to 45° the closer the altered wave's polarization is towards the circular polarization (Hecht, 2015).

***Figure 0-14: Polarization conversion through the quarter-wave plate** (Hecht, 2015)*



Another method that is lately growing in popularity is the application of metasurfaces in place of standard crystalized surfaces. The metasurface would be constructed from multiple repeated metamaterial unit cells that hold special characteristics and act as a method of polarization conversion. The unit cells can take on many shapes, with a lot being custom made, while others taking staple metamaterial shapes such as the split ring resonator (SRR) (Akgol, et al., 2018).

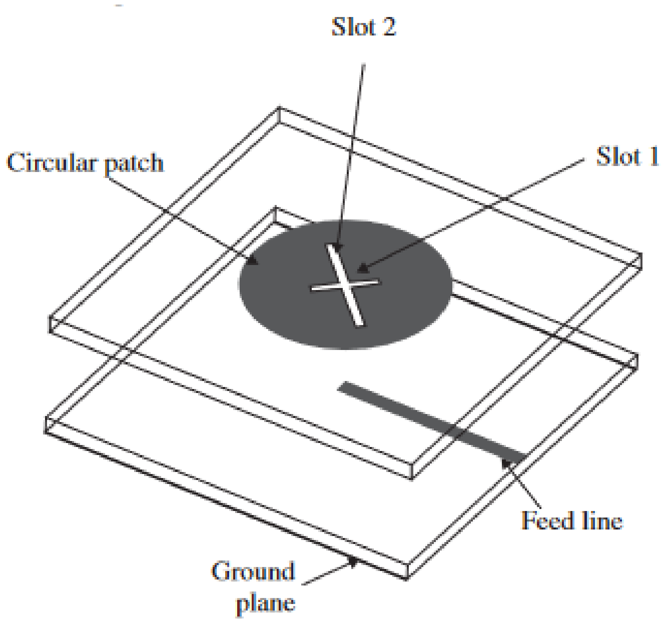
Figure 0-15: An example of a 4 x 4 metasurface converter (Akgol, et al., 2018)



There is method that also relies on a layer of repeated unit cells but not necessarily in the form of metamaterials. This method is referred to as the frequency selective surface (FSS) method and is primarily used for frequency filtering, but can also produce the effect of polarization conversion. This method uses the inductive and capacitive behavior produced by FSS to divide a single wave in to two elements of almost equal power with a phase difference of 90° (Tarn & Chung, 2007).

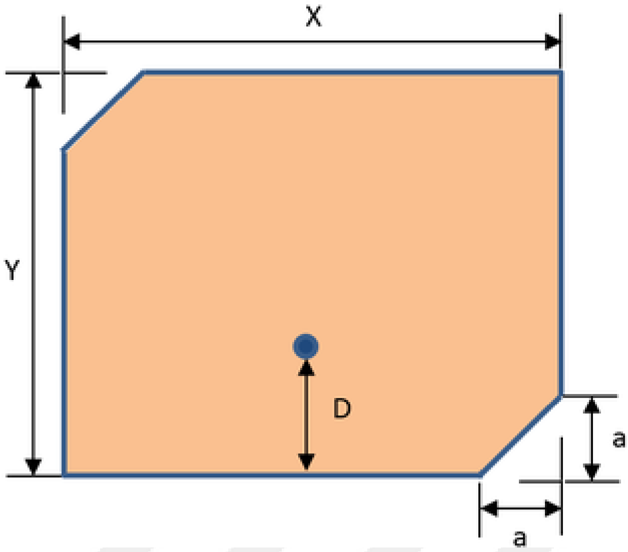
The obtainment of circular polarization from the starting point can be done through the implementation of slots on a circular patch antenna. The slots need to be heavily calculated in terms of location and dimension to achieve a phase difference of 90°. By implementing two intersecting slots with one slightly longer than the other, as seen in Figure 0-16, we can obtain a polarization with a specific direction, in this case it is right handed. By exchanging the lengths of the two slots, left handed polarization is obtained (Gao, et al., 2014).

Figure 0-16: Implementing slots on circular patch antenna (Gao, et al., 2014)



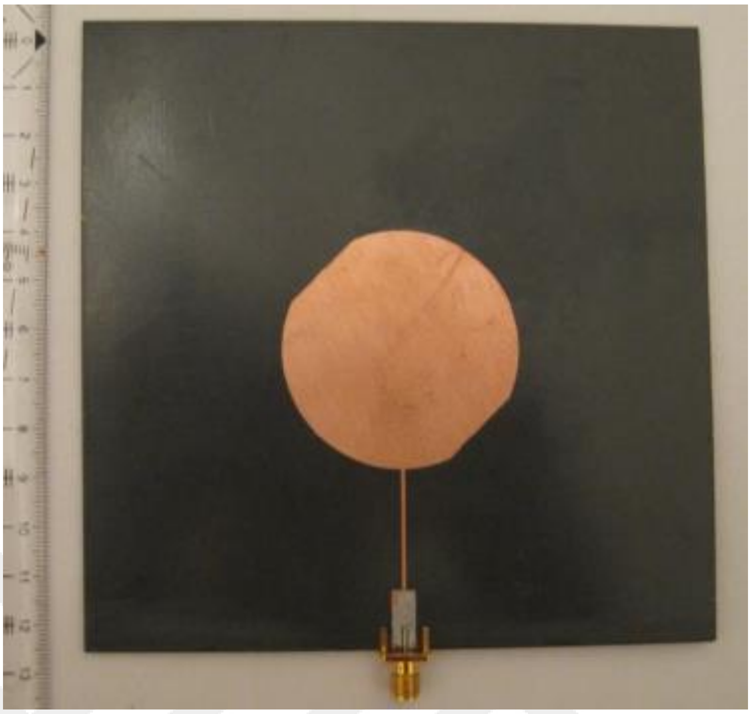
A broadband propagation L-probe patch antennas is shown in Figure 0-17. The antenna presents the removal of two orthogonal corners of the patch that is fed by an L-shaped probe at the middle of one of its edges. The excitation of these two orthogonal modes causes (due to patch perturbation) the production of circular polarization with a 90° phase shift. The implemented probe, piled with its coupling with the patch, causes a capacitance that compensates for the inductance produced by the long probe. This assists in impedance matching and parameter improvement, as the height and length of the probe ease the obtainment of optimal performance of the antenna. The L-shaped probe feed is effective in countering the problem of impedance mismatching caused by the long probe's large inductance (Lin & Wong, 2017).

Figure 0-17: L-probe circular polarization patch antenna



A thesis designed a single fed circularly polarized microstrip antenna based on using a circular patch. The antenna operates at 2.4 GHz and uses single feeding due to being simple to construct, easy to manufacture, low in cost and compact. The method of generating circular polarized waves in this research is based on truncating (splits the field into two orthogonal modes with equal magnitude and 90° phase shift) two opposite edges from a circular patch antenna at 45° to the feed. This design uses the aforementioned dimension perturbation to obtain the low axial ratio necessary to achieve circular polarization at the desired frequency. The microstrip antenna required the implementation of a quarter wavelength transformer between the 50 feed line and the patch (Shakeeb, 2010).

Figure 0-18: Fabricated antenna's layout (Shakeeb, 2010)



The research also included a comparison of the results attained from the same antenna after applying three different feeding techniques on it. Results show that microstrip fed antenna design in this thesis achieved 8.11 dB directive gain of 0.83 %, axial ratio and impedance bandwidth of 2.92 %. Meanwhile, the proximity feeding technique yielded 8 dB directive gain, axial ratio of 1.45 % and impedance bandwidth of 5.36 %. The aperture fed antenna gave 7.92 dB directive gain, axial ratio of 0.83 % and impedance bandwidth of 2.92 % respectively (Shakeeb, 2010).

Table 0.2: Antenna results per feed technique (Shafique, et al., 2020)

Point of comparison	Microstrip feed	Proximity feed	Aperture feed
rad mm	23.96	23.3	22.9
d	22.6	21.35	21.6
W_f	4.88	4.62	4.36
Impedance bandwidth %	2.92	5.36	2.92
Axial ratio bandwidth %	0.833	1.45	0.833
Directive antenna gain dB	8.11	8	7.9
Design frequency GHz	2.4	2.4	2.4
Difference between co and cross-polarization in E-plane dB	31.08	28.14	29.9
Difference between co and cross-polarization in H-plane dB	31.08	28.14	29.9
Half power beamwidth in the E-plane °	70	70	72.5
Half power beamwidth in the H-plane	73	77.5	75

There are also researches that include the inception of antennas capable of omnidirectional circular polarization, which in turn can make it cover large areas. This was brought through a planar and low profile microstrip antenna (Narbudowicz, 2013).

The study enhanced the performance of the antenna by integrating four lumped capacitors that allow precise tuning towards the desired band. This is in addition to slots which, along with the capacitors, allow to steer the current path of the first and second resonant mode. Beam reconfiguration was required for rotating the antenna’s dipole-like radiation pattern around an axis, thus allowing reception or transmission from any spherical angle. In addition, this structure had also presented good flexibility and small feed network size, and was capable of achieving dual sense circular polarization through the use of odd and even transmission line modes (Narbudowicz, 2013).

*Figure 0-19: **Design of omnidirectional circular polarization** antenna (Narbudowicz, 2013)*

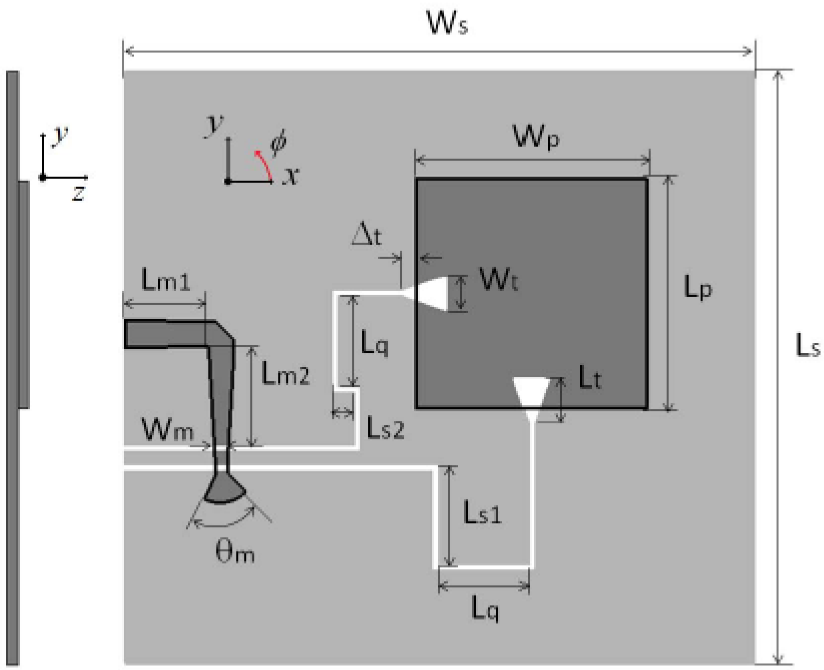
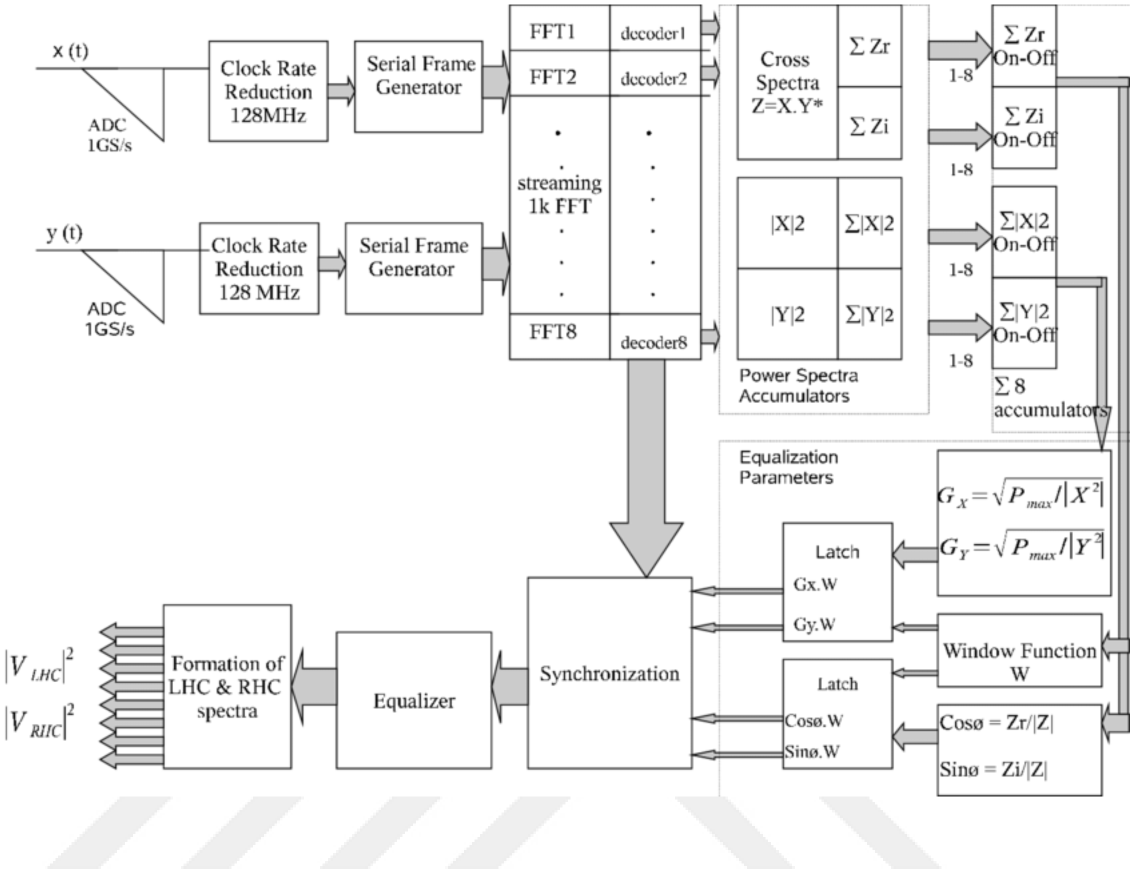


*Table 0.3: **Omnidirectional antenna parameters** (Narbudowicz, 2013)*

Parameter	Ws	Ls	Wp	Lp	Lt	Wt	Dt
Value (mm)	85	80	31	31	6	4.4	1.3
Parameter	Lq	Ls1	Ls2	Lm1	Lm2	Wm	
Value (mm)	12.7	13.5	3	11.3	13.7	1.7	

A more obscure approach is utilizing FPGAs (field-programmable gate arrays) for polarization conversion through digital circuit techniques. This method is produced primarily for applications in very-long baseline interferometry (VLBI) for astronomical-level communication. It requires a complicated digital structure, as presented in Figure 1.20, that systematically breaks down the wave using micro-processing technology and performs the presented equations on it, then synchronizes and equalizes the results, presenting a new circularly polarized wave (Das, et al., 2010).

