ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

DESIGN AND SIMULATION OF FRACTAL-BASED RING ANTENNAS FOR 5G WIRELESS COMMUNICATIONS

M.Sc. THESIS

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

5G KABLOSUZ HABERLEŞME İÇİN FRAKTAL TABANLI HALKA ANTENLERİN TASARIMI VE SİMÜLASYONU

YÜKSEK LİSANS TEZİ

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ARALIK 2022

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Date of Submission :04 November 2022
Date of Defense :02 December 2022

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ABBREVIATIONS

dB	**:** Decibel
dBi	**:** Decibel isotropic
B.W.	**:** Band Width
MSL	**:** Microstrip Line
5G	**:** Fifth generation of wireless communications
VHF	**:** Very High Frequency
UHF	**:** Ultra High Frequency
UWB	**:** Ultra Wide Band
EM	: Electromagnetic

SYMBOLS

i	: Iteration factor
n	: Iteration number
λ	: Lambda (wavelength)
f	: Frequency
ε_o	: permittivity of free space
ε_r	: permitivity of dielectric
ε_{eff}	: Effective dielectric constant
c	: Speed of Light
S_{11}	: Reflection Coefficient

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DESIGN AND SIMULATION OF FRACTAL-BASED RING ANTENNAS FOR 5G WIRELESS COMMUNICATIONS

SUMMARY

After the rolling-out of 5G communication systems the develpement of smaller and more effective components are still on-going since it is always important to keep up with the development of the technology, therefore smaller and compact and easy to fabricate components are the main aim of the sicentific community these days. Since the 5G systems are somehow smaller than the old systems' components it arises the fact that the newly- designed components have to has space limitations during the design stages. In this work, by focusing on two of the main 5G bands which are the bands centered on 3.5 GHz and 7GHz three types of antennas were designed and implemented by using CST Microwave studio simulator. The antennas were designed using the fractal concept which charactarized by space-filling and self-similarity so that no need for an extra space when we already have a limited one. The design of the first antenna started by designing a cut-angles rectangular patch antenna that propagates at 3.5 GHz, then by copying and then scaling-down the same patch and later substracting it from the main patch we got a single ring cut-angles rectangular patch antenna that propagates at 3.5 GHz with a reflection coefficient of -19 dB and a gain of 2dBi. The second antenna was created by scaling-down the full ring of the first antenna and create a similar inner ring that propagates at 7 GHz center frequency and has a bandwidth between 6.25-8.1 GHz, this antenna is able to propagate at two different 5G frequency bands centered at 3.5 GHZ and 7 GHz respectivey. This antenna has a reflection coefficient S_{11} of around -20 dB for both resonant frequencies of both bands, and has a gain of 2.29 dBi and 2.51 dBi for the two bands at their center frequency. All these antennas have a microstrip feeding line with a length of 16 mm which equal to something around λ/4 of the first band's center frequency, all the antennas have an FR-4 substrate thickness of 1 mm and a width of the feeding line of 1.6 mm so that together they provide a 50-ohm impedance at the input port which assure that most of the input port's waves are being propagated. Finally, in order to increase the gain a 4x1 antenna array was designed to propagate at the same bands, this array has two feeding ports that designed in an inverted way to improve the matching between the array elements, each port is connected to only two propagating elements by a tree shaped λ/4 length microstrip has a reflection coefficient of around -45 dBi and -35 dB for both bands at their center frequencies, respectively. This array antenna has also a gain for the 3.5Ghz centered band of 5.64 dBi for port 1 and 5.648 dBi for port 2, and for the 7 GHz band the gain was equal to 8.39 dBi and 8.4 dBi for port 1 and port 2, respectively.

5G KABLOSUZ İLETİŞİM İÇİN FRAKTAL TABANLI HALKA ANTENLERİN TASARIMI VE SİMÜLASYONU

ÖZET

Doğada bulunan karmaşık yapıları açıklamak için klasik geometrik yöntemler uygulanamazdı, bu nedenle Mendelbort kitaplarından birinde fraktaldan bahsetmişti ve o zamandan beri elektronikte şimşek, yaprak, kıyı kenarları ve gürültü gibi karmaşık doğaları açıklamak için yaygın olarak kullanılıyordu. sistemler. Bu fraktal geometrik şekiller, bilimsel açıklamalarda etkili bir şekilde kullanılabilecek tekrarlayan bir desen oluşturan parçanın bütünün ölçekli bir kopyası olduğu, kendi kendine benzerlik ve boşluk doldurma ile karakterize edilir. Bunu düzensizliği açıklamanın bir yolu olarak düşünebiliriz. örneğin aydınlatmaların bir ana gövdesi vardır ve daha sonra ana gövdeye benzer ancak daha küçük bir kopya olarak daha küçük olanlar ve ardından ana gövdeye benzer üçüncü daha küçük olanlar ve benzer parçalardan oluşan karmaşık bir şekil oluşturmak için alt aydınlatma vardır. Şekiller, benzer şekilde, ağaç yaprağı, tüm yaprak şeklini oluşturmak için tekrar tekrar küçültülmüş bir ana şekilden oluşur, başka bir örnek de kesirli şekilli kar tanesinde görebildiğimiz, parçalarının küçültülmüş bir kopyası olduğu yerde. daha büyük olanlar Bununla birlikte, tüm bu küçültülmüş şekillerin kendi yineleme faktörü ve yineleme sayısı vardır; burada yineleme sayısı, bu şeklin kaç kez küçültüldüğünü ve yineleme faktörü, bu şekillerin ne kadar ölçeklendiğini gösterir. Genellikle yineleme sayısı "n" ile ve yineleme faktörü "i" ile temsil edilir, bu nedenle kendi fraktalımızı oluşturmak istiyorsak "n"nin "i" tarafından kaç kez uygulanacağını seçmemiz gerekir. Fraktal şekiller doğrusal fraktallara ve doğrusal olmayan fraktallara ayrılabilir. Artımlı Fonksiyon Sistemi doğrusal olanı oluşturmak için kullanılır. doğrusal olanlara örnek olarak Koch eğrisi, Cantor eğrisi, Minkowski eğrisi, Sierpinski contası ve diğerleri verilebilir. Boşluk doldurma ve kendine benzerlik, fraktal şekillerin ana özellikleridir, örneğin bulutlar, şimşek, ağaçlar, kar taneleri ve kıyı şeritleri fraktal geometri kullanılmadan modellenemez. Aynı prensip, daha fazla elektrik uzunluğuna ihtiyaç duyulduğu ancak küçük bir hacmin mevcut olduğu anten tasarım endüstrisi gibi bazı uygulamalarda kullanılabilir. Fraktal şekiller, anten tasarımında uygun bir minyatürleştirme tekniği olarak kullanılabilecek çok benzersiz özelliklere sahiptir. Tüm fraktal şekillerin iki özelliği vardır; iterasyon faktörü 'i' ve iterasyon sayısı 'n', çünkü bunlar yinelemeli olarak üretilirler. Birkaç fraktal tabanlı mikroşerit yama anteni, tek kutuplular, UWB ve diğer birçok anten, yıllar içinde tasarlandı ve araştırıldı, çünkü bu tür fraktal tabanlı antenler, kompakt boyut, düşük seviye gibi normal eski moda klasik tasarıma göre tercih edilen bazı özelliklere sahiptir. profili, çok bantlı ve/veya geniş bantlı ve uygulanması kolay. Mikroşerit yama antenleri, en yaygın baskılı devre antenlerdir. Genel tasarımın tümü tek bir kazınmış baskılı devre olabilir. Bir yama anteni, adını temel olarak bir yer düzlemi üzerinde asılı duran metal bir yamadan oluşması gerçeğinden alır. Bir yama anteninde, yayılmanın çoğu yer düzleminin üzerindedir ve yüksek yönlü kazanca sahip olabilir. Mikroşerit antenler, şerit besleme hattı, dielektrik sabiti olan bir alt tabaka ve iletken bir zemin düzlemi olmak üzere üç ana parçaya sahiptir. Herhangi bir anten tasarlamaya başlamanın anahtarı, bu antenin hangi bantta