Figure 0-20: Linear to circular conversion through FPGA (Das, et al., 2010)



1.6. Aims and Objectives

5G technology opened up many new features and upgrades to consumers. Its architecture is able to provide great speeds and stability for many users to come, making it more than sufficient for the near future. Its importance is most apparent in how many prominent companies and cities started implementing it immediately after its release.

The release of 5G meant that the need for new devices that could keep up with its standards, whether it be on the provider side or consumer side. As the antennas integrated into previous devices cannot use 5G to its full potential, an upgrade in antenna design and technology was needed.

This project seeks to design a circularly polarized antenna that is able to conform to 5G's standards. To further boost its characteristics, it will be equipped with MIMO technology that has become a necessity in modern-day wireless telecommunication. The antenna will be designed and simulated on CST software, a powerful tool for electromagnetic field simulation. The results will be extracted and studied accordingly.

The outline of the project steps are as follows:

- Research different technologies applied in wireless telecommunications
- Research types and versions of antennas
- Decide a basis of the design
- Perform calculations based on antenna theory equations
- Learn the know-hows of antenna simulation software
- Design the antenna with the implementation of MIMO that follow standards set by 5G
- Simulate the designed antennas on CST
- Evaluate the attained results
- Produce the final version of the device that holds the best obtained parameters

5G technology has brought the ability to operate at mmWaves, which are extremely high frequencies. As such, it also brought new challenges that newly developed antennas seek to transcend. Meanwhile, the implementation of circularly polarized antennas is being relatively neglected when compared to its linear counterpart, making circularly polarized laptop antennas a fresh domain with more room for discoveries.

While the majority of the antennas are designed primarily for mobile phones, this project will focus on an antenna to be implemented in laptops. Laptops are mobile devices too and, with the increasing dependency on the internet, need immediate access to surrounding networks at any given time. The final product will be a 5G MIMO antenna that holds good parameters and performances and can be easily implemented in modern laptops.

Chapter 2

Literature review

To advance with this research, it is essential to study other scholarly research conducted on this matter to compare results and analyze shortcomings. The literature review chapter includes other papers conducted for 5G antennas with the use in laptops in mind. The results of each paper are summarized accordingly.

2.1. Small-Size 5G C-Band/WLAN5.2/5.8GHz MIMO Antennas for Laptop Computer Applications

A paper that proposes a MIMO antenna designed for laptops presented here has a design highlighted in Figure 0-1 with its respective parameters in Table **0.1**.1 (Chen & Chang, 2018). The antenna has the dimensions of 5 × 30 × 3 mm^3, and a ground plane with a dimension of 200 × 260 mm^2. Its substrate of choice is an FR4 with 0.8 mm thickness and 4.4 relative permittivity.

Figure 0-1: Geometry of the C-Band/WLAN5.2/5.8GHz antenna from the (a) top view and the (b) side view

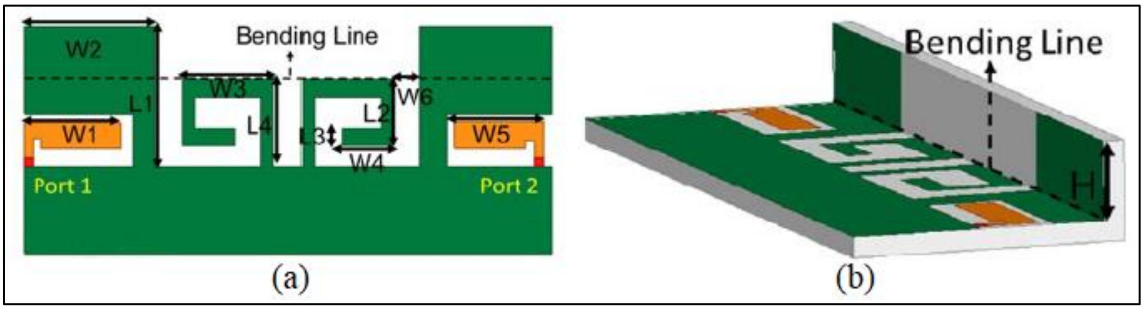


Table 0.1: C-Band/WLAN5.2/5.8GHz Antenna parameters

Parameters	W	W_1	W_2	W_3	W_4	W_5	W_6	H	L	L1	L2	L3	L4
Unit (mm)	260	5.5	7.5	5.2	3	5.1	1.5	3	200	8	4	1	5

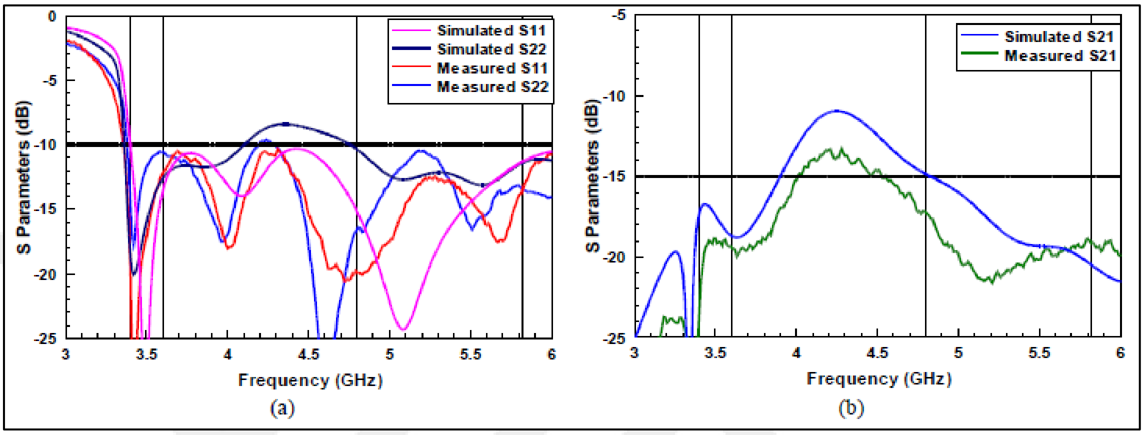
The antenna is designed to operate at three different bands:

- 5G C-Band: 3.4 – 3.6 GHz
- China 5G C-Band: 4.8 – 5 GHz

- WLAN 5.2/5.8: 5.15 – 5.825 GHz

The utilization of the two inverted L-shaped strips are for enhancing isolation. The study of the S-parameters in Figure 0-2 shows that both produced results less than -10 dB at all the required frequency bands.

Figure 0-2: S11 and S21 of the C-Band/WLAN5.2/5.8GHz antenna



The gain produced at the C-band varied between 3.69 and 5.07 dBi, while the gain at the other two bands (from 4.8 GHz to 5.825 GHz) varied between 4.15 to 2.83 dBi. The design had a size small enough for integration into laptop devices, but had sub-par efficiency at the C-Band.

2.2. Small-size WLAN/5G MIMO antenna for laptop computer applications

A small sized antenna built for laptop applications is printed on a 0.8 mm thick FR4 substrate with 4.4 relative permittivity [Chen, et al., 2017]. The antenna is composed of two smaller antenna elements with dual features, each with its own port, as can be seen in Figure 0-3. Both ports are fed through a coaxial cable.

The MIMO antenna has a dimension of 35 × 9 mm^2. It operates across the WLAN frequency bands (2.4/5.2/5.8 GHz) and a spectrum of the 5G band (3.4–3.6 GHz). It is designed for the intention of mounting it on the metal frame of the laptop display, which acts as the antenna’s ground plane.

Figure 0-3: Geometry of the WLAN MIMO antenna

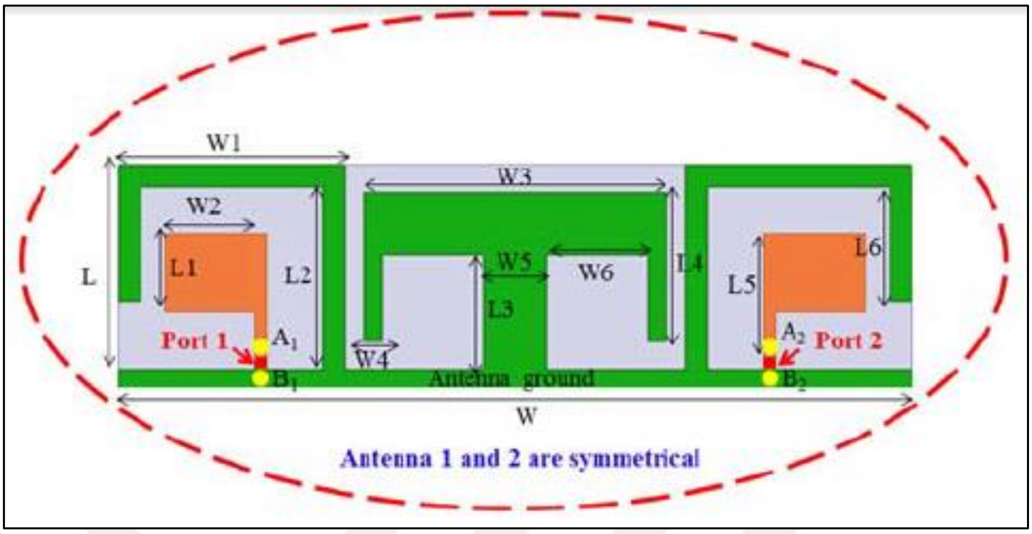
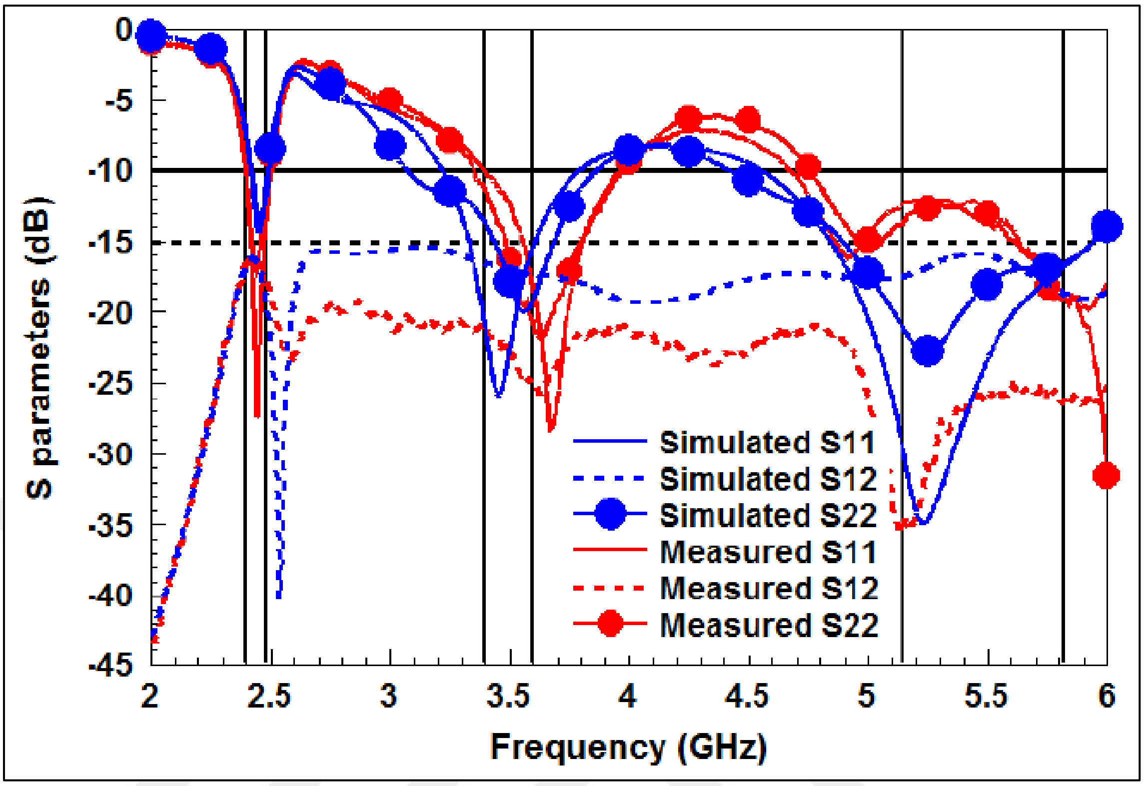


Table 0.2: Parameters of the WLAN MIMO antenna

Parameter	L	L1	L2	L3	L4	L5	L6
Unit (mm)	9	3.5	8	5	6.5	5.5	5
Parameter	W	W1	W2	W3	W4	W5	W6
Unit (mm)	35	10	4.5	13.5	0.85	2.8	4.5

The simulated graph found in Figure 0-4 shows the S-parameters of the antenna. It is apparent that both antennas produced sufficient results, with the return being loss lower than -10 dB at the specified frequency bands.