çalışacağını belirlemektir, çünkü tüm boyut ve malzeme seçimi antenin hangi frekans bandında çalışacağına bağlıdır. Bizim durumumuz için önerilen üç anten Bu bölümde ele alınacaklar, ana 5G bantlarından ikisi olarak kabul edilen 3.1 – 4.1 GHz ve 6.1 – 8.1 GHz bantları için önerilmiştir, 3.1 – 4.1 GHz bandı farklı bantlara ayrılmıştır, ancak bu alt bantların neredeyse tamamı -bantlar, 5G iletişim sistemlerinin çalışma spektrumu için gerçekten önemli kabul ediliyor. Özellikle Güney ve Kuzey Amerika'da uluslararası mobil telekomünikasyon (IMT) şimdiden bu bantlara kaydırılıyor. Ve henüz kullanılmadıysa, en azından kullanılmak üzere analiz ediliyor, aynı zamanda 5G orta bant spektrumu olarak da adlandırılıyor. Diğer önemli bant, gelecekteki 5G uygulamaları için çok umut verici olduğu düşünülen 6.5 ile 8.5 arasındaki bantlar olan Wi-Fi6 etrafındaki spektrum bandıdır. Herhangi bir fraktal şeklin oluşturulması iki faktöre bağlıdır; yineleme sayısı "n" ve yineleme sayısı fraktal şeklin kaç kez küçültüldüğünü temsil ettiği yineleme faktörü "i" veya yukarı ölçeklendirilmiş ve yineleme faktörü nasıl ölçeklendiğini tanımlar. Birkaç fraktal tabanlı mikroşerit yama anteni, monopoller, UWB ve diğer pek çok anten gibi yıllar içinde tasarlandı ve araştırıldı, çünkü bu tür fraktal tabanlı antenler, kompakt boyut, düşük güç gibi normal eski moda klasik tasarıma göre tercih edilen bazı özelliklere sahiptir. profili, çok bantlı ve/veya geniş bantlı ve uygulanması kolay. Minkowski ve Koch fraktalları mikroşerit yama anten tasarımlarında daha önce birçok araştırmada uygulanmış olsa da, iterasyon faktörü "i" değiştirmenin etkisi birçok araştırmada da incelenmiştir. Benzer şekilde, fraktal antenleri tasarlarken, ilk antenimiz için prosedür, çalışma bandını belirlemekle başlar, çünkü antenimiz 5G orta bandında yayılmaya yöneliktir, bu nedenle rezonans frekansı 3.5 GHz civarında olmalıdır. Antenin parametreleri, hangi anten tipine ve hangi bantlarda çalışacağına göre dikkatlice seçilmelidir, bizim durumumuzda seçilen tip mikroşerit yama antendir ve çalışma bandı 3.5 GHz'dir, bu nedenle besleme yöntemi olarak tasarımda basitlik ve kompaktlık sağlayan mikroşerit hat beslemesini (MSL) seçtik. Bununla birlikte, mikroşerit besleme hattının (Lf) uzunluğu, rezonans frekansının λ/4'ü civarında olmalıdır. Mikroşerit yama antenlerde bilindiği gibi birbirine kazınmış üç katmandan oluştuğu için ilk katman zemin katmanı, ardından altlık katmanı ve son olarak da en üstte yayılan yamadır. Ancak FR-4 substratı olan orta tabakanın kalınlığı 1 mm ve mikroşerit hattının genişliği 1.6 mm olarak seçilmiştir, böylece anten portunda birlikte 50 ohm'luk bir empedans sağlarlar. daha iyi yayılım için, bu mikroşerit hat besleme empedansı hesaplamaları mikroşerit antenlerin hesaplamalarına göre yapılmıştır. Ayrıca, yayılan yamanın tahmini genişliği ve uzunluğu aynı hesaplamalara göre hesaplanmıştır. yaklaşık 3x10^8 m/s'ye eşittir, f_0 yayılmanın rezonans frekansıdır, εr dielektrik sabitidir, FR-4 substratının kalınlığıdır ve W yamanın genişliğidir. denklemlere göre 16 mm genişliğinde ve 11 mm uzunluğunda dikdörtgen şekilli bir yama. Daha sonra dikdörtgen yamanın dört açısını inceltildi. Bu anten, -22 dB civarında S11 ile 3.1- 4.9 GHz arasında yayılır ve yansıma katsayısının 1.97 dBi kazancına sahiptir. Daha sonra, fraktal konsept kullanılarak, antenin bu aynı yayılan yaması kopyalandı ve i=0.8 kadar küçültüldü, ardından elde edilen küçültülmüş yama, tek halkalı anteni oluşturmak için ilk yamadan çıkarıldı. ayrıca yaklaşık -18 dB'lik bir S11'e sahip olan 3.5 GHz'de bir rezonans frekansı ile 3.1 – 4.3 GHz arasında yayılır. Ancak antenin önden, yandan ve arkadan görünüşünü göstermektedir. Anten arkadan görünümünde de görebileceğimiz gibi, zemin katmanının üst kısmı hem sağdan hem de soldan ayna gibi inceliyor. Zemin katmanındaki bu incelmeler, antenin yayılmasını ve S11 performansını iyileştirmeye yardımcı olur. Bu fraktal tabanlı tek halkalı anten, iyi bir radyasyon modeline ve 2.0 dBi civarında bir kazanca sahiptir. Tek halkalı antenin aynı parametreleri kullanılarak, ancak bu sefer iki farklı bantta yayılma elde etmek için ana halkanın içine daha küçük bir halka daha eklenerek, iç halka, dış halkanın 0,75 oranında küçültülmüş bir kopyasıdır. Her halkanın çevresi, bu halkanın merkez frekansındaki frekans bandına karşılık gelir. simülasyonlar CST mikrodalga stüdyo simülatörü kullanılarak gerçekleştirilmiştir. Önerilen anten kendine benzeyen iki yayılan halkası nedeniyle, merkez frekansları sırasıyla 3.5 GHz ve 7 GHz olan 3.1 – 4.1 GHz ve 6.1 - 8.1 GHz'lik ana 5G çalışma bantlarından ikisini kapsıyor. Tasarlanan anten, aynı bantlarda çalışan diğer antenlerden daha küçük kabul edilen 27x16 mm^2 darbe boyutuna sahiptir. Ayrıca, mikroşerit hat beslemesinin genişliği 1.9 mm'ye ayarlanmıştır ve FR4 substratının kalınlığı 1 mm'ye ayarlanarak 50 ohm'luk bir empedans uyumu oluşturulur. Anten, -20 dB civarında iyi bir yansıma katsayısı (S11), geniş bant genişliği, her iki bant için iyi bir radyasyon modeli ve birinci ve ikinci bantlar için sırasıyla 2.29 dBi ve 2.51 dBi kazanç gösterdi; 5G uygulamaları için iyi bir adaydır. Son olarak, zemin katmanına iki simetrik üçgen kesim eklemenin etkisi, farklı kesim boyutlarının yanı sıra daha küçük halkanın ölçek faktörünün ve zemin katmanının uzunluğunun değiştirilmesi için incelenmiştir. Dual-ring dual-band anteni geliştirmek için 4x1 MSL MIMO (Multi Input Multi Output) anten yapısı gerçekleştirilmiş, anten önceki antenlere benzer şekilde dielektrik sabitli FR-4 substrat üzerinde tasarlanmıştır. 4.3'ün 90.70 x 42.50 x 2.2 mm^3 boyutuna sahip. iki yayılan eleman arasındaki mesafe, rezonans frekansı 3.5GHz'de düşük frekans bandının λ/8'ine eşit olacak şekilde ayarlanır. Her antenin toplam MSL'sinin uzunluğu, alt bandın rezonans frekansının λ/4'ü civarında bir şeye eşit olacak şekilde ayarlanmıştır. Bu MIMO antenin S11 performansı, daha önce bahsedilen çift halkalı antene göre çok daha iyi, görüldüğü gibi bu anten ilk bandında hem S11 hem de S22 için -45 ile -55 dBi arasında bir yansıma katsayısı değerine sahip. merkez frekansı. İkinci bantların da S11 ve S22 performansı, merkez frekansında -30 ila -35 dBi civarında bir değere yükseltildi.

1. INTRODUCTION TO ANTENNAS

A proper design of such a critical component as the antenna in wireless systems can relax system requirements and improve overall system performance. However, its size may differ from 100m by 100m to parts of millimeters but, in general all antennas hold the same importance in their corresponding systems. Today, we enjoy much benefit from wireless, and the significant contributions of antennas should not be underestimated. An antenna is an electromagnetic transducer, used to convert, in the transmitting mode, guided waves within transmission lines to radiated free-space waves, or to convert, in the receiving mode, free-space waves to guided waves [1].

1.1 Antenna Selection Considerations

Any Wireless gadget contains an antenna that changes the electric flows produced by the handset circuits into electromagnetic (EM) waves, and as shown in figure 1.1 the full duplex communication systems contains of a transmitting (Tx) antenna and a Receiving (Rx) antenna. The Tx antenna transmit the EM waves to the Rx antenna. However, Antennas has different shapes, sizes, gains, and impedances. Choosing the right Antenna for an application can significantly affect the general exhibition, propagation range, and size of the wireless hubs. This segment surveys the essential standards of antennas just as qualities of various Antennas.

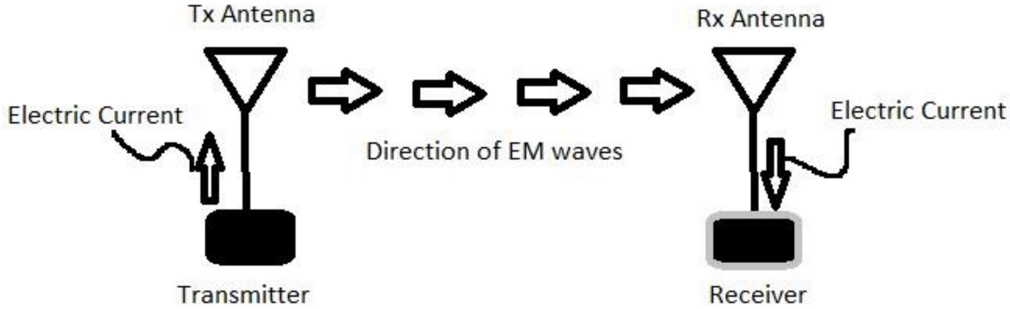

Figure 1.1: Transmitting and receiving antennas.

1.1.1 Gain

Comparing different types of antennas must be done according to a reference, where there are specific considerations that are ideal, so whenever we need to measure the performance of an antenna, we compare it with this hypothetical or in other words isotropic antenna which is not feasible in real life. The isotropic antenna is considered to have the same transmitted power in any direction at distance d. However, in real life there are directional antennas where the strength of the signal is stronger in some directions and weaker in the others. Accordingly, the antenna's gain is the ratio of the signal strength in the direction of strongest radiation to that of an ideal isotropic antenna. Giving "i" and "d" refers to isotropic and half wavelength dipole gain respectively, the gain is usually measured by dBi or dBd [2]. It should be mentioned that the radiated power in one direction is less than that of an isotropic antenna, meaning that no matter how perfectly the antenna is designed it has some losses and radiation in other directions. As the radiated frequency of an antenna changes the gain changes as well, usually, higher frequencies have lower gains.

1.1.2 Radiation pattern

To graphically comparing different antennas there is nothing better than radiation pattern graph. Figure 1.2 shows the radiation pattern of a chip antenna for different angles. therefore, for non-isotropic, i.e., real-life antennas the gain changes with the angles from the antenna, from the figure we can notice that it goes above 0 dBi at some angles and below it in others to ensure that it does not exceed the gain of the isotropic ideal case. Also, each operating frequency should have its own radiation pattern graph.

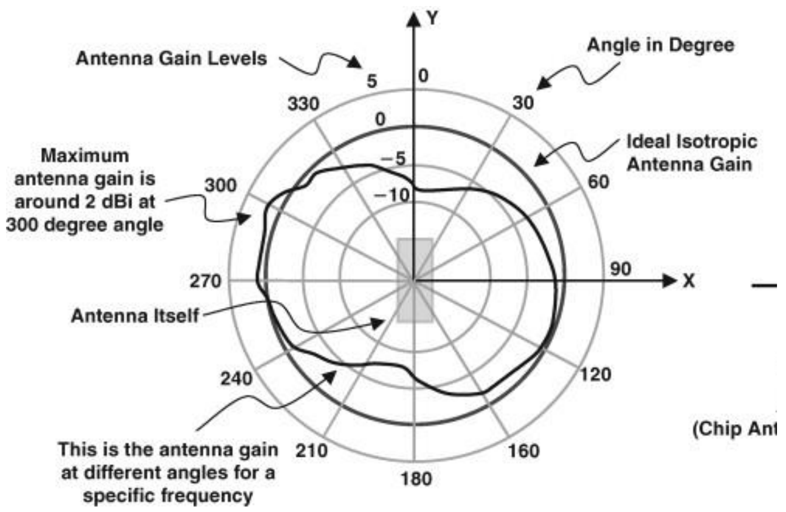

Figure 1.2: Radiation pattern [1].

1.1.3 Efficiency

The main idea of a receiving antenna is to change the electromagnetic waves into electric signals inside the receiving circuit, and in a transmitting antenna, changing the electric signals inside the transmitting circuit into electromagnetic waves to the space. Now, how effectively the antenna is applying these conversions is called the efficiency. The efficiency is taken into considerations in calculating the gain. So, providing the gain in some designs is enough sometimes [3].

1.1.4 Impedance

In a lot of analyzing tasks, an antenna can be replaced with a grounded for example, 50-ohm resistor, and it should be mentioned that this value is different for different types of antennas and according to the operating frequency. Antenna impedance is also known as radiation resistance. Usually, the antenna designers specify the resistor's value of their antenna in its equivalent circuit. Usually, the values of these impedances vary from 50 to 200 Ohm. On the other hand, we have the VSWR value which indicates how efficient the power source is in transferring RF power to the load. Part of the power will reflect back to the source if an impedance mismatch occurs in the design stage. An ideal VSWR value is 1, which means no undesired reflections is happening because of the impedance mismatch.

1.1.5 Tuning

Antenna's shape and size have high effect on the impedance. Changing the shape and the size of the antenna is called tuning. Matching on the other hand, is series or parallel connecting passive components to the antenna in order to change the impedance of the transmitting/ receiving circuit.

1.1.6 Polarization

If a combination of perpendicular travelling Electric (E) and Magnetic (M) fields are in the same speed they are called Electro Magnetic (EM) wave. the direction of E specifies the antenna's polarization. The type of antenna's polarization is according to the changes in phase and amplitude during the wave propagation. Depending on how the antenna is propagating the EM waves into space, along the electric field propagation if we have straight line moving E, rotating same-speed-changing phase causing circular E field or changing amplitude and phase elliptically rotating E, they are called Circular, Vertical, Elliptical or Horizontal polarization, respectively. Antenna, especially in Line of Sight (LOS) Applications should have the same polarization in receiving (Rx) and transmitting (Tx) antennas. Figures 1.3 and 1.4 show the EM wave propagation and polarization respectively.

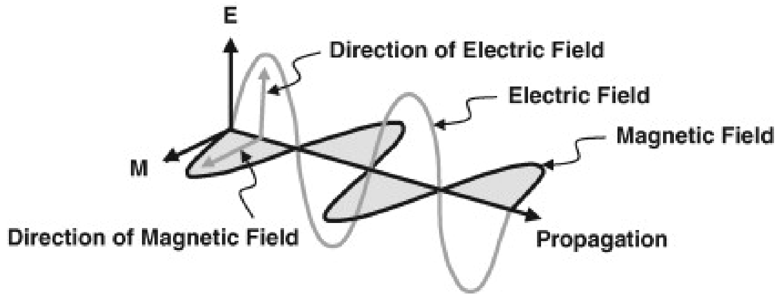

Figure 1.3: EM Wave Propagation [2].

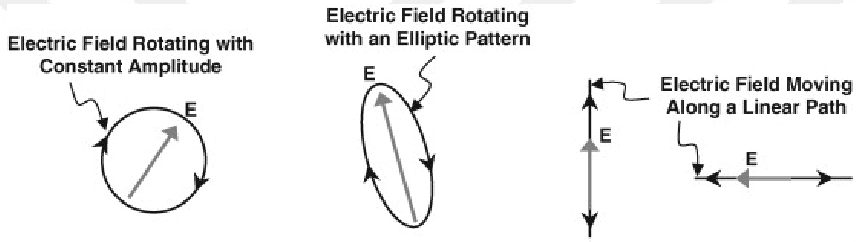

Figure 1.4: EM Wave Polarization [2].

1.2 Common Antennas

In the EM research field, any conductor is a radiating candidate and can be considered as an antenna [2]. In this section we listed some of the common types antennas that are widely used in the wireless communication field.

1.2.1 Dipole antenna

Two middle-fed 0.25 wavelength-long segments with a theoretical gain of 2.14dB can represent the dipole antenna [2]. Sometimes they are called half-wave dipoles because the antenna's length is 0.5 the wavelength. 73-ohm resistance usually used to represent the dipole antennas in their equivalent circuit [4].

1.2.2 Monopole antenna

The 0.25 lambda-long antennas that are portable on a reflective ground plane are often called monopole antennas, it usually has an impedance of 0.25 wave antenna is 36 Ohms. The ground plane can be thought of as a nonideal complexation that acts as the other half of a half-wave dipole. However, as long as the 0.25 electrical length is satisfied the antenna can physically be shortened. Helix antenna can present a good example of the shortened-monopole antenna that used for VHF as well as UHF radios [5]. At the same time these antennas can have -3dB less gain than the regular 0.25 wave antenna. But, adding a large conductive ground plane can accordingly improve the antenna's performance.

1.3 Microstrip Patch Antennas

The microstrip patch (MSP) is the most common printed-circuit antenna. As shown in figure 1.5 it contains a rectangular or circular patch of metal with a microstrip feeding. The overall design can all be a single etched printed-circuit board.

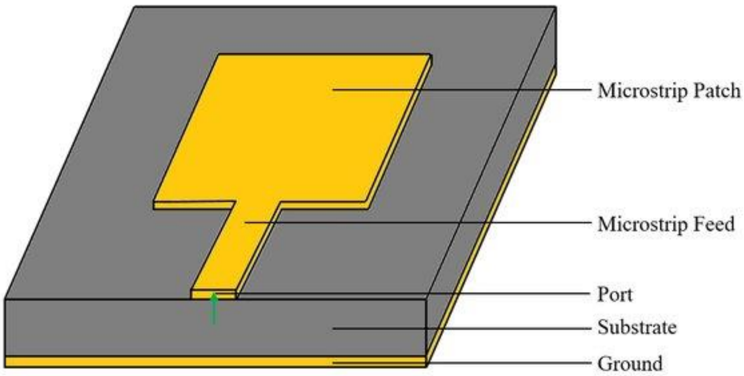

Figure 1.5: MSP Antenna [3].

The microstrip patch is the most common printed-circuit antenna. The overall design can all be a single etched printed-circuit. A patch antenna gains its name from the fact that it basically consists of a metal patch suspended over a ground plane [3]. In a patch antenna, most of the propagation is above the ground plane and can have high directional gain. Microstrip antennas have three main parts, a strip feeding line, a substrate with a dielectric constant ε, and a conductive ground plane.

2. FRACTAL SHAPES

To explain complex structures that are found in nature the classic geometric ways were inapplicable, therefore Mendelbort in [6] said fractal once in one of his books and since then they were widely used to explain such complex natures as lightening, leaves, coastal sides, and noise in electronic systems. These fractal geometrical shapes are characterized as seen in figures 2.1 and 2.2 by self similarity and space-filling, where the part is a scaled copy of the whole that creates a repetitive patterns that can be used effectively in the scientific explanations. We can think of it as a way to explain irregularity. As shown in figures 2.1 the lightening have a main body and then smaller ones similar to the main body but as a smaller copy, and then third smaller ones that are similar to the main body and the sub-lightening, to form a complex shape that consist of similar shapes, similarly in figure 2.2 the tree leaf is consist of a main shape that is repetitively down-scaled to form the whole leaf shape, another example is what

Figure 2.1 : Fractals in Lightening [6].

Figure 2.2 : Fractals in tree leaves [6].

we can see in figure 2.3 that the snowflake is also fractional shaped where its parts are a down-scaled copy of the bigger ones. However, all theses down-scaled shapes have their own iteration factor and iteration number, where the iteration number represent how many times this shape is down-scaled and the iteration factor represent how scaled are these shapes are. Usually, the iteration number is represented by "n" and the iteration factor by "i" so if we want to form our own fractal we need to choose how many times "n" is going to be applied by "i". Fractal shapes can be divided into linear fractals and non-linear fractals. The Incremental Function System is used to generate the linear one. An example of the linear ones is the Koch curve, Cantor curve, Minkowski curve, Sierpinski gasket, and many others. Space-filling and self-similarity are the main characteristics of fractal shapes, for instance, clouds, lightening, trees, snowflakes, and coastlines cannot be modeled without using the fractal geometry [7]. The same principal can be used in some applications for example antenna design industry when more electrical length is needed but a small volume is available. Fractal shapes has very unique properties that can be used as a viable miniaturization technique in designing antennas. All the fractal shapes have two characteristics, the iteration factor 'i' and the iteration number 'n' since they are generated in an iterative process that leads to self-similar structures. Generating fractal shapes starts with an initiator and by keep adding the generator with an iteration function ‘i’ for a specific number of times ‘n’. Figure 2.3 shows the generating process of some fractal shapes. Fractal antennas as same as the fractal shapes mentioned above have subdivisions or parts that are reduced copy of the whole antenna shape. Fractal antennas are characterized by self-similarity, low profile, compact size, good radiation pattern and can be operated in multiband and/or broadband [8]. Because of their self-similarity property fractal antennas can be designed to have more electrical length without degrading the antenna’s performance [9]. Using a repetitive pattern and by keeping the self-similarity process, antennas with fractal shapes can be designed.