Figure 0-4: S-parameters of the WLAN MIMO antenna



2.3. MIMO IFA Antennas for Laptop Computer Application at WLAN/5G C-band operation

This laptop MIMO antenna uses the inverted-F design (IFA). There are two IFA antennas, both connected to a single ground loop and, like the previous paper, the antenna uses the laptop system's ground (Chen, et al., 2019). The antenna uses the staple FR4 substrate of 4.4 relative permittivity at 0.8 mm thickness. The three-dimensional size of the antenna was 10 × 35 ×3.8 mm^3. Both of the antenna strips are fed through a coaxial cable. The longer strip operates at the WLAN 2.4 GHz, while the other strip operates at the WRC-15 C-band of 3.5 GHz. The loop that connects the front strip to the back strip operates at both the 5G C-band and WLAN 5.2/5.8 GHz.

Figure 0-5: Front view of IFA antenna

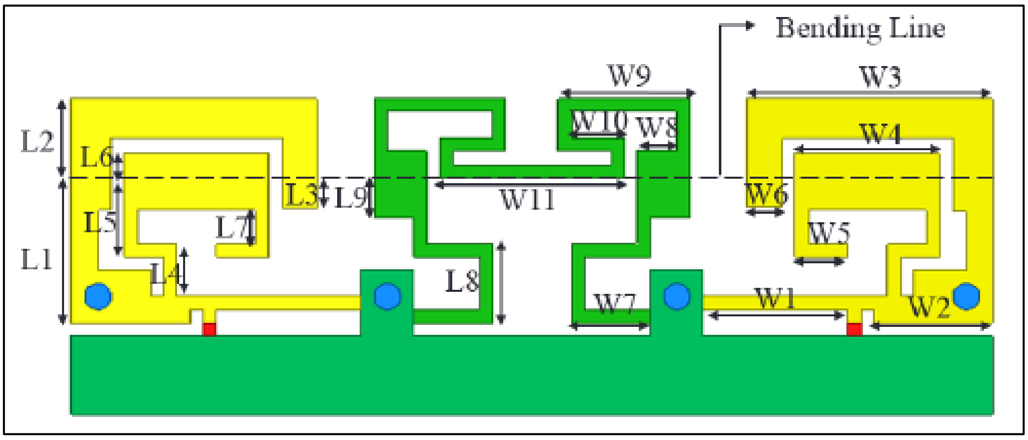


Figure 0-6: Side view of IFA antenna

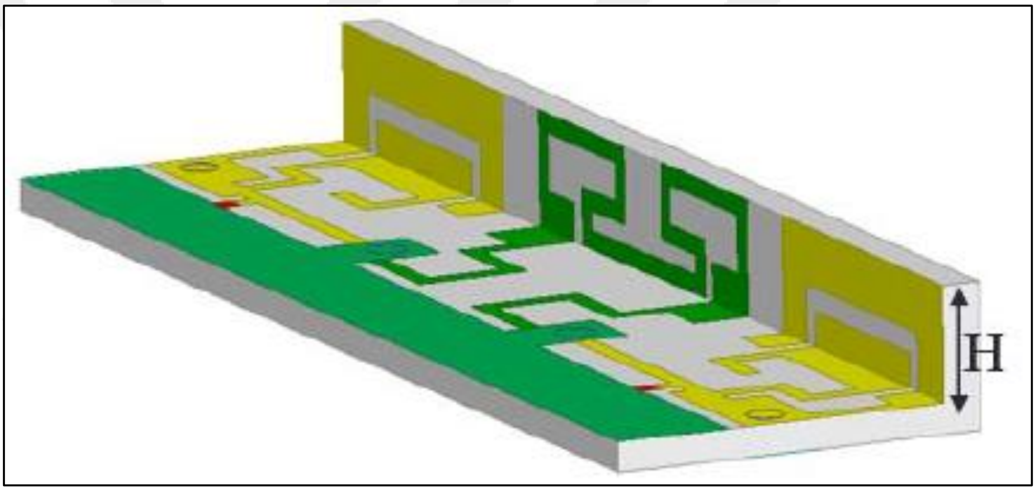
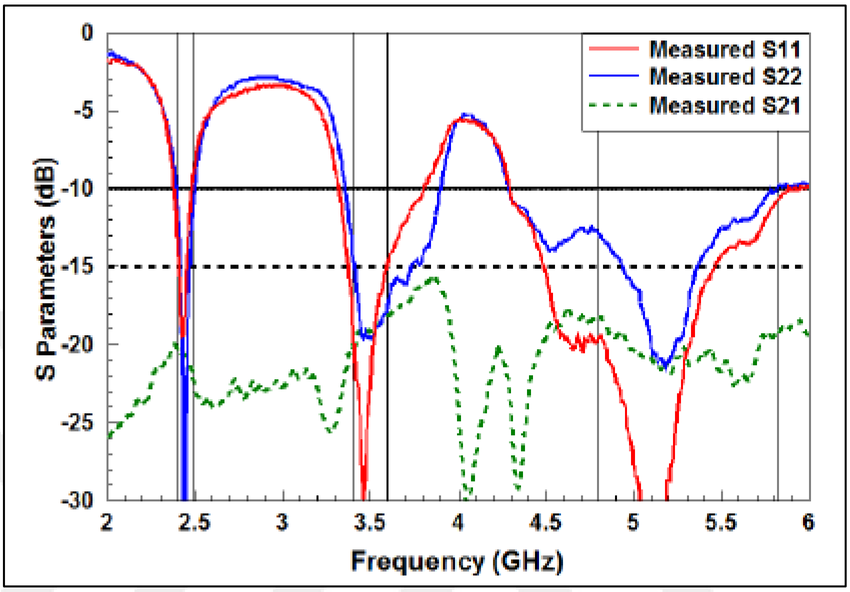


Table 0.3: IFA antenna parameters

Parameter	L	L1	L2	L3	L4	L5	L6	L7
Unit (mm)	200	5.5	3	1.2	2	3	0.9	1.3
Parameter	L8	L9	L10	L11	L12	L13		
Unit (mm)	3	1.5	2	1	3	4.5		
Parameter	W	W1	W2	W3	W4	W5	W6	W7
Unit (mm)	260	5.5	4.5	9.35	5.5	2	1.35	3
Parameter	W8	W9	W10	W11	W12	W13	W14	H
Unit (mm)	1.5	5	2	7	4	5.5	4.5	3

The graph in Figure 0-7 expresses the S-parameters of the IFA antenna. Both the S11 and S22 produced results less than -10 dB, which satisfied the needed requirements. The S21 also generated results below -15 dB.

Figure 0-7: S-parameters of the IFA antenna



The gain produced by the first antenna had an average of 1.3 dBi at the WLAN 2.4 band, 3.4 dBi at the WRC-15 C-band, 4 dBi at the China C-band, and 3.2 dBi at the WLAN 5.2/5.8 band. Meanwhile, the gain produced by the second antenna had an average of 2.0 dBi at the WLAN 2.4 band, 6.0 dBi at the WRC-15 C-band, 3.9 dBi at the China C-band, and 5.5 dBi at the WLAN 5.2/5.8 band.

2.4. Design of MIMO Antennas for 5G C-band/WLAN Operation in the Laptop Computer

This research uses two sets of MIMO antenna to operate at 5G's C-band and WLAN frequency bands to be integrated into laptops [Liang, et al., 2019]. The two MIMO antennas have a three-dimensional size of 5 × 45 × 5 mm^3. Between the two antennas is a small loop antenna with design highlighted in Figure 0-9 has a length of 15.8 mm and width of 10.3 mm.

Figure 0-8: Geometry of 5G C-band/WLAN antenna

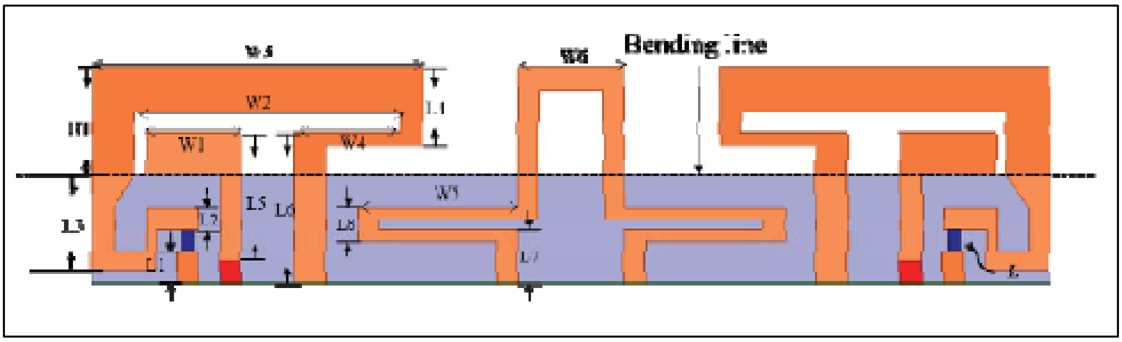


Table 0.4: 5G C-band/WLAN antenna parameters

Parameter	L1	L2	L3	L4	L5	L6	L7	L8
Unit (mm)	1.5	1	4.5	3.5	6	7	2.5	1.5
Parameter	W1	W2	W3	W4	W5	W6	H1	
Unit (mm)	4.5	12.5	15.5	5	7.5	5	5	

Figure 0-9: Geometry of the loop antenna

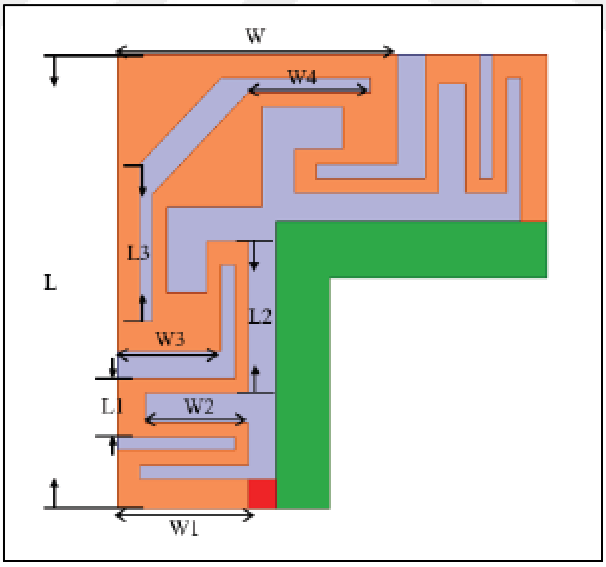


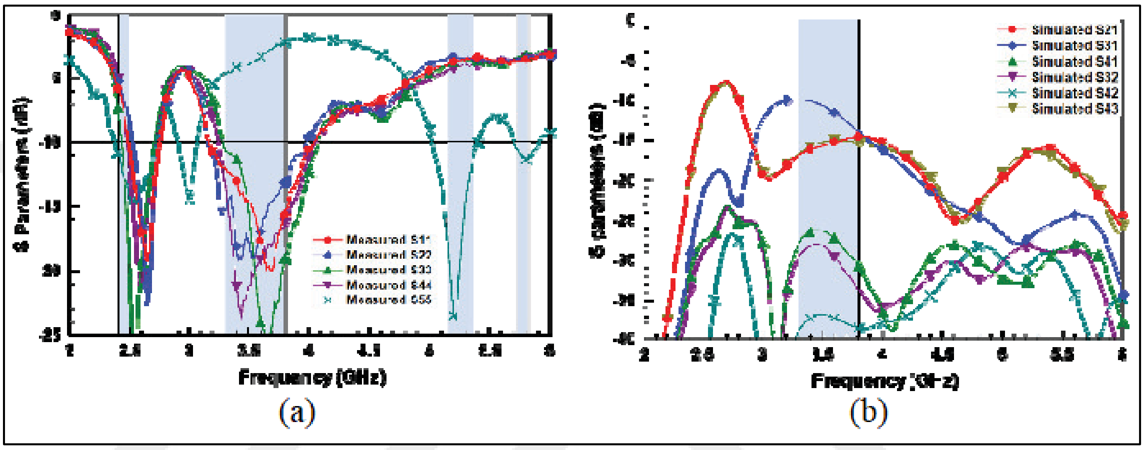
Table 0.5: Loop antenna parameters

Parameter	L	L1	L2	L3	
Unit (mm)	15.8	2	5.3	5.5	
Parameter	W	W1	W2	W3	W4
Unit (mm)	10.3	4.8	3.8	4	4.5

The antennas use the FR4 substrate and utilize the system ground. The two MIMO antennas are for C-band operations, while the loop antenna is for WLAN frequency band, while also doubling as an isolating element between the two MIMO antennas.

Figure 0-10 shows the S-parameters of the antenna. The measured results were all less than -10 dB at the frequency bands of operation. These results, along with the antenna design, make it sufficient for deployment in laptops.

Figure 0-10: (a) S11 to S44 and (b) S21 to S43

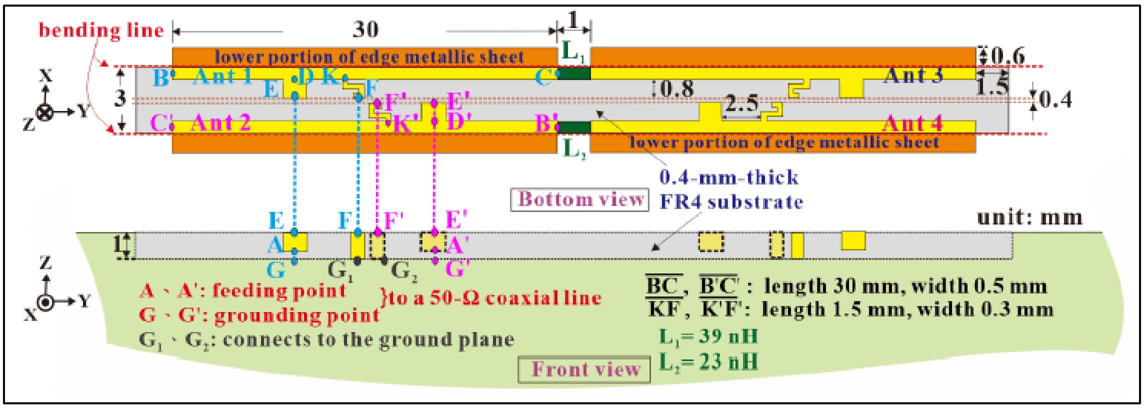


2.5. Compact Four-Element MIMO Antenna System for 5G Laptops

This paper discusses the design of a dual band MIMO antenna for use in laptops (Chen, et al., 2019). The system is composed of four three-dimensional inverted-F antennas (IFA) and utilizes a 0.4 mm thin FR4 substrate. The antenna operates at the 5G frequency bands 3.3 to 3.6 GHz and 4.8 to 5.0 GHz.

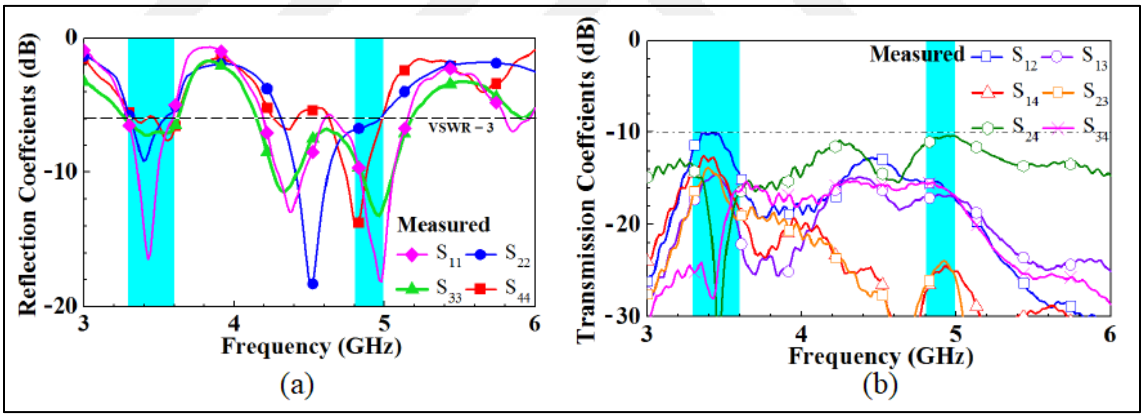
The design in Figure 0-11 shows the structure of the antenna system. Each of the four antennas is constructed on the substrate, which here takes a T-cross sectioned shape. The display ground of the laptop acts as the ground for the system, which the antennas are symmetric over, with their short-circuit points drawing near each other. This is to create a form of short-circuit decoupling.

Figure 0-11: Structure of the four element MIMO antenna



The S-parameters are highlighted in Figure 0-12. The reflection coefficient displays that MIMO antenna system is able to operate at the designated frequencies, as they all produced return loss less than -10 dB. While the transmission coefficient meets the isolation requirements.

Figure 0-12: S-Parameters of the four element MIMO antenna



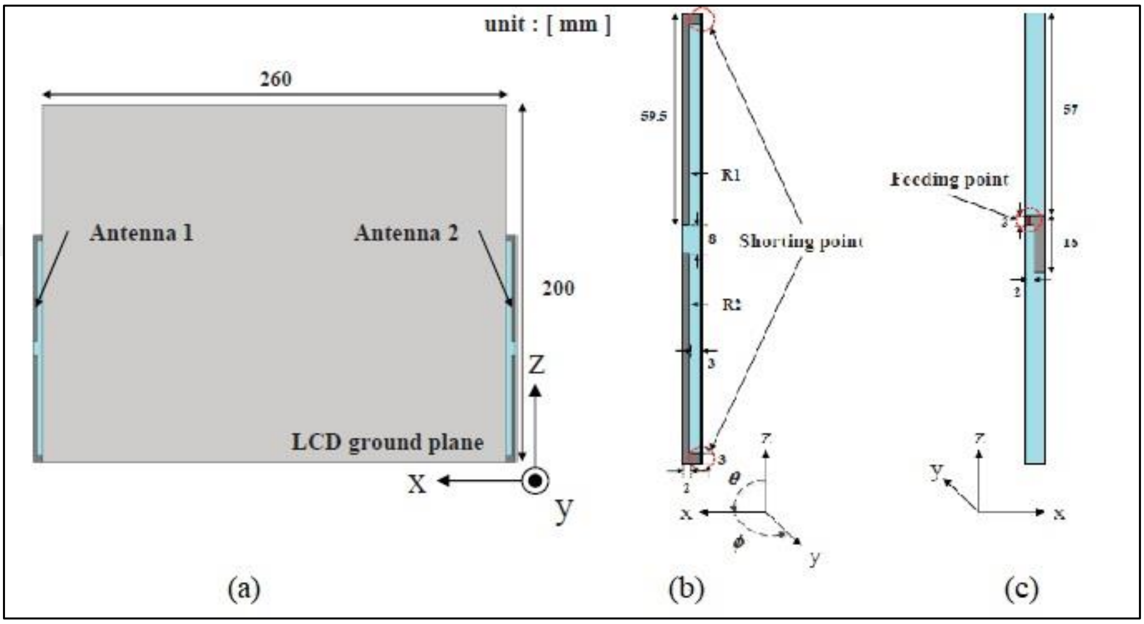
The antenna produced was roughly compact, with a dimension of 1.4 × 64 × 3 mm^3, which makes it deployable in modern laptops with narrow bezels. It operates at two wide frequency bands that are used in 5G applications.

2.6. Multiband LTE MIMO antenna for laptop applications

A MIMO antenna that operates at four LTE bands (LTE12, LTE13, LTE14 and LTE17) and composed of two planar inverted-F antennas (PIFA) as its respected elements (Lee, et al., 2011). Each element has a dimension of 127 × 5× 1 mm^3. The Aforementioned LTE bands resonate at the following frequencies:

- LTE12: 698 to 746 MHz
- LTE13: 746 to 787 MHz
- LTE 14: 758 to 798 MHz
- LTE17: 704 to 746 MHz

Figure 0-13: Structure of the LTE MIMO antenna with (a) top view (b) radiating element view and (c) feedline view



The LTE antenna is designed to fit into a laptop, and would be mounted on its LCD screen as represented by a 260 × 200 mm^2 FR4 substrate plane with 1 mm thickness. The first antenna element resonates at the higher frequency bands with the second antenna element resonates at the lower ones.

Figure 0-14: Simulated (a) S-parameters and (b) correlation coefficients

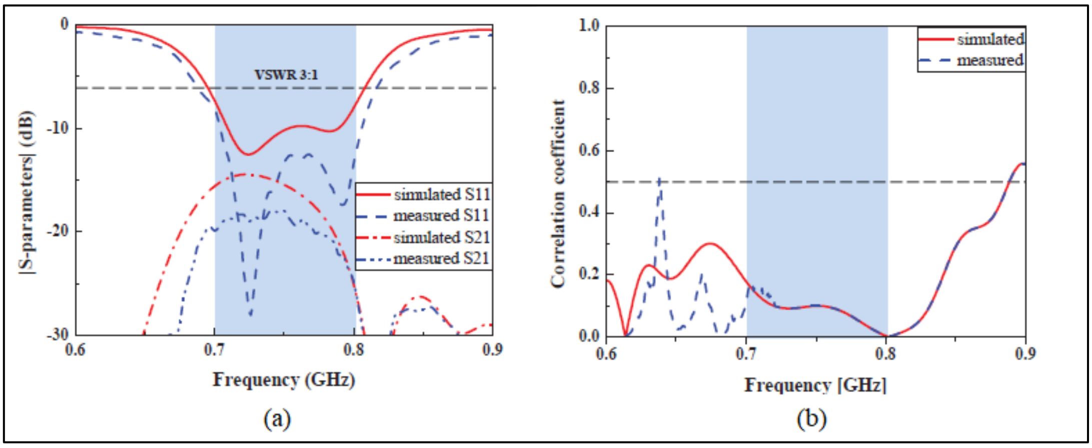
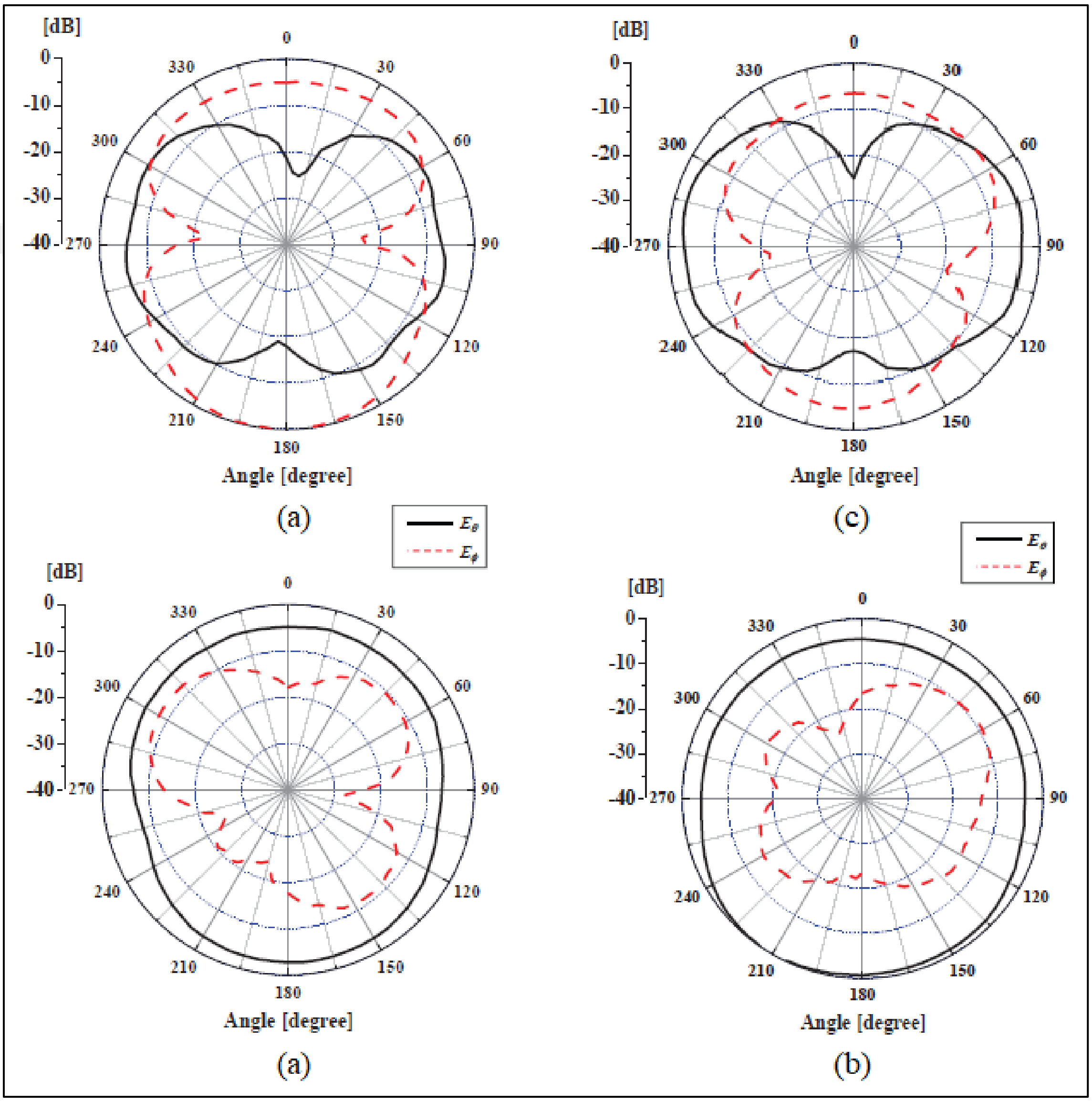


Figure 0-14 shows the S-parameters and correlation coefficient of the LTE antenna. The simulated results proved that the antenna was able to operate at the desired frequencies, as seen in the S-parameters graph. In addition, it had a good isolation of more than 15 dB at both ends of the antenna.

Figure 0-15: Radiation pattern of the LTE antenna at (a) z-y plane 725 MHz, (b) x-y plane at 725 MHz, (c) z-y plane at 785 and (d) x-y plane at 785 MHz



The produced radiation patterns are highlighted in Figure 0-15, showing omnidirectional radiation patterns in the horizontal plane, combined with an efficiency that is only slightly above 60%.

2.7. Dielectric Substrate

A dielectric is a substance with poor electric conductivity. It includes glass, ceramics, porcelain, and plastic, among others. What makes a dielectric better than others is how small its dielectric loss is.

The dielectric substrate part exists right below the conducting surface. The reason for using dielectrics in antenna design is because of its lossy characteristics that help improve stability and efficiency, as well as play a role in decreasing the antenna's size. When the antenna is excited, the dielectric layer assists in producing a time varying electric field, and a propagating electro-magnetic field, causing a boost for the antenna's radiation.

There are many types of dielectric substrates, like Bakelite, FR4, Taconic, etc… The most prevalent types are FR-4 and Rogers.

FR-4: FR stands for "flame redundant". This substrate is made up of woven fiberglass cloth with a flame resistant epoxy resin binder. It is a popular choice as an electric insulator because of its mechanical strength and resistance towards humidity. This composite material has great characteristics, but still falls a little short in terms of loss.

Rogers: in layman's term, Roger's core is the FR-4. However, it is laminated with copper. Roger's substrate is more expensive, but is also more efficient at high frequencies, and has an overall low dielectric loss, making it a popular go-to for building RF PCBs

2.8. Antenna Fabrication

Fabrication requires an antenna printing machine that takes in a PCB sheet (fiberglass board cladded in copper) and prints the shape of the antenna onto it. We print the design on a piece of vellum and place it below an unused PCB inside a PCB printer. The PCB printer takes care of the etching of the design onto the PCB, and by the time it finishes, the structure of the antenna will be etched on the PCB.

2.9. Literature Synopsis

This chapter includes five different scientific papers that touch on the design and analysis of MIMO antennas that can be integrated into modern laptop computers. Each of the mentioned antennas has its own method to achieve its specified requirements, which depended on external structure and/or size.