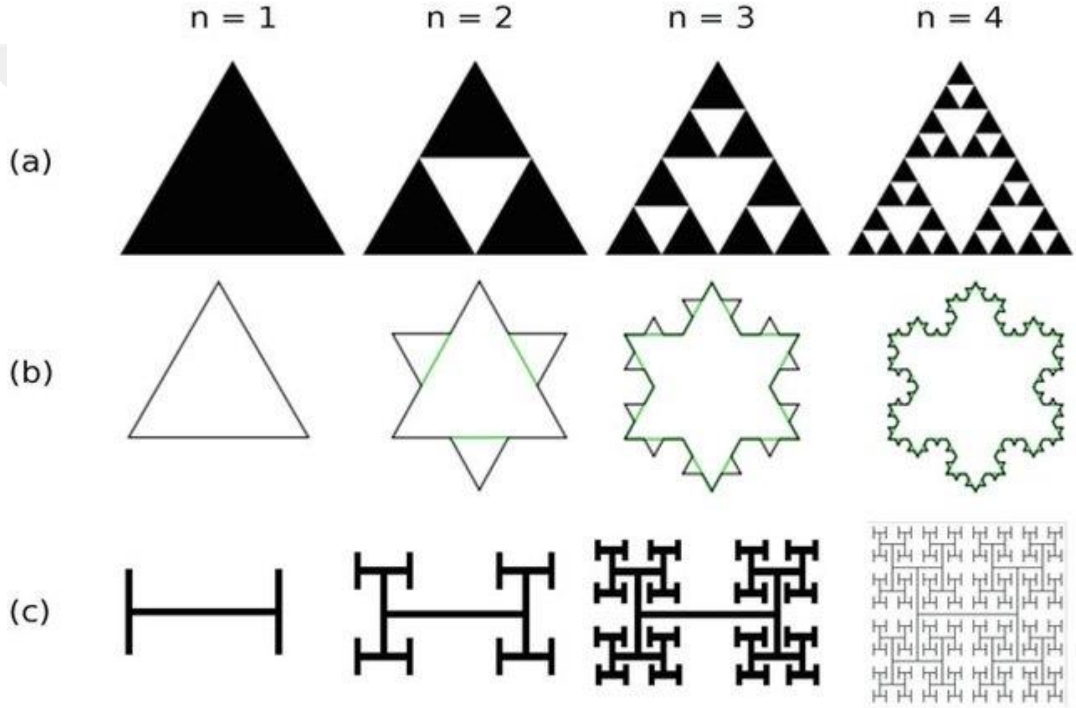

Figure 2.3 : Generating process of fractal shapes: (a) Sierpinski gasket (b) Koch snowflake and (c) H-fractal [10].

3. FRACTAL ANTENNAS – A LITERATURE REVIEW

Antennas are required for military, industrial and civil communication networks. The compact overall size and multi-band capabilities of antennas are critical in their design. Fractal antennas as similar as the fractal shapes are distinguished by characteristics such as self-similarity and space-filling which is an effective way to achieve the required miniaturized size and multi-band or even broad-band characteristics. the self-similarity of fractal configuration to end up causing multi-frequency and then designing multiband antenna; increasing bandwidth on the core principle of multi-band to obtain broadband. Fractals' space-filling characteristic results in curved longer electrical lengths that suit a small physical region. Fractal geometries can provide a huge surface area or a long length in a small volume or space, for example, the increment in electrical paths in microstrip patch antennas leads to a reduction in frequency and, as a result, a downsizing of the antenna's electrical length [10]. The number of bands defined by the fractal iteration number broad-banding monopole antennas to meet UWB standards has indeed been done using the fractal approach [11, 12, 13].

3.1 A Review On Fractal-Based Antennas

The usage of fractal's repetitive characteristic has been implemented in [14] to create a simple-in-design Crown Hexagonal fractal shaped metal unit cells and then create adjacent regular hexagons as shown in figure 3.1. In [15] the zero iterative structure

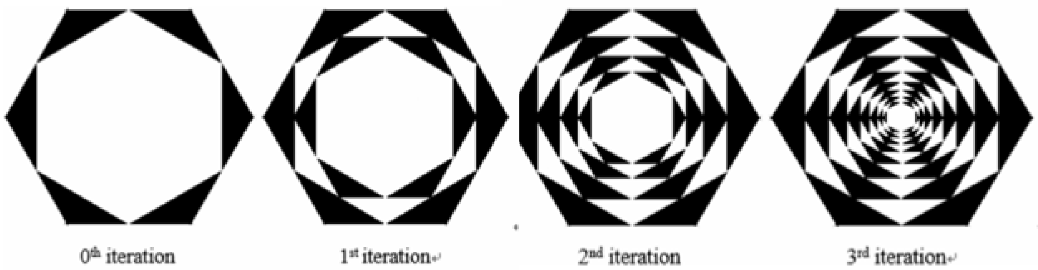

Figure 3.1 : Crown hexagonal fractal shape [14].

was a straight line, as shown in figure 3.3 by Y-shaping the straight line, i.e., applying the first stage of fractal structure, in other meanings n=1, then changing the second iterated into Y-shaped structure as well meaning n=2 now, then by keep repeating the same process until n=3 we get the antenna shown in figure 3.2. Similarly until n=4 the antenna in [7] has been designed as shown in figure 3.3.

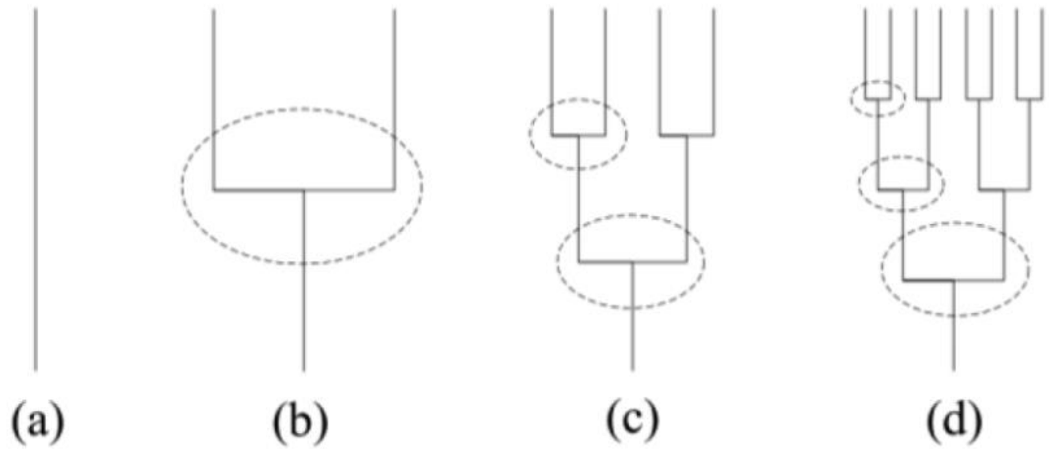

Figure 3.2 : (a) Zero iteration. (b) First iteration. (c) Second iteration. (d) Third iteration of the tree shaped antenna in [15].

Figure 3.3 : Tree-shaped antenna stages [16].

Also, a fractally tapered square shaped antenna has been implemented until n=2 in [11], as shown in figure 3.4. By using the same concept, and by applying Hilbert curves concept, the antenna in figure 3.5 (a) is designed, and by using moore pre-fractals the antenna in figure 3.5 (b) was implemented in [17].

Figure 3.4 : Fractally-tapered square-shaped antenna [11].

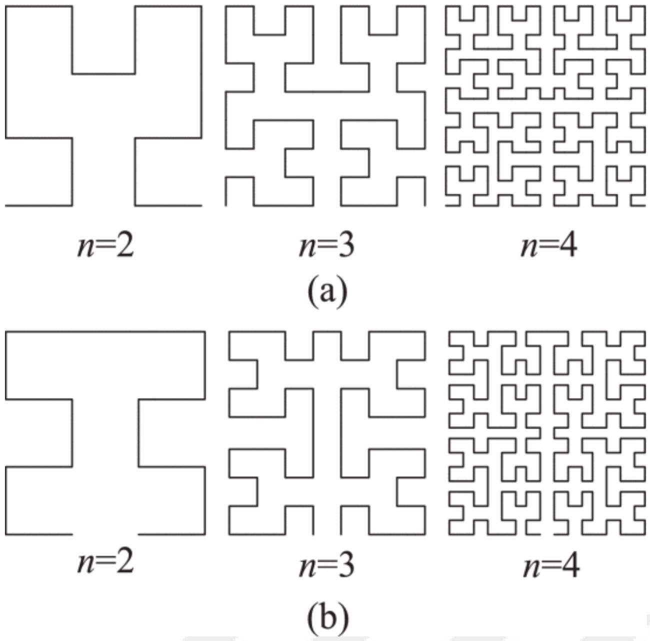

Figure 3.5 : Creating stage-4 of (a) Hilbert and (b) Moore pre-fractal curves-based antennas [17].

In figure 3.6, 3.7 and 3.8 the creation of six stages of Sierpinski carpet fractals, the creation of the Giuspe-Peano fractals and the Giuspe-Peano fractals applied to antenna's patch is shown [12], respectively.

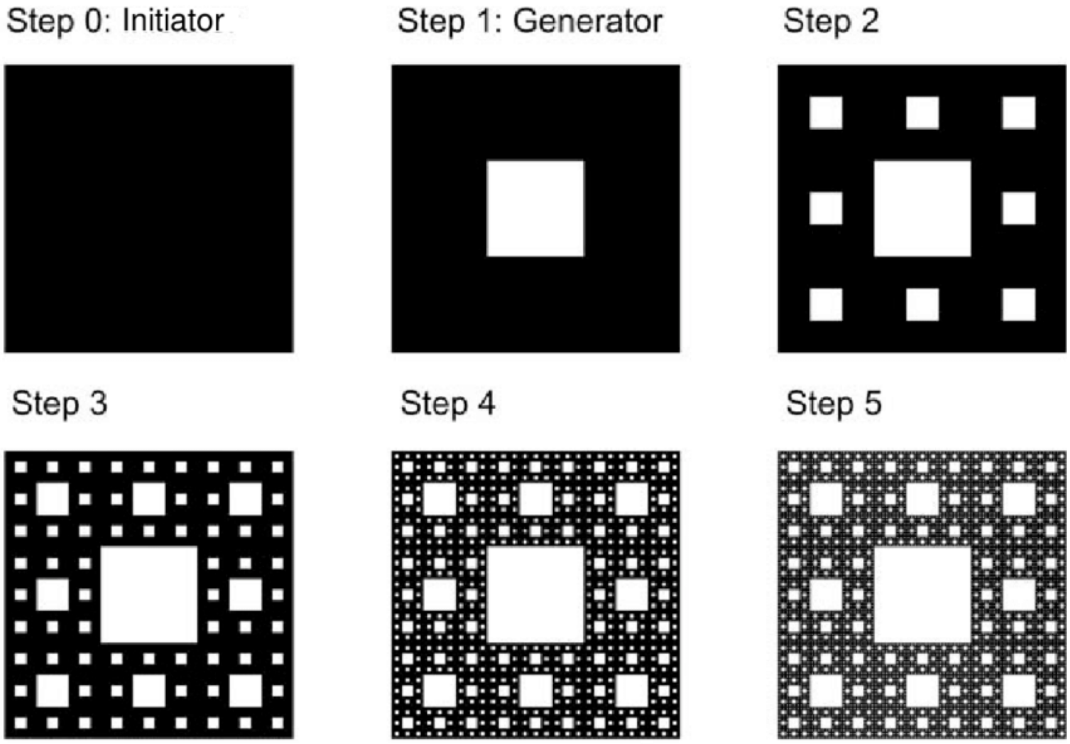

Figure 3.6 : Sierpinski carpet fractal shape creation [12].