Table 0.6: Literature review comparison

Antenna	Area	Resonant frequency	Material
2.1	5 × 30 mm^2	3.4 – 3.6 GHz 4.8 – 5 GHz 5.15 – 5.825 GHz	FR4
2.2	35 × 9 mm^2	2.4 GHz 5.15 – 5.825 GHz 3.4 – 3.6 GHz	FR4
2.3	35 × 7 mm^2	2.4 GHz 5.15 – 5.825 GHz 3.4 – 3.6 GHz 4.8 – 5 GHz	FR4
2.4	5 × 45 mm^2	3.3 – 3.8 GHz 2.4 – 2.484 GHz 5.15 – 5.35 GHz 5.725 – 5.825 GHz	FR4
2.5	1.4 × 64 mm^2	3.3 – 3.6 GHz 4.8 – 5.0 GHz	FR4
2.6	127 × 5 mm^2	0.689 – 0.787 GHz 0.758 – 0.798 GHz	FR4

While different from PEC, the use of FR4 seems predominant in these types of antennas. The results aforementioned in Table 0.6 will be used as a reference to assist in the design of the 5G laptop MIMO antenna presented in this thesis. This will assist in giving higher results and producing an antenna that rivals its modern counterparts.

Chapter 3

Data and methodology

This chapter discusses the choices considered for the implementation of the design of the antenna, from its substrate to its geometry. It includes the numerous alterations the antenna goes through to achieve the required results, and finishes off with a presentation of its final design and features.

3.1. Components Used

The choice of the dielectric substance is detrimental for the performance of the antenna, especially in the case of a microstrip antenna. As the dielectric substance is characterized with low electric conductivity, it can include anything from glass, ceramics, porcelain, etc. The dielectric substrate is positioned right below the conducting surface of the antenna. The reason for using dielectrics in antenna design is because of its lossy characteristics that help improve stability and efficiency, as well as decreasing the antenna's size. When the antenna is excited, the dielectric layer assists in producing a time varying electric field, and a propagating electro-magnetic field, causing a boost for the antenna's radiation.

Through the comparison from the literature review, and the analysis of the intended performance of this laptop antenna and its need to propagate at frequencies that are relatively low when compared to other applications, the dielectric of was FR-4 (FR "flame redundant"). This substrate is constructed from woven fiberglass cloth with a flame resistant epoxy resin binder. It is a popular choice as an electric insulator because of its mechanical strength and good resistance towards humidity. This composite material has therefore competitive characteristics, and match the requirements of the proposed antenna in this thesis.

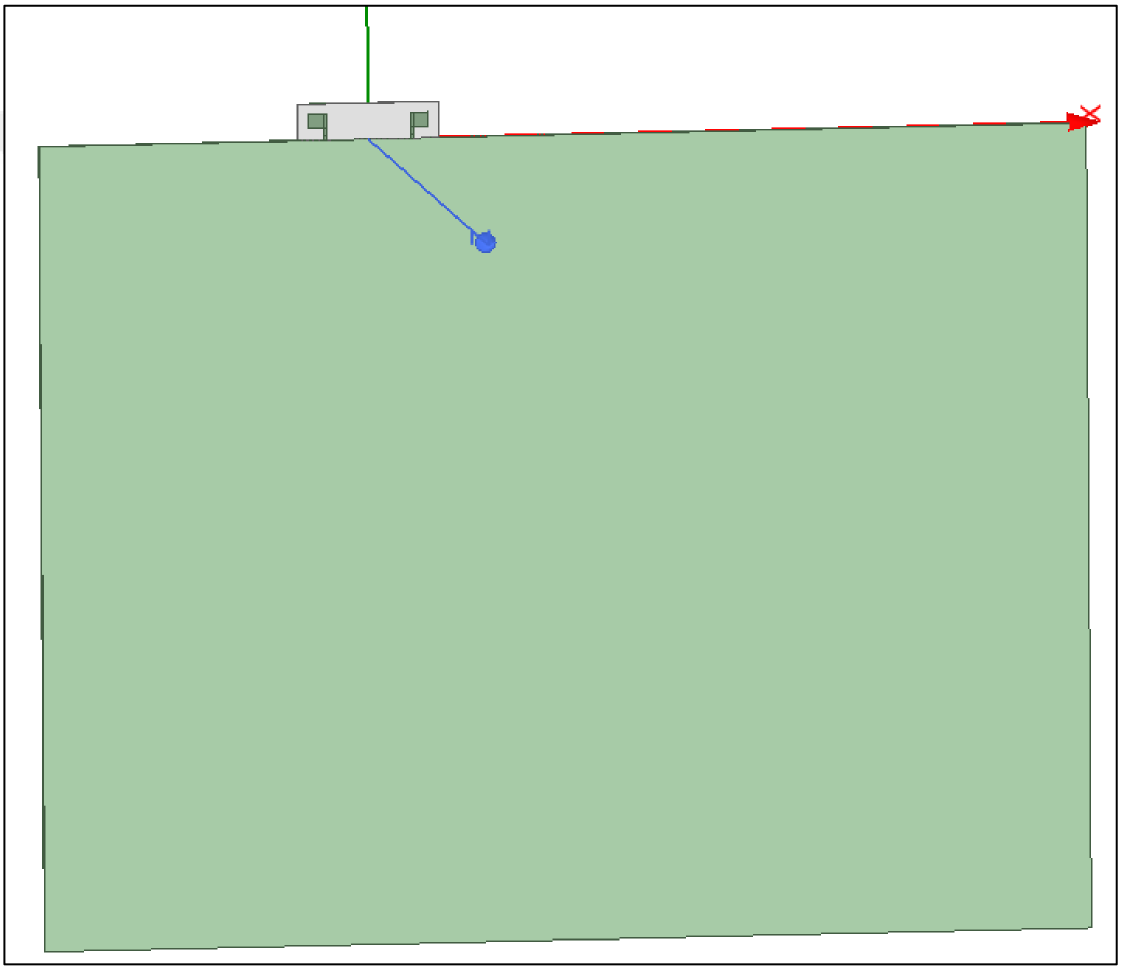
The laptop's internal structure will be used as the designated ground plane of the microstrip antenna. Meanwhile, the antenna's metallic patch will initially take on a rectangular shape, but may be subject to numerous alterations in order to achieve higher-level results.

3.2. Design Development

The start of the design is a rectangular microstrip antenna with two patches on each sides. The antenna itself is positioned on the outer edge of the laptop, third the length's distance away from the corner.

Figure 0-1 presents a demonstration of the shape of the antenna and how it is positioned with respect to the laptop.

Figure 0-1: Abstract laptop shape with antenna positioned on its side



This is the basic design attained through antenna theory analysis. It should therefore produce linear polarized waves. This, coupled with the fact that its attained results might fall behind what this thesis sets to produce, means that the design will definitely see further advancements.

Figure 0-2 and Figure 0-3 show the antenna up close, from both the upper side and the ground plane side, respectively. Each of the two rectangular patches is fed through a transmission line from their inner sides.

Figure 0-2: Top layer of the antenna

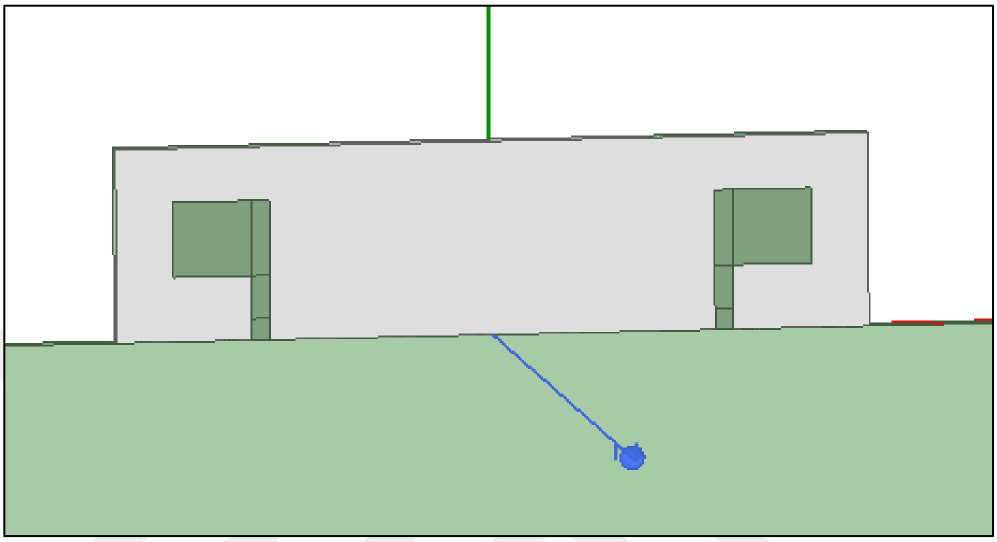
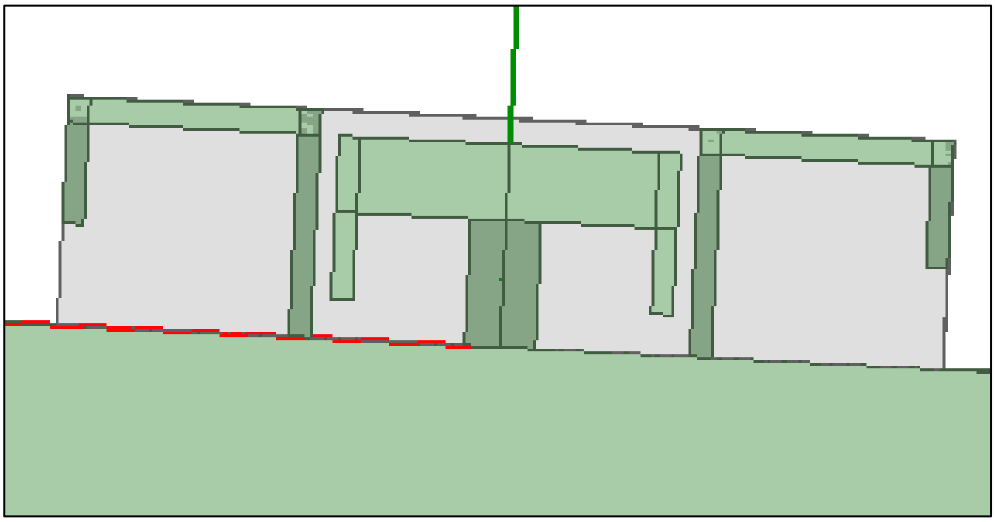
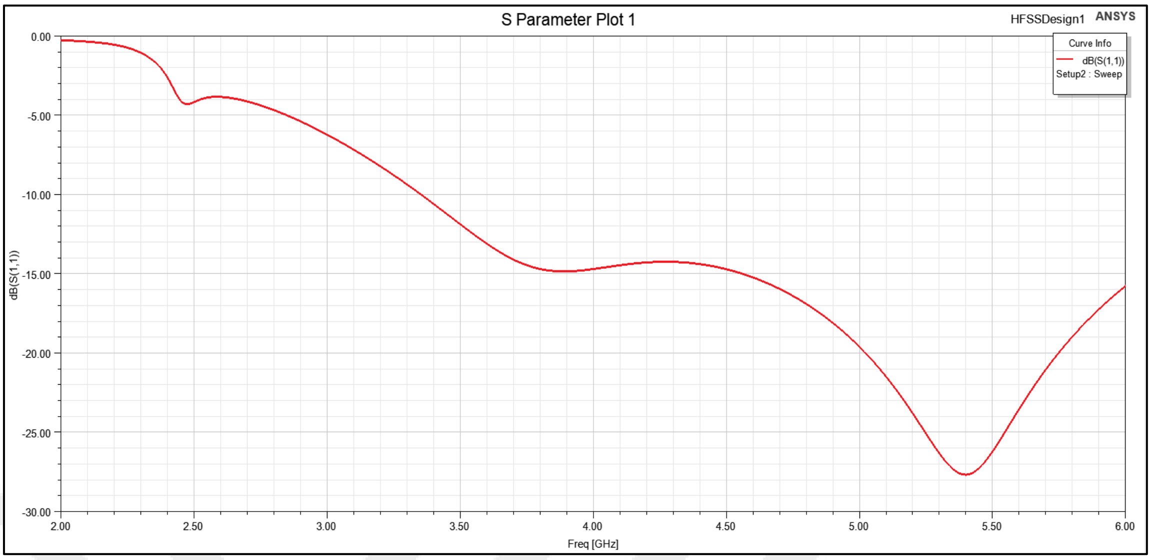


Figure 0-3: Bottom layer of the antenna



This essential antenna design was constructed on the CST software for analysis. Using CST, we attain a simulation of this antenna's S11 parameters which are presented in Figure 0-4 in terms of decibels with respect to bandwidth.

Figure 0-4: S11 parameters of the inceptive antenna design



The simulated S11 parameter of the antenna gave a very good return loss of -28 dB, way lower than the highest required -10 dB. However, the antenna lacks sufficient bandgap. The antenna should at least propagate at a band near the 3 GHz mark and above.

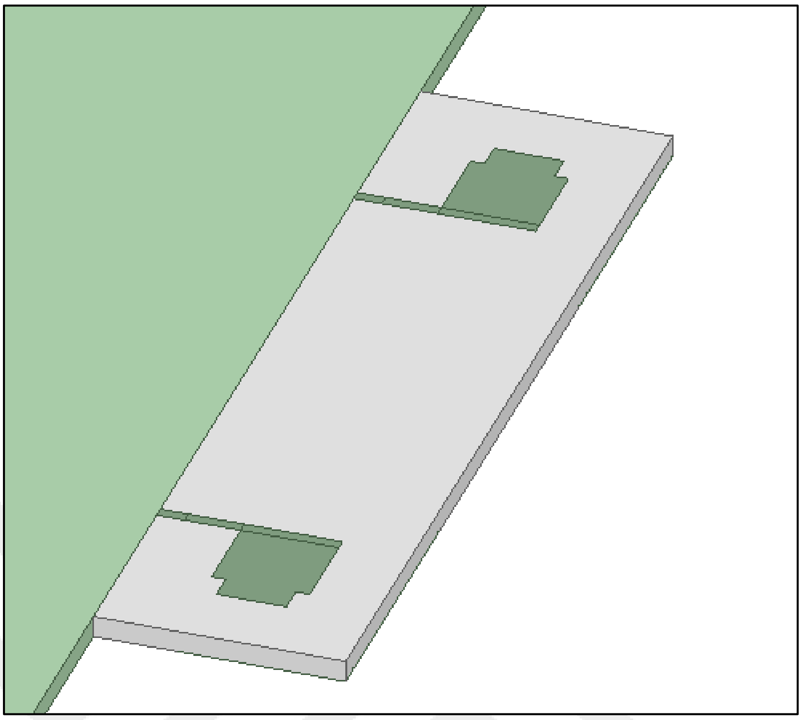
Therefore, the antenna needs further tinkering to achieve circular polarization and to preferably enlarge its band(s) of propagation. These alteration will be performed on the upper side of the antenna, with emphasis on the patches.

3.2.1. Slitting of corners

Experimentation was done on the top layer through the modification of the patch's design. This is composed of removing the outer corners of each patch, giving the patches a convex shape, as seen in Figure 0-5.

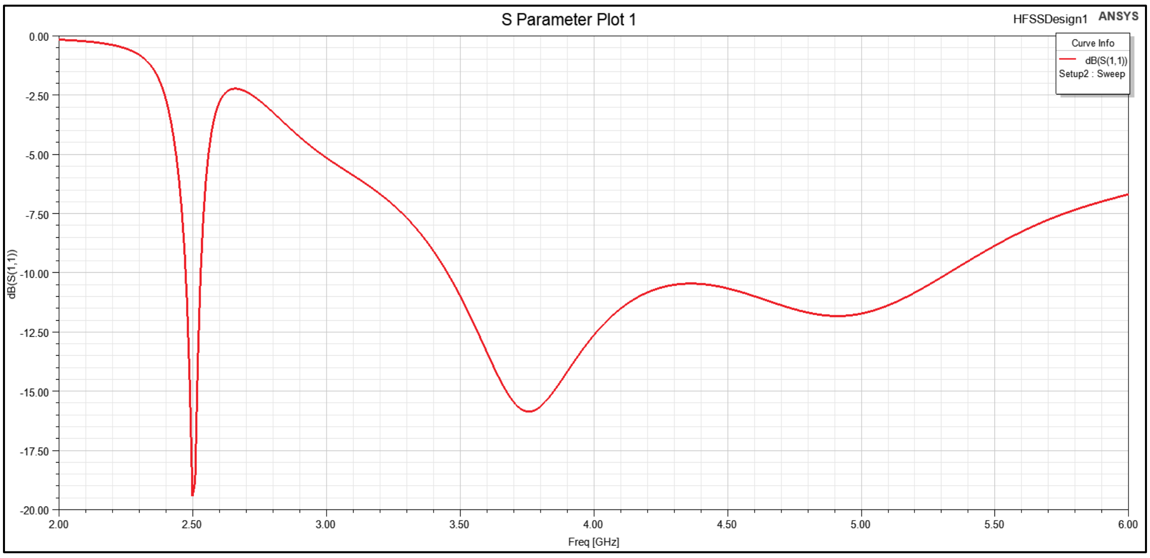
Each of the two patches has two corners carved out, these corners being the ones facing the outer sides of the antenna, opposite to the inner points that are connected to the transmission lines.

Figure 0-5: Antenna with patch corners



This alteration of carving out parts of the corners needs to be tested, and thus the amended design is simulated again on the CST software to attain its S-parameters. The S11 parameter presented in Figure 0-6 shows excessive change from the first simulation that used simple dual rectangular patches.

Figure 0-6: S11 parameter of the cornered patch antenna

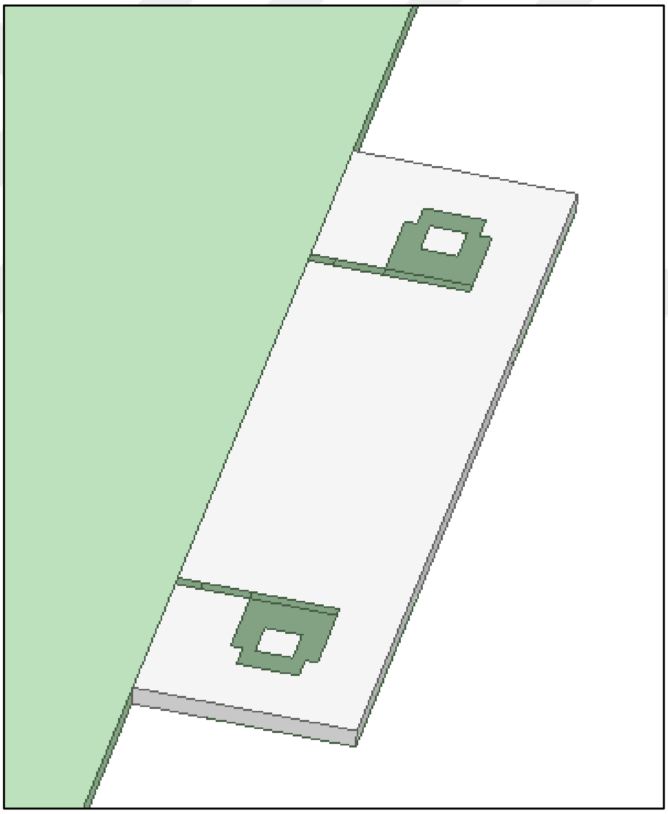


This time the antenna started closing in on producing dual resonance, but with the first one being before the 3 GHz mark, and the second one having inadequate characteristics. In addition, similar to the initial simulation, the antenna did not manage to produce circularly polarized waves.

3.2.2. Implementation of slots

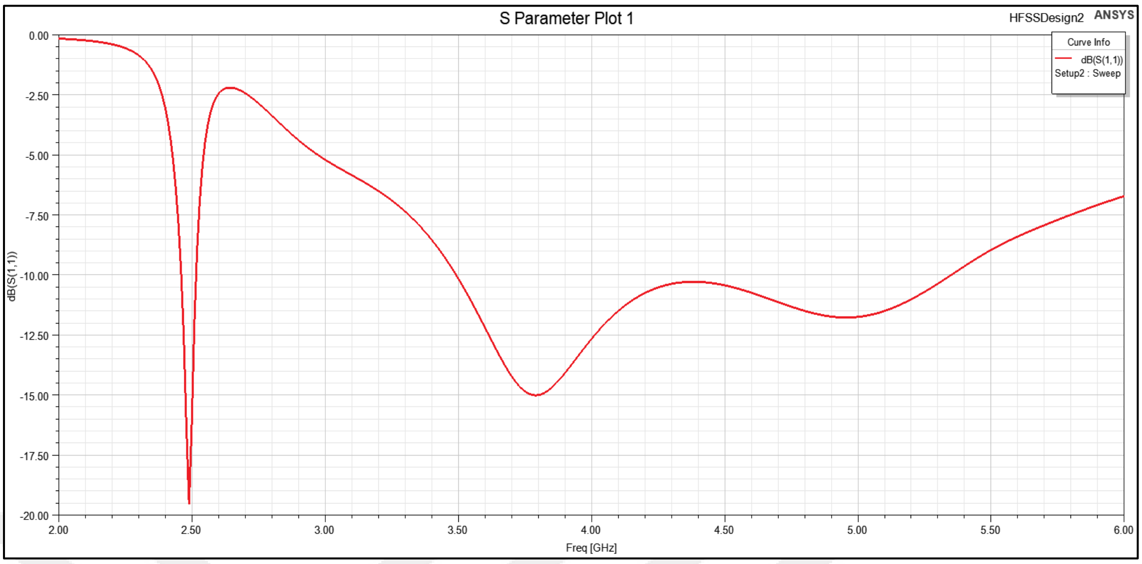
The addition of slots is seen as one of the popular ways to implement circular polarization for an antenna. The slot's shape and position play an important role on the effects of the produced wave. The slot is of rectangular shape and, just like previously, it is applied concurrently to both patches of the microstrip antenna.

Figure 0-7: Slotted antenna design



Like previously conducted, the antenna's S11 parameter is simulated again on CST and presented in Figure 0-8. This time, there was surprisingly minimal difference, with only a little change in the return loss of the second resonance.

Figure 0-8: S11 parameters of the slotted antenna



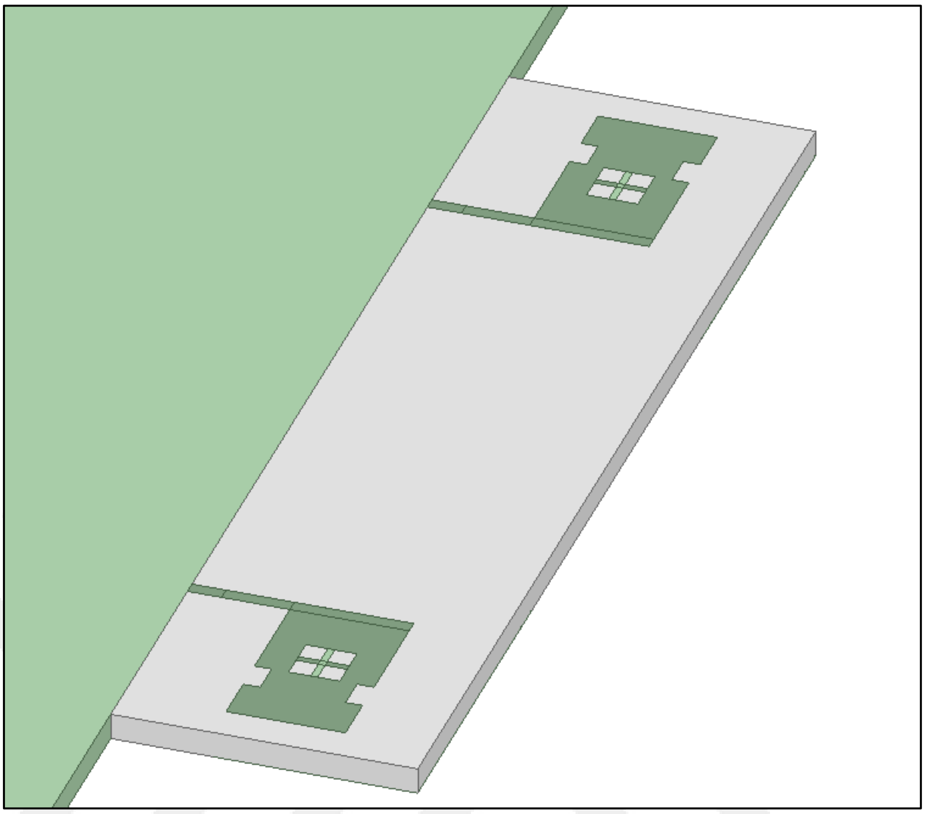
This presented antenna also came out short in terms of the set goals of this research. As the numerous alterations have failed to present an antenna that produces circularly polarized waves, more alterations needed to be studied and executed in the hopes of attaining the demanded results.

3.2.3. Addition of crosses inside the slots

The geometry of the antenna witnessed further alterations on both the corners and the previously added slot. As for the corners, extra padding was added, making the patch look like a larger rectangle. This made the previously slit off corners of the patch to be now located at almost third the rectangular patch's length.

As for the slot, while its position remained fixed, cross-like strips were added intersecting the center of the patch. The strips are thin, with one connecting the width of the rectangular slot, and one connecting the length of the slot.

Figure 0-9: Final design



This upgraded antenna's interior has a square slot of dimensions 1.50 × 1.50 mm^2, therefore the inner crosses share the same length. Each of the rectangular patches has a dimension of 3.50 × 6.0 mm^2 and the slotted side is at 1.0 mm in length.

This presented alteration produced noticeable dual resonance as spectated in the S11 graph shown Figure 0-10. The first resonance is at around 3.30 GHz with a -20.8 dB return loss, while the second one came out at 4.85 GHz with a return loss of -23.2 dB. The resonance bands comply with the set requirement of being above the 3 GHz band, while the return losses both came out favorable at way below the -10 dB mark.