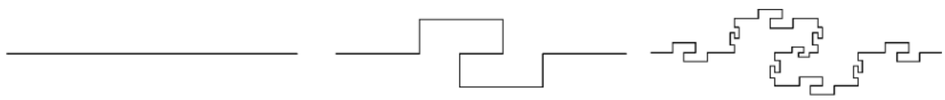

Figure 3.7 : Initiator and generator of the Giusepe-Peano fractal [12].

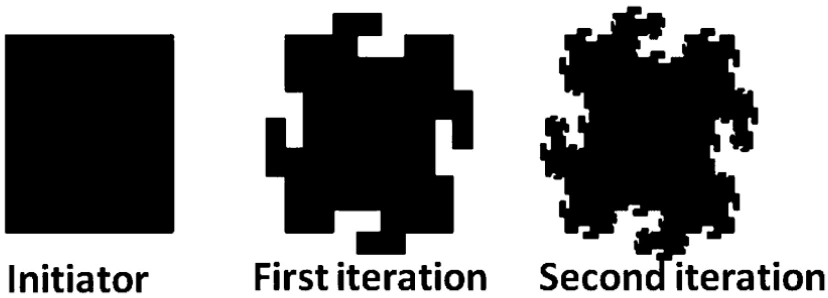

Figure 3.8 : Giusepe-Peano fractals applied on the edges of patch antenna [12].

3.2 Performance of Fractal-Based Microstrip Patch Antennas

Several fractal based microstrip patch antennas were designed and investigated over the years, monopoles, UWB and many other antennas, since these type of fractal-based antennas have some characteristics that are preferable over the regular old-fashioned classic design such as compact size, low profile, multi-band and/or broad band and that they are easy to implement. An example of such fractal antennas is the design in [15] were the Minkowski and Koch fractals were implemented in the design of microstrip patch antennas, the proposed Minkowski fractal antennas has a bandwidth of 64% (5.52 –10.72 GHz) and a gain of 4.9 dBi, the effect of changing the iteration factor "i" is shown in figure 3.9 below. The effect of changing the iteration factor 'i' for this antenna for when n=1 were on the S_{11} performance of the antennas when i was 0.33 the antenna had four resonance frequencies between (6-12) GHz with S_{11} of maximum -30 dB, then when i was 1 the antenna had four resonance frequencies for the same bands but with best S_{11} value of -20 dB at 6 GHz while when i was 1.67 the antenna had three resonance frequencies between (5-10) GHz with best S_{11} at 7 GHz of -15 dB, then by increasing the iteration number n=2 the performance got affected a little bit so when i was 0.42 the antenna had four resonance frequencies between (6-12) GHz with S_{11} of maximum -35 dB, then when i was 1 the antenna had three resonance frequencies between (6-10) GHz with maximum S_{11} value of -20 dB at 6.1 GHz while when i was 1.67 the antenna had three resonance frequencies between (6.5-12) GHz with best S_{11} at 11.5 GHz of -15 dB.

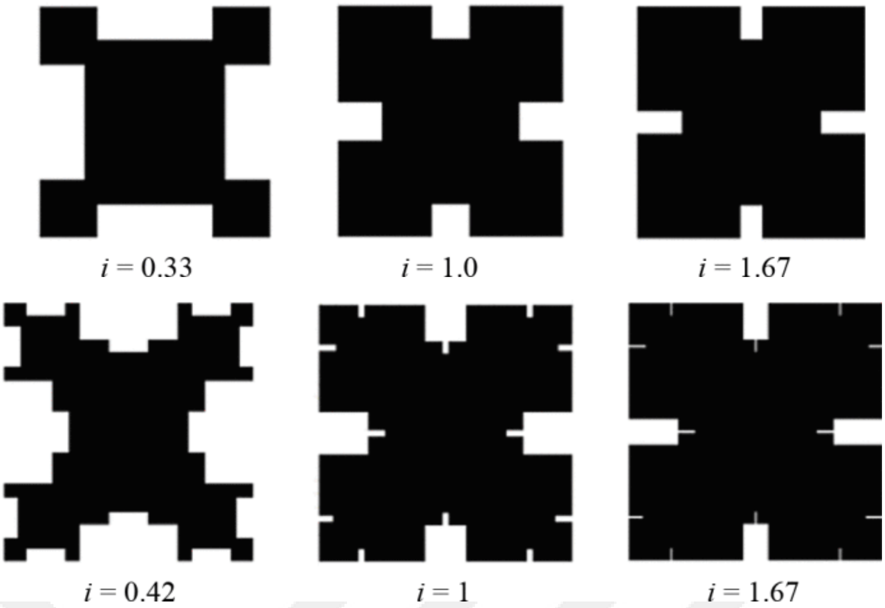

Figure 3.9 : The antenna in [15] with different "i" values and n=1 (Above) and n=2 (Below).

A novel UWB microstrip patch antenna is presented in [16] using a Pythagorean tree-shaped fractal design to get more bandwidth and get a multi-band performance. İncreasing the n factor of the design more resonance frequencies will appear, the proposed design is considered compact in size since it is 25 × 25 mm^2, it resonates at 2.6 and 11.12 GHz with good radiation pattern, the proposed designs are shown in figures 3.10.

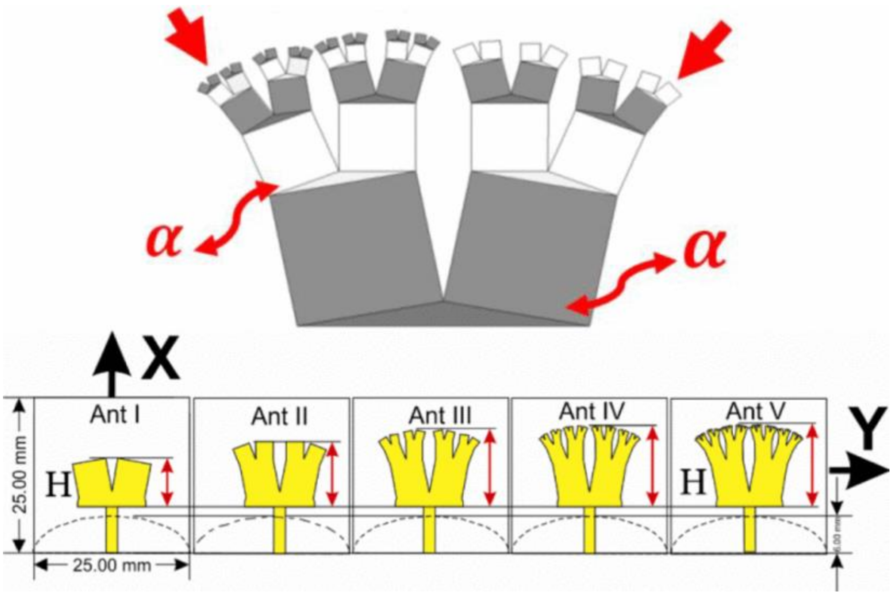

Figure 3.10 : Pythagorean tree-shaped MSL patch antenna [16].

The design in [18] is used to get double the BW, the design is consist of fractal-based square shaped log periodic small in-size patches printed on an FR-4 substrate for ultra wide band application which are the frequency band between 3.1 to 10.6 GHz, the design is shown in figure 3.11, this design showed multiband performance.

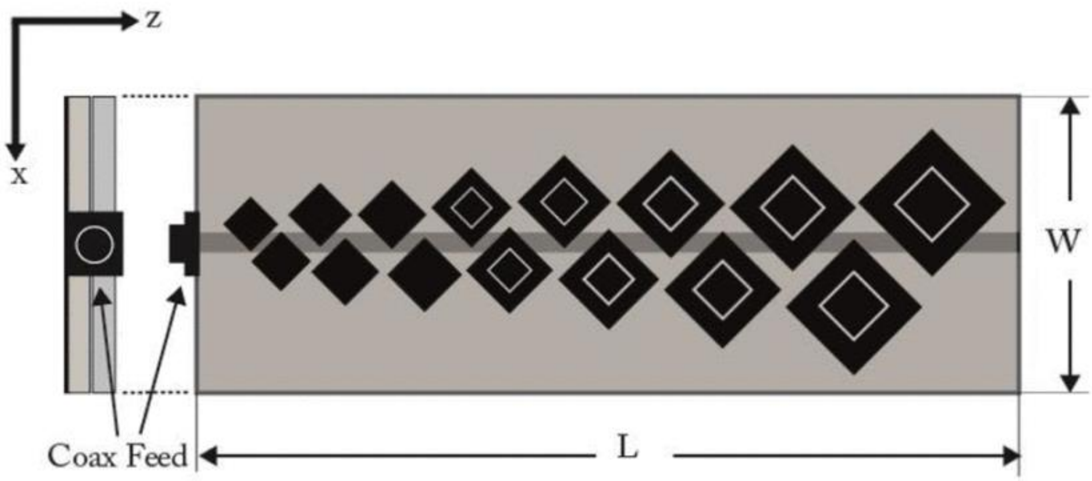

Figure 3.11 : Log-Periodic square shaped antenna in [18].

The classic fractal shapes of classic Koch Island and Giusepe-Peano fractals as well as Minkowski and T-type shaped design were investigated in [12] as 20 x 13 mm^2 sized designs, the four investigated designs are shown in figure 3.12. all these antennas shown in figure 3.12 except the T-type one have multi-band performances between (4-14) GHz and S_{11} that varies between (-25 to -45) dB.

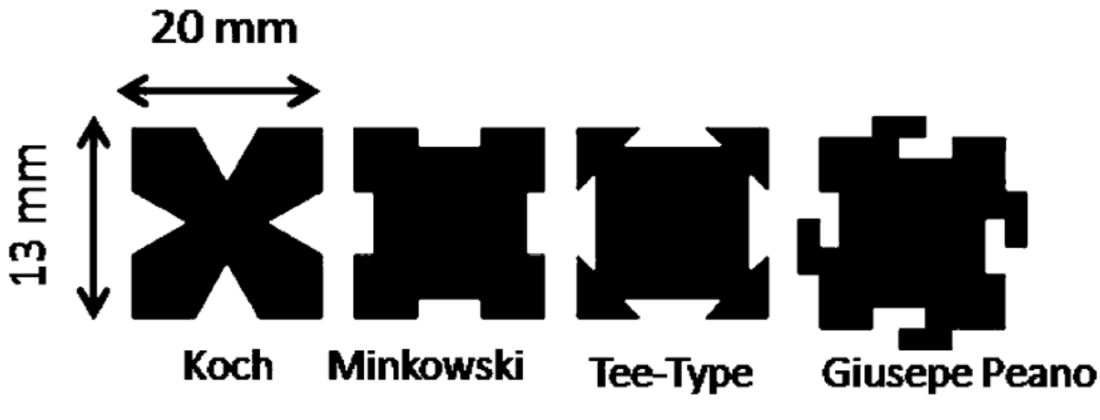

Figure 3.12 : The antennas investigated in [12].

Each one of these antennas has a good radiation pattern, gain and efficiency. However, by differently applying the fractal concept on MSL Patch antennas such antennas as the ones shown in figures 3.13 and 3.14 can be designed, each one of these antennas is explained in [13] and showed good S_{11} performance, which indicates that they are good candidates for applications between 2-16 GHz.

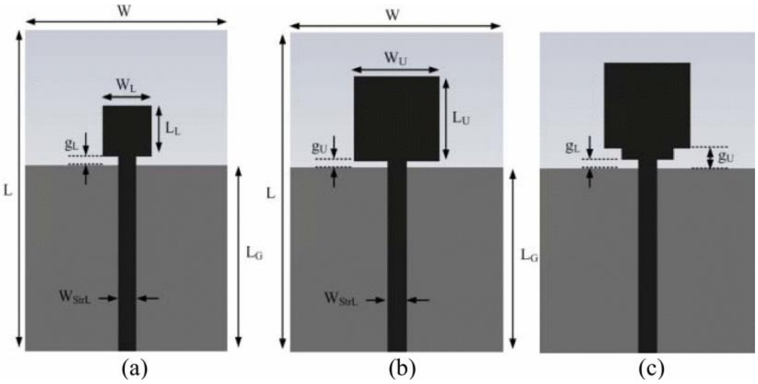

Figure 3.13 : (a) Lower (b) Upper and (c) Fractal square monopole [13].

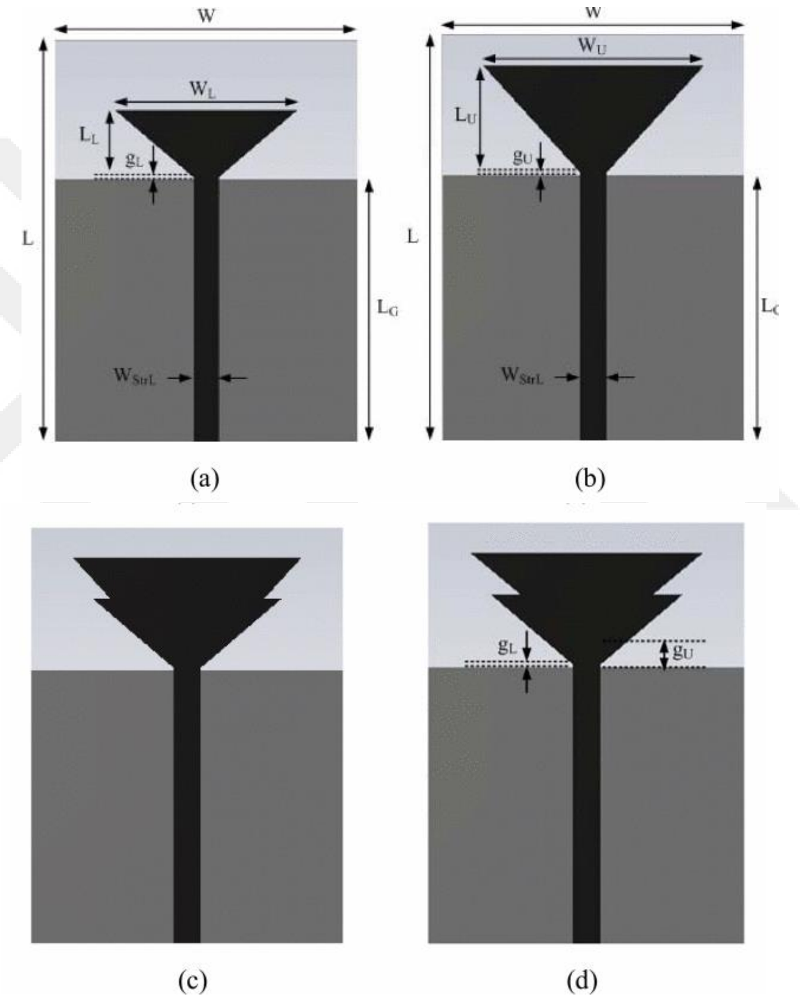

Figure 3.14 : (a) Lower, (b) Upper, (c) same vertex, (d) same slope fractal monopoles [13].

The phased array antennas have limitations such as that they operate narrow-bandy which results in more sidelobes and coupling issues a good solution were proposed as a poly-fractal arrays in [42] that provide the antenna a wide-band operating capabilities.

3.3 Comparing Between Different Fractal Antennas Performance And Designs

İn this part in table 3.1 below we have listed some fractal based antenna designs and showed which fractal geometry have been used an how many times it has been applied in the design, and what was the performance of such antennas.

Table 3.1 : Comparison between fractal-based antennas.

Ref	Fractal Geometry	i	Freq. Band (Simulated)	Size	B.W. (Simulated)
[13]	a) Rectangular b) Triangular		UWB	a) 48X40 b) 40X30	a) 9.68 GHz b) 9.1 GHz
[10]	hexagonal crown fractal structure	3	(0.61, 1.26, 2.31, 5.35, etc.) GHz	340x340 mm	-
[19]	modified Sierpinski-carpet	3	Four resonant frequencies between 1GHz-20GHz; The lower band bandwidth covers from 1.1GHz-10.8GHz	88.7x16x76. 3 mm	-
[20]	Giuseppe Peano	1	600 MHz	-	-
[21]	Sierpinski		LTE: (700, 2600) MHz	76 X 33 mm^2	-
[22]	DNA Shaped		a) sub-terahertz band (0.22− 0.32 THz) b) Terahertz (1.38–2.89 THz) Band	500x400 µm	a) 0.1 THz b) 1.51 THz
[23]	modified Sierpinski gasket	2	WLAN (2.25-2.60GHz), WiMAX (3.10-4.10GHz)	-	14.46% 27.78%

Table 3.1 (Continued): Comparison between fractal-based antennas.

Ref	Fractal Geometry	i	Freq. Band (Simulated)	Size	BW (Simulated)
[24]	Tree-liked	4	UHF RFID (900MHz)	88x30.8x1.5 mm	25% (630MHz-1050MHz)
[25]	Sierpinski shaped	-	5.8-8.0 GHz	20x20x1.55 mm	41% (5.3 GHz -8.0 GHz)
[19]	Koch-Like Bow-Tie		PCS, WLAN, WiFi, WiMAX	67x84x1.0 mm	-
[26]	Half T-Square		Radiolocation, deep space research, Aeronautical Radio Navigation services (ARNS), Maritime Radio Navigation services (MRNS), and Fixed Satellite Services (FSS)	26×20×1mm	-
[27]	Minkowski Fractal		5G Wireless	40×40×1.6 mm	3.01 GHz
[28]	Nested Square Shaped Ring		2.4/4.8/7.8/11.7/16.5 GHz	36x32 mm	3.23 GHz
[29]	Hexagonal-square shaped		UWB (2.1–13.5) GHz	54x35 mm	11.4 GHz
[30]	Hilbert Curve		a) 1.8 GHz b) 3.3 GHz c) 5.5 GHz	18x16.5x1.6 mm	a) 160 MHz b) 410 MHz c) 2670MHz
[31]	Minkowski-like sided		2.14 GHz	68×48 mm	-

Table 3.1 (Continued): Comparison between fractal-based antennas.

Ref	**Fractal Geometry**		**Freq. Band. (Simulated)**	**Size**	**B.W. (Simulated)**
[32]	Hilbert Curve		200 – 300 MHz	9x4x1.6 mm	100 MHz
[33]	Novel Snowflake		28 GHz	8x5x0.245 mm	3.76 GHz
[34]	Tree-Shaped Elliptical		SWB (0.66 – 35.4) GHz	170x150 mm	34.74 GHz
[35]	Hexagonal Sierpinski Gasket	4	C/X/Ku and K Bands: a)3.46 b) 8.28, c) 12.26, d) 17.21, e) 23.40, f) 26.01 GHz	50x50 mm	a) 81 b)152 c)179 d)330 e)82 f)160 GHz
[36]	DGS	3	S and C Bands (2.05 -4.88) GHz	32x30x1.6 mm	2830 MHz
[37]	Modified Hilbert Curve	2	a) 0.8 b) 4.2 5.1 6.5 c) 8.3 9.5 10 10.7 d)13 GHz	50x60x3 mm	a) 0.315 b) 3.220 c) 2.957 d)1.940 GHz
[38]	Fractal slot structure	-	(3.1 – 4.7) GHz	-	1.6 GHz
[39]	Koch Curves	2	(1.488 – 1.520) GHz	90x90 mm	31.52 MHz
[40]	Koch-Sierpinski Gasket	1	10 GHz	50x50 mm	~9 GHz

4. DESIGN AND SIMULATIONS

The fifth-generation (5G) of communication systems has already been rolled out in some countries worldwide. However, the development of smaller and more practical components is still in need. In this work, the design of three different microstrip patch based fractal antennas have been designed and simulated, First a fractal-based single ring patch antenna, then a double-ring dual-band patch and finally a fractal-based MIMO antenna for 5G systems have been proposed, these three antennas implemented by using the principle of fractal geometry so that single ring antenna propagates at 3.5 GHz and both the double ring and 4X1 MIMO antennas propagates at two bands with center frequencies the 3.5 GHz and 7GHz. This chapter has been dedicated to sow the design and the simulations of these three antennas.