Figure 0-10: S11 parameters of the final design

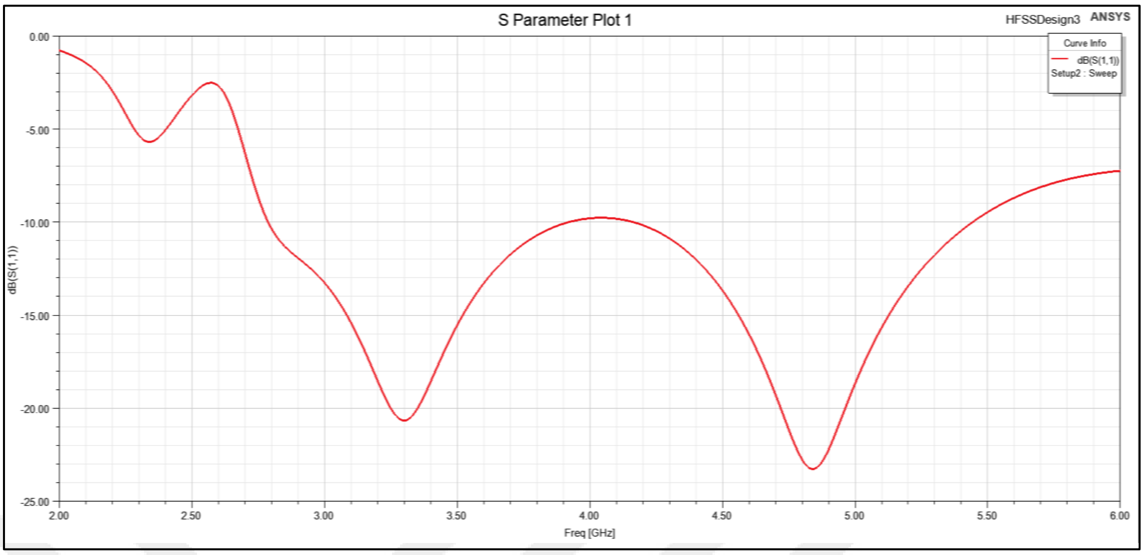
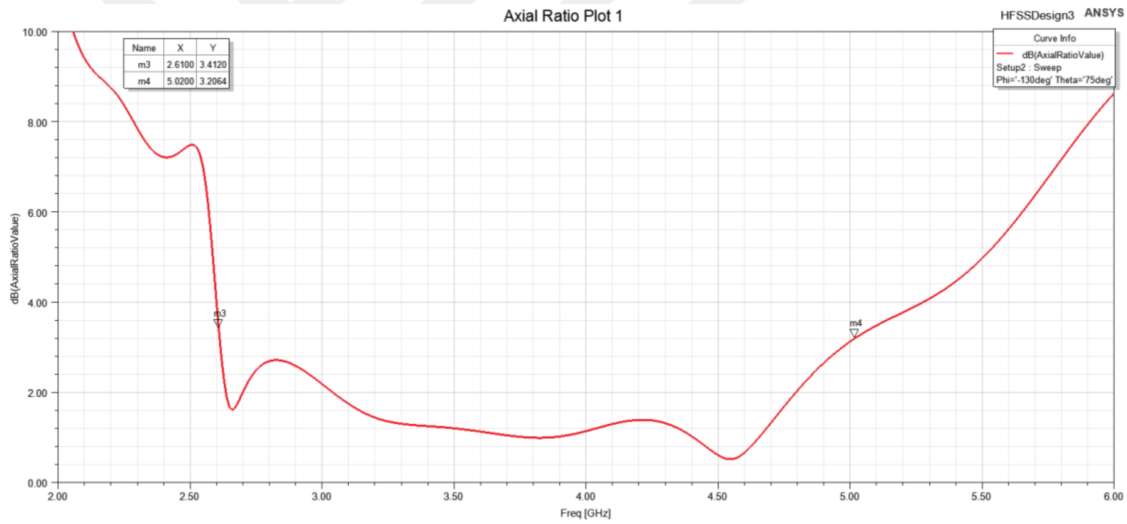


Figure 0-11: Axial ration of the proposed antenna



This design also finally managed to accomplish the circular polarization of the produced waves, causing a breakthrough for this research. Thus, the simulation of the radiation pattern is presented below. The produced gain of the antenna came out at a decent 5 dB through CST's simulation with an axial ratio slightly below 3 dB.

Figure 0-12: Radiation pattern of the final design

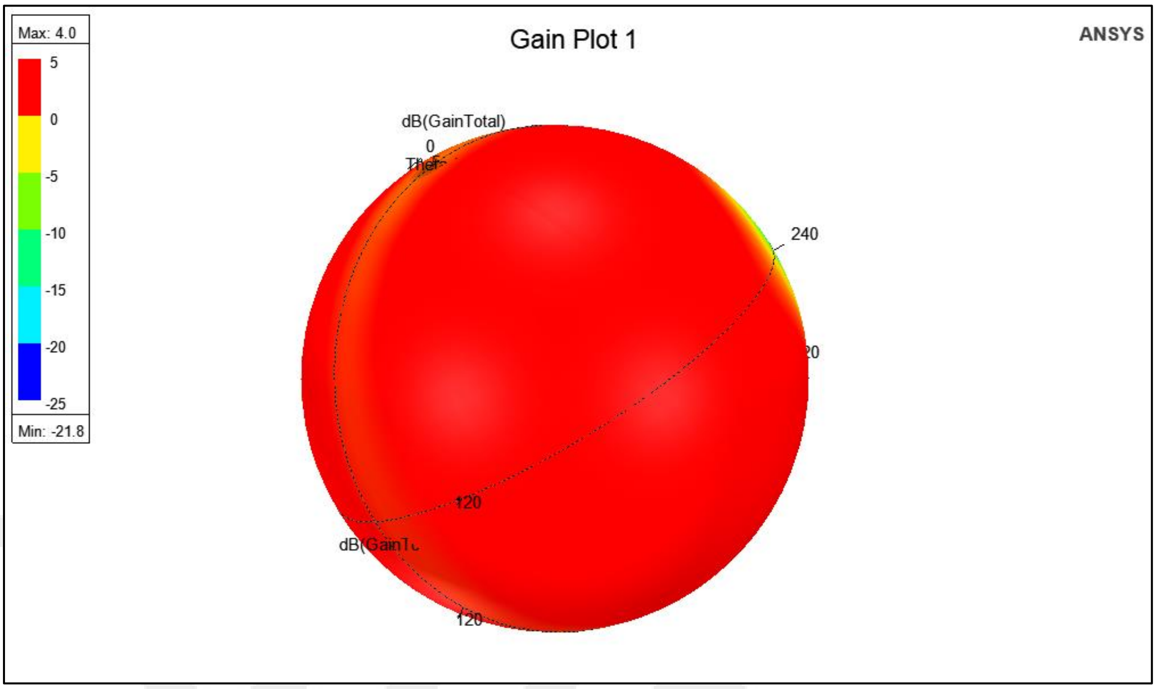
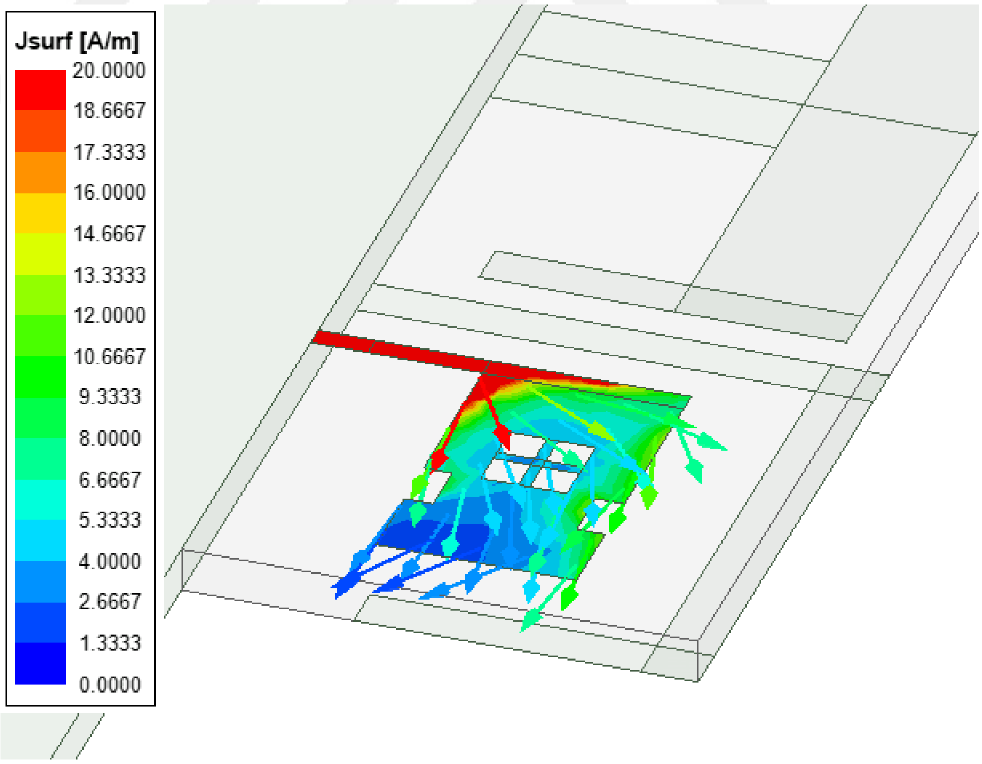


Figure 0-13: Current distribution of the final design



3.2.4. Development Summary

The chronology of the development of the antenna included numerous alterations to the design of the antenna. These alterations were done through utilizing a combination of research of previous work and constant trial and error through simulation. The simulation proved useful to compare results and further improve the design. Further additions were included based on the literature reference of sub-chapter 2.2, which originally contained similar features to the antenna presented in this thesis.

The final design that contains the combination of all the mentioned concepts combined consists of a dual-patch microstrip antenna with each patches being identical as they include:

- Rectangular slot at the center
- Cross-shaped stub within the slot
- Slotted area at third the patch's length

Figure 0-14: Final design top view

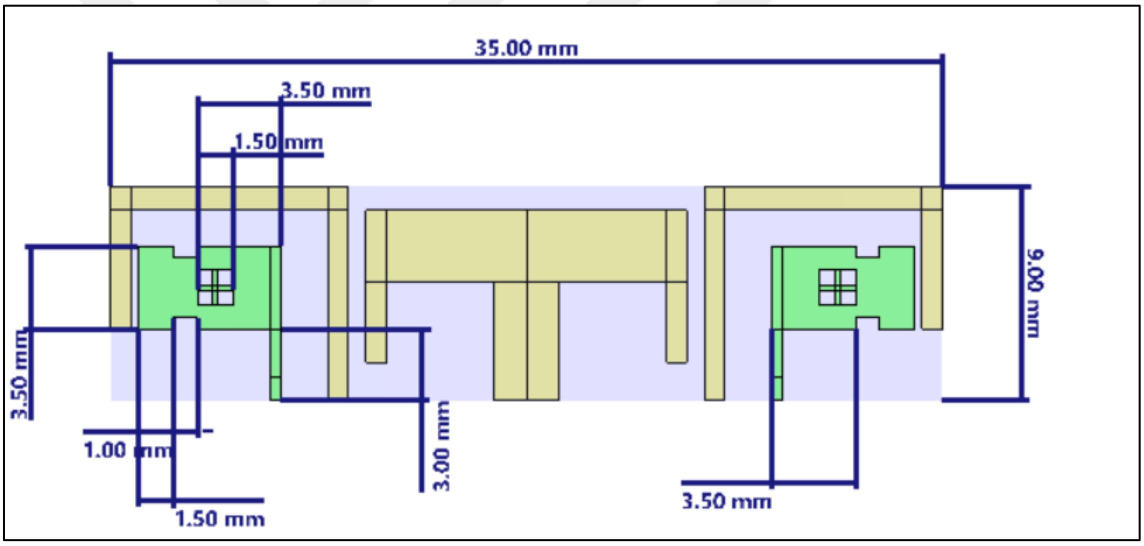
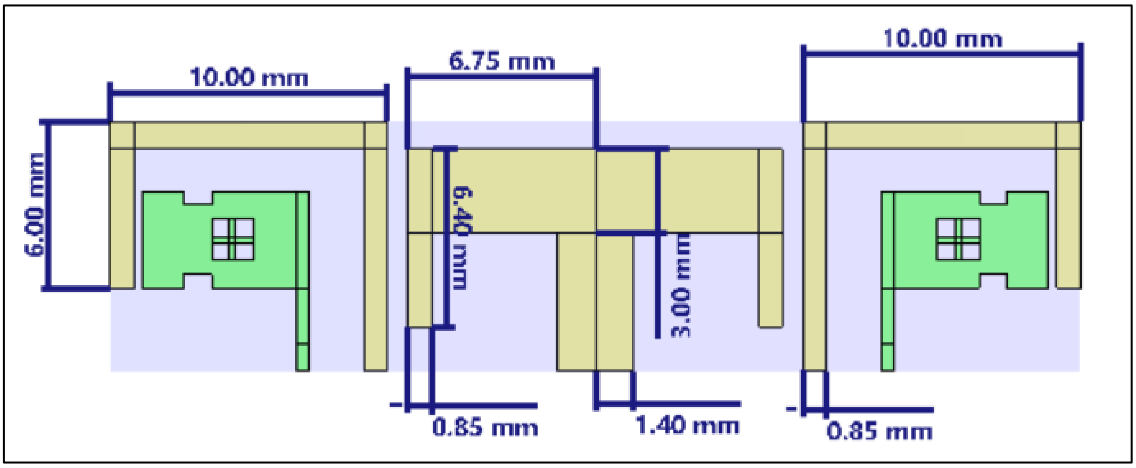


Figure 0-15: Final design bottom view



The top and bottom views of the antenna presented in Figure 0-14 and Figure 0-15 include the dimensions of the antenna as well as all of its interior components. The antenna came out at a suitable size for implementation within modern laptops. The final design was successful at producing circular polarization with dual resonance and a gain of 5 dB.

Chapter 4

Findings and discussion

This chapter discusses the attained results of the antenna presented in the thesis and checks how it holds up through comparison with other antennas of its caliber and with similar intended use.

4.1. Antenna Comparison

The obtained device is a MIMO circularly polarized antenna designed for the sake of implementation within laptop computers and confines with 5G standards. The obtained antenna boasts of dual resonance. Its results were then compared to the results of its previous designs and then to the results of the other researched antennas.

4.1.1. Comparison of all conducted antenna designs

The antenna went through three chronological steps:

- Implementing corner slits to the initial design
- Implementing slots
- Addition of inner crosses

These steps are labeled as steps 1, 2, and 3 respectively, with step 3 marking the final design of the antenna.

A comparison of these three steps includes presenting them on two graphs, one for analyzing the S11 that is presented in Figure 0-1, and one for the axial ratio that is presented in Figure 0-2.

As stated in the 3.2.4Development Summary, Step 3 provided with the most ideal results and was therefore taken as the final design of the antenna to be implemented in this paper. This was proven by the antenna's successful propagation at the desired frequencies that are after the 3 GHz mark.