4.1 Operating Bands of The Proposed Antennas

The key to start designing any antenna is to specify in which band this antenna is going to operate, since all of the dimension and materials selection depends on which frequency band tis antenna is going to operates in. For our case, the three proposed antennas that will be discussed in this chapter are proposed for the 3.1 – 4.1 GHz and 6.1 – 8.1 GHz bands which are considered two of he main 5G bands, the 3.1 – 4.1 GHz band is sub divided into different band , however, almost all of these sub-bands are considered really important for 5G communication systems operating spectrum. Especially in South and North Americas the international mobile telecommunications (IMT) is already being shifted to these bands. And if it has not yet then at least it is being analyzed in order to e used, it is also being called the 5G mid-band spectrum. The other important band is the spectrum band around Wi-Fi6 which is the bands between 6.5 to 8.5 which are considered very promising for the future 5G applications.

4.2 Single Ring Fractal-Based Microstrip Patch Antenna

As it has been discussed in the previous chapters, the creation of any fractal shape depends on two factors, the iteration number “n” and the iteration factor “i” where the iteration number represent how many times the fractal shape is being down-scaled or up-scaled, and the iteration factor define how it is being scaled. Similarly, in designing fractal antennas, for our first antenna the procedure starts with specifying the operating band, since our antenna is intended to propagate at the 5G mid-band therefore the resonance frequency should be something around 3.5 GHz. The antenna’s parameters should be chosen carefully according to what type of antenna and in which bands the antenna is going to operate, in our case the chosen type is the microstrip patch antenna and the operating band is the 3.5 GHz, therefore, as a feeding method we chose the microstrip line feeding (MSL) which provides simplicity in design and compactness. However, the length of the microstrip feeding line (Lf) should be around λ/4 of the resonance frequency. As it is known in the microstrip patch antennas that it is constructed from three layers etched to each others, the first layer is the ground layer and then the substrate layer, and finally the radiating patch on the top. However, the thickness of the middle layer which is the FR-4 substrate was chosen to be 1 mm and the width of the microstrip line was chosen to be 1.6 mm so that together they provide a 50 ohm impedance at the antennas port which provide a better propagation, these microstrip line feed impedance calculations were done according to figure 4.1 equations.

$If \left(\frac{W}{H}\right) < 1:$

$$\varepsilon_{eff} = \frac{\varepsilon_R+1}{2} + \frac{\varepsilon_R-1}{2}\left[\frac{1}{\sqrt{1+12\left(\frac{H}{W}\right)}} + 0.04\left(1-\left(\frac{W}{H}\right)\right)^2\right]$$

$$Z_0 = \frac{60}{\sqrt{\varepsilon_{eff}}}\ln\left(8\left(\frac{H}{W}\right)+0.25\left(\frac{W}{H}\right)\right)$$

$If \left(\frac{W}{H}\right) > 1:$

$$\varepsilon_{eff} = \frac{\varepsilon_R+1}{2} + \left[\frac{\varepsilon_R-1}{2\sqrt{1+12\left(\frac{H}{W}\right)}}\right]; \quad Z_0 = \frac{120\pi}{\sqrt{\varepsilon_{eff}}\left[\frac{W}{H}+1.393+\frac{2}{3}\ln\left(\frac{W}{H}+1.444\right)\right]}$$

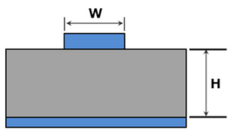

Figure 4.1 : MSL calculations [36].

Furthermore, the estimated width and the length of the radiating patch were calculated according to the two equations shown in figure 4.2 below, where c is the speed of light which equals to almost 3x10^8 m/s, f_0 is the resonance frequency of propagation, ε_R is the dielectric constant, h is the thickness of the FR-4 substrate and W is the width of the patch.

$$Width = \frac{c}{2f_0\sqrt{\frac{\varepsilon_R+1}{2}}}; \quad \varepsilon_{eff} = \frac{\varepsilon_R+1}{2} + \frac{\varepsilon_R-1}{2}\left[\frac{1}{\sqrt{1+12\left(\frac{h}{W}\right)}}\right]$$

$$Length = \frac{c}{2f_0\sqrt{\varepsilon_{eff}}} - 0.824h\left(\frac{(\varepsilon_{eff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{eff}-0.258)\left(\frac{W}{h}+0.8\right)}\right)$$

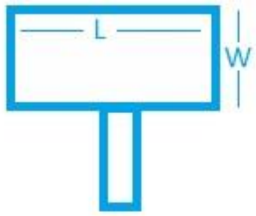

Figure 4.2 : The calculation of the antennas parameters [35].

The radiating patch design was started by creating a rectangular-shaped patch with a 16 mm width and Length of 11 mm according to the equations in figure 4.2. Then by tapering the four angles of the rectangular patch we got the shape shown in figure 4.3,

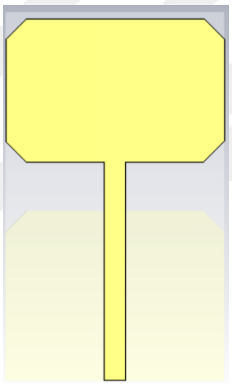

Figure 4.3 : The Tapered-Angles Antenna.

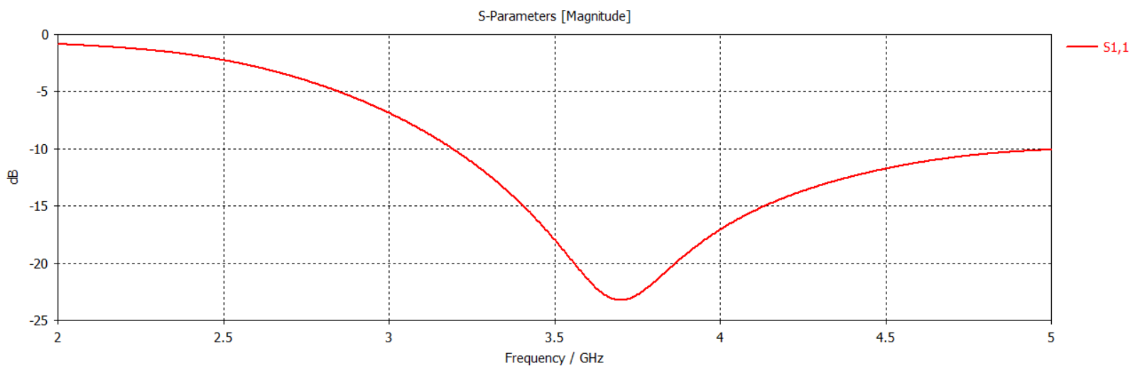

Figure 4.4 : The S_{11} performance of the antenna in figure 4.2.

This antenna propagates between 3.1-4.9 GHz with S_{11} around -22 dB and has a gain of 1.97 dBi as shown in figure 4.4 of the reflection coefficient. Later, by using the fractal concept, this same radiating patch of the antenna was copied and down-scaled by i=0.8, then the resulted down-scaled patch was subtracted from the first patch to create the single ring antenna shown in figure 4.5 which also propagates between 3.1 – 4.3 GHz with a resonance frequency at 3.5 GHz that has an S_{11} of around -18 dB as shown in figure 4.6. However, Figure 4.5 shows the front, side and back view of the antenna. As we can notice in the back view of the antenna in figure 4.5 the ground layer's upper part is mirrory tapered from both the right and the left sides. These tapers in the ground layer help in improving the propagation and S_{11} performance of the antenna. This fractal based single ring antenna has a good radiation pattern as shown in figure 4.7 and a gain around 2.0 dBi.

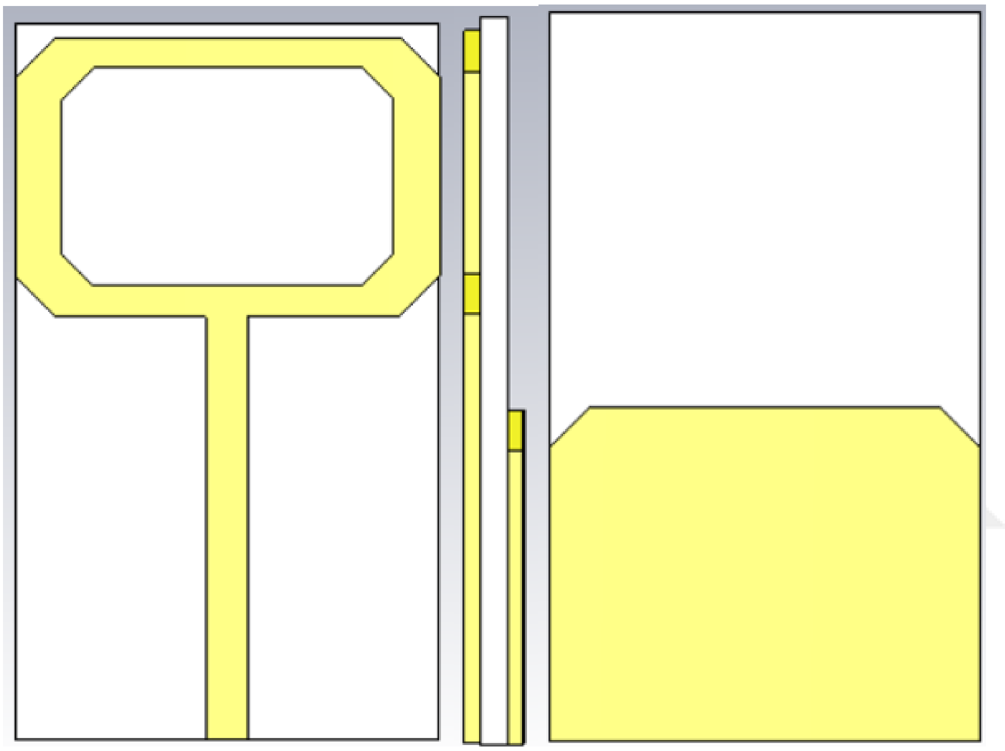

Figure 4.5 : The proposed single ring antenna.