Figure 0-1: S11 comparison of the three design steps

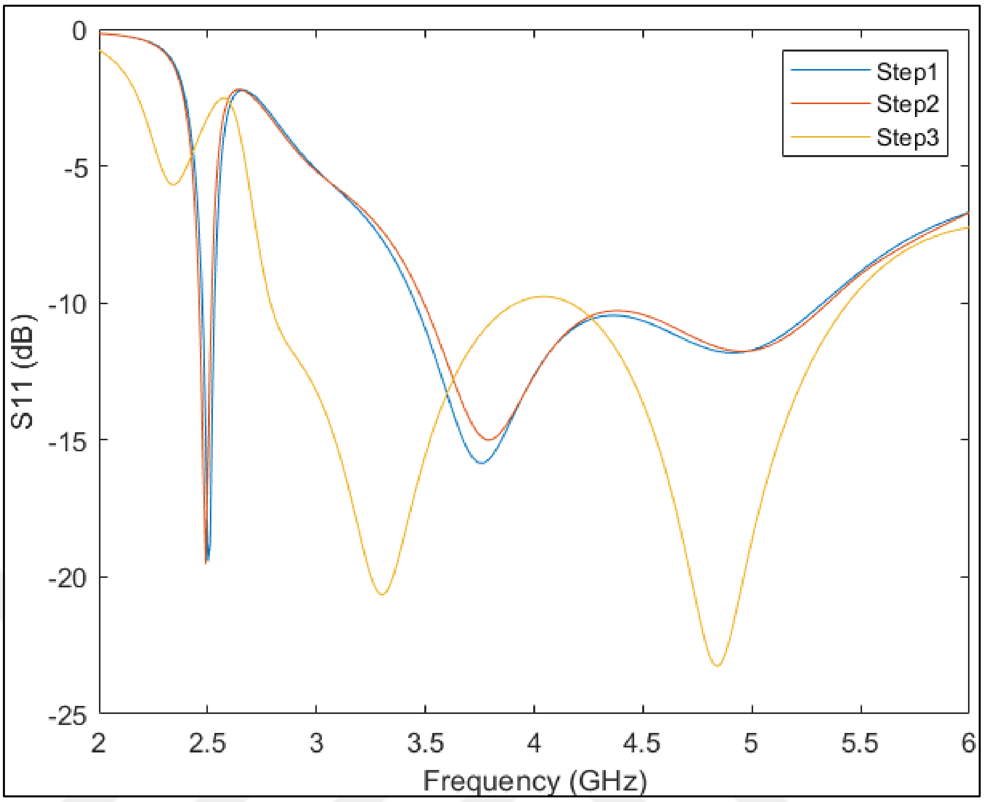
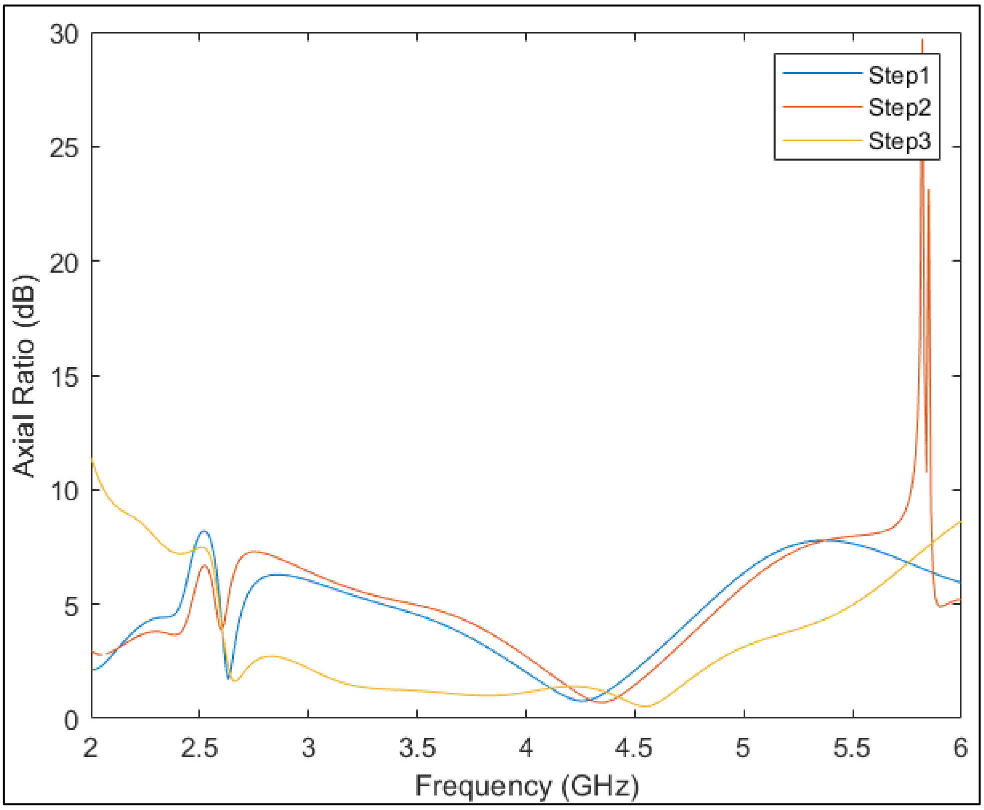


Figure 0-2: Axial ratio comparison of the three design steps



4.1.2. Comparison of antenna with literature review antennas

The antenna utilized similar designs and dimensions that were applied in the antenna mentioned in section 2.2, but extended it with extra design options and features to obtain its own unique set of results. Further comparison can be found in Table 0.1 that is based on Table 0.6 from the Literature Review section.

Table 0.1: Analysis of the presented antenna with respect to the literature review

Antenna	Area	Resonant frequency	Material	Polarization
2.1	5 × 30 mm^2	3.4 – 3.6 GHz 4.8 – 5 GHz 5.15 – 5.825 GHz	FR4	Linear
2.2	35 × 9 mm^2	2.4 GHz 5.15 – 5.825 GHz 3.4 – 3.6 GHz	FR4	Linear
2.3	35 × 7 mm^2	2.4 GHz 5.15 – 5.825 GHz 3.4 – 3.6 GHz 4.8 – 5 GHz	FR4	Linear
2.4	5 × 45 mm^2	3.3 – 3.8 GHz 2.4 – 2.484 GHz 5.15 – 5.35 GHz 5.725 – 5.825 GHz	FR4	Linear
2.5	1.4 × 64 mm^2	3.3 – 3.6 GHz 4.8 – 5.0 GHz	FR4	Linear
2.6	127 × 5 mm^2	0.689 – 0.787 GHz 0.758 – 0.798 GHz	FR4	Linear
Presented antenna	35 × 9 mm^2	3.30 GHz 4.85 GHz	FR4	Linear to Circular

4.2. Antenna Characteristics

The MIMO laptop antenna implements cross-section slots and stubbed corners to achieve MIMO and circular polarization characteristics, and holds a small size that is sufficient for it to be applied within modern laptops with ease.

The axial ratio of the produced antenna came out below 3 dB, accomplishing the requirement needed for an antenna to be deployed in circular polarization applications, which include areas where waves are harder to intercept. This is because the characteristics circularly polarized waves give them better interception range and therefore become more suitable for propagation over long regions.

Chapter 5

Conclusion

To conclude our findings, this thesis studied the implementation of a microstrip MIMO antenna that was designed for the purpose of implementation within laptop computers. The antenna boasts with a small size and the production of circularly polarized waves, which are suitable for long-distance communications.

Figure 0-1: 3D shape of final design

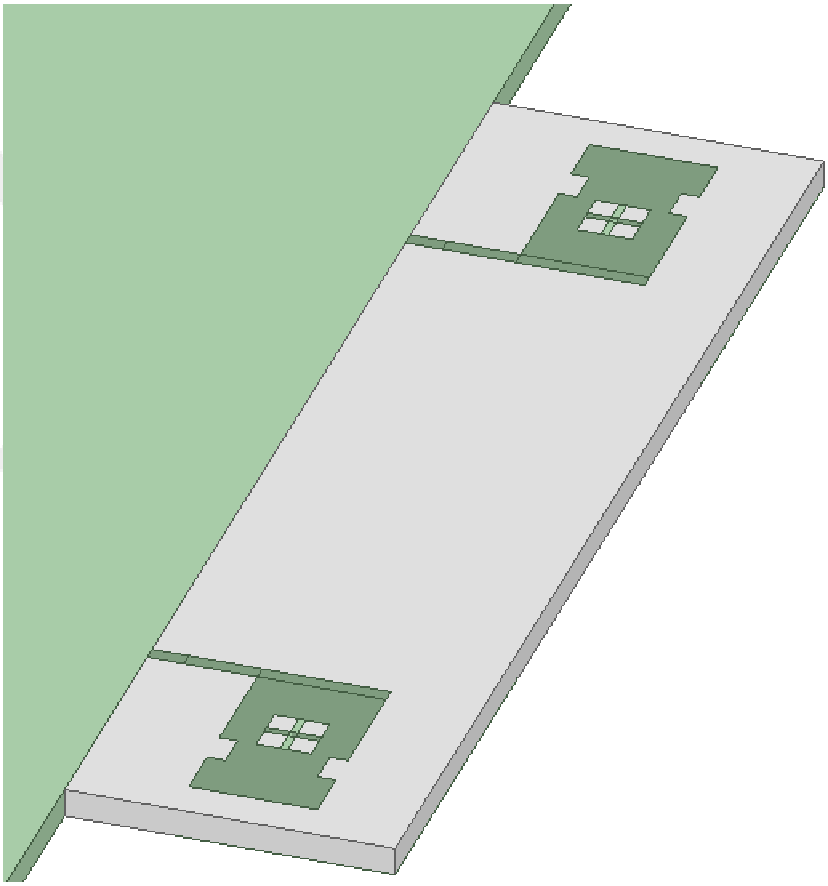
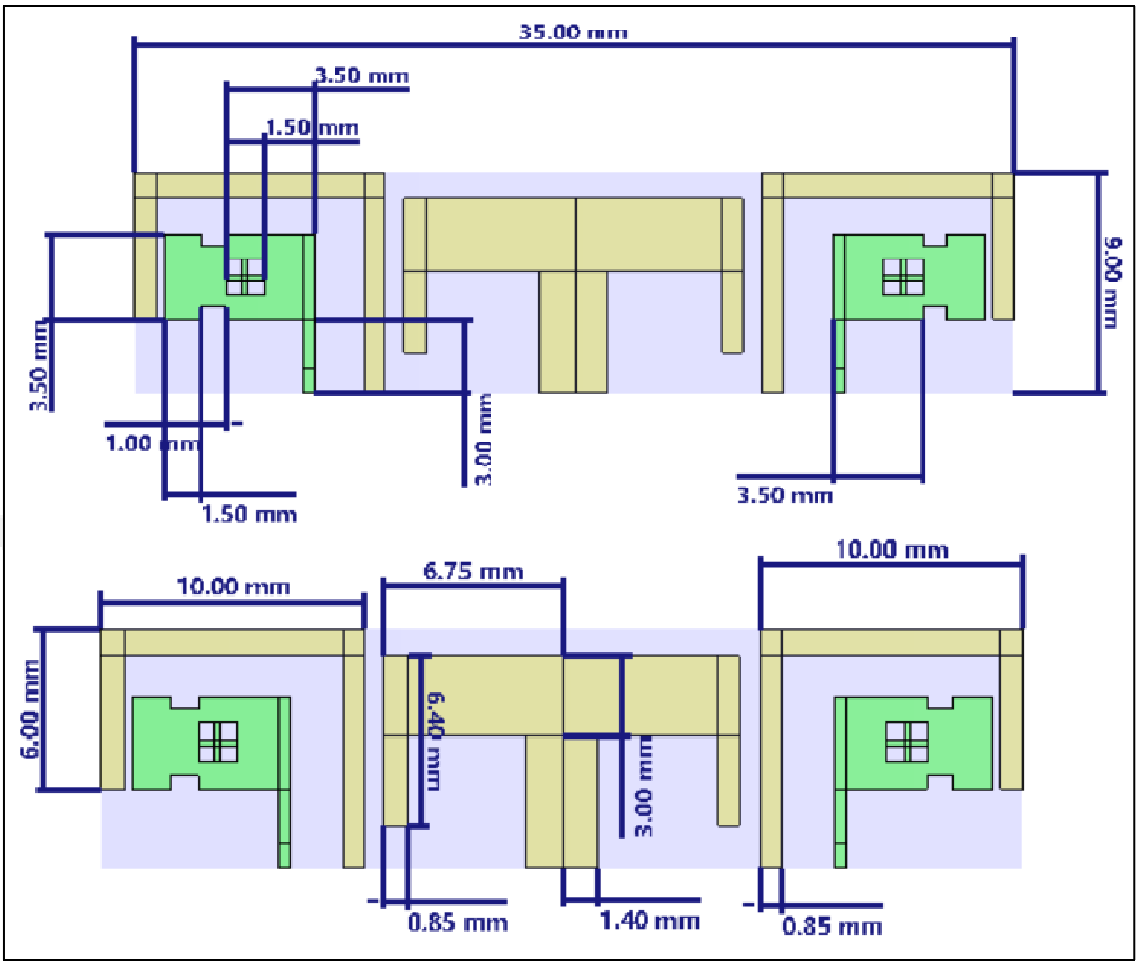


Figure 0-2: Top and bottom side of the presented antenna



Many previous antennas were studied in order to gain an idea on what constitutes a good MIMO laptop antenna. The presented antenna also went through multiple alterations until it reached its final ideal form and favorable characteristics. The alterations include the slitting of the corners of the antenna's patch layer, the implementation of slots within the patch, and the addition of cross-like shapes inside the patch for refining the axial ratio of the antenna. These alterations were compounded with each for the final design. The alterations and comparisons were performed through the simulation on the electromagnetic field simulation software CST.

The produced antenna is of a small rectangular shape with the dimensions of 35 × 9 mm^2, and a gain of 5 dB. It utilizes the FR4 dielectric as its substrate and the laptop's body as its ground. The antenna propagates at the 3.30 GHz and 4.85 GHz bands, with great return loss for both of them (20.8 dB and 23.2 dB respectively).

Putting in the antenna’s small size into account, it would be more expensive to manufacture as it requires special techniques. However, seeing its novel and satisfactory results, it should be able to enter the competitive market of antenna technology.

Chapter 6

Future Work

1. Publish this work as a paper.
2. Apply for a patent for the antenna designed.
3. Create a mathematical model to know exactly how to control the shift of frequency band.
4. Study the market needs and methods of fabrication.
5. Fabricate this antenna and release it to the market if possible.

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