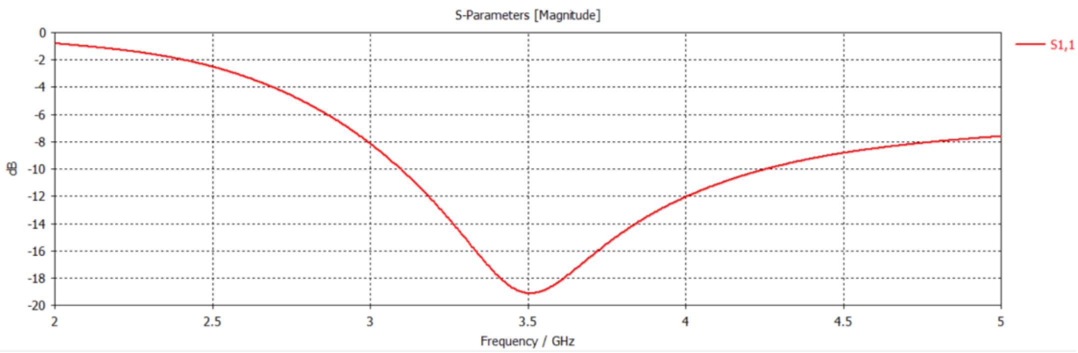

Figure 4.6 : S_{11} of the Single ring fractal-based antenna.

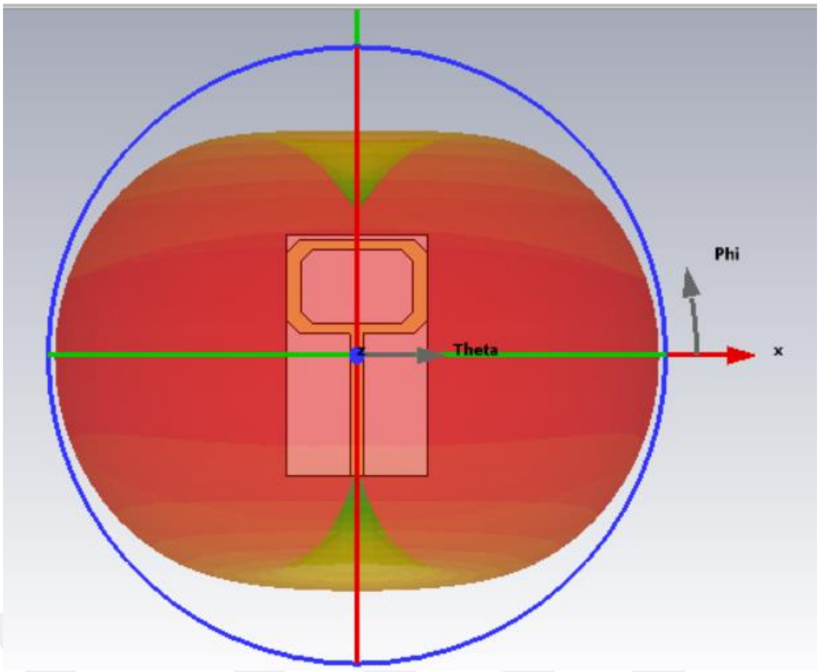

Figure 4.7 : Radiation pattern of the single ring antenna.

4.3 Double-Ring Dual-Band Fractal Antenna

By using the same parameters of the single ring antenna but this time with adding another smaller ring inside the main ring to get a propagation at two different bands, the inner ring is a by-0.75 down scaled copy of the outer ring. The circumference of each ring corresponds to this ring's frequency band at its center frequency. the simulations have been implemented using CST microwave studio simulator. Because of its two self-similar propagating rings the proposed antenna covers two of the main 5G operating bands of 3.1-4.1 GHz and 6.1-8.1 GHz, with center frequencies of 3.5 GHz and 7 GHz, respectively. The designed antenna has an impact size of 27x16 mm2 which is considered smaller than the other antennas operating in the same bands. Furthermore, the width of the microstrip line feeding has been set to 1.9 mm and the thickness of the FR4 substrate is set to 1 mm to create a 50 ohm impedance matching. The antenna showed a good reflection coefficient (S_{11}) of around -20 dB, wide bandwidth, a good radiation pattern for both bands, and a gain of 2.29 dBi and 2.51 dBi for the first and second bands, respectively, which indicates that the antenna is a good candidate for 5G applications. Finally, the effect of adding two symmetrical triangular cuts on the ground layer has been studied for different cut sizes as well as the changing of the scale factor of the smaller ring and the length of the ground layer.

Figure 4.8 shows the front, side and back view of the antenna. And Figure 4.9 shows the S_{11} of the double-ring fractal antenna, whether figure 4.10 shows the radiation pattern of the antenna.

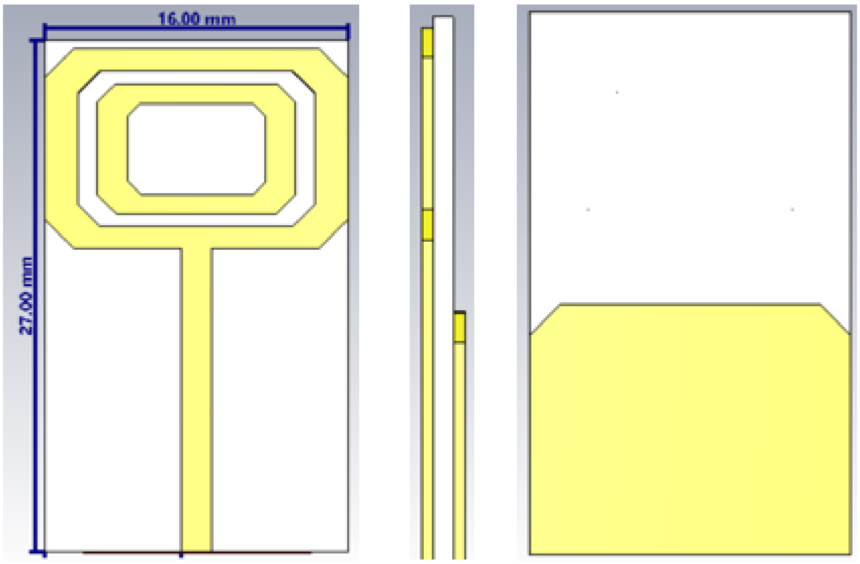

Figure 4.8 : Double-ring Dual-band fractal antenna.

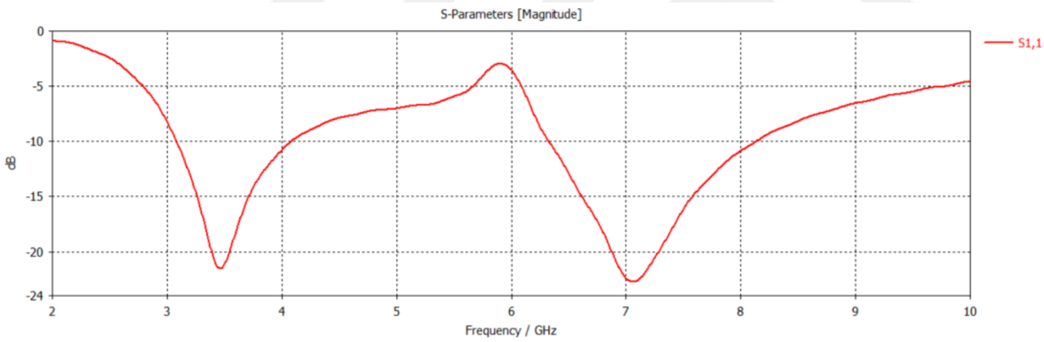

Figure 4.9 : S_{11} of the double-ring Dual-band fractal antenna.

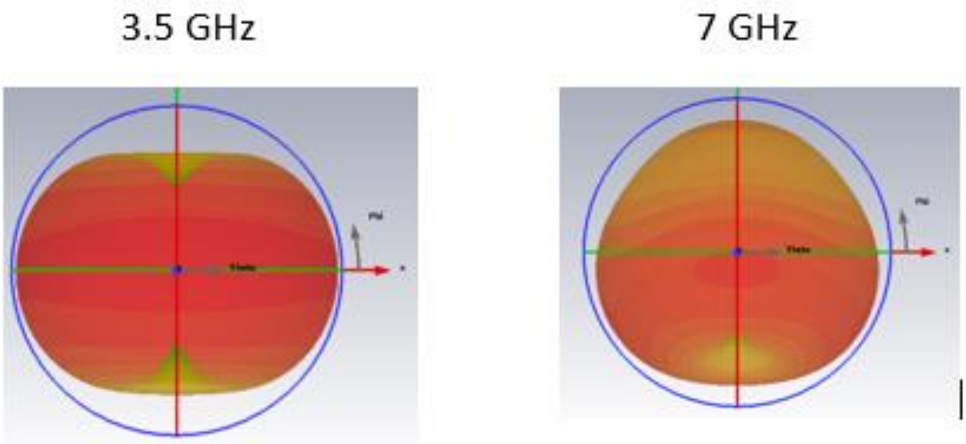

Figure 4.10 : Radiation pattern of the Double-ring dual-band antenna at its resonant frequencies.

4.4 4x1 Fractal-Based Dual-Band Microstrip Array Antenna

In order to improve the dual-ring dual-band antenna a structure of a 4x1 MSL MIMO (Multi Input Multi Output) antenna have been implemented, the antenna is designed as similar to the previous antennas on an FR-4 substrate with a dielectric constant of 4.3, this antenna has a size of 90.70 x 42.50 x 2.2 mm^3 the front view of this antenna is shown in figure 4.11 below while the back view (ground layer) and the top view are shown in figures 4.12 and 4.13, respectively. the distance between two propagating elements is set to equal λ/8 of the lower frequency band at its resonant frequency 3.5GHz, and the length of the total MSL of each antenna were set to equal something around λ/4 of the resonance frequency of the lower band.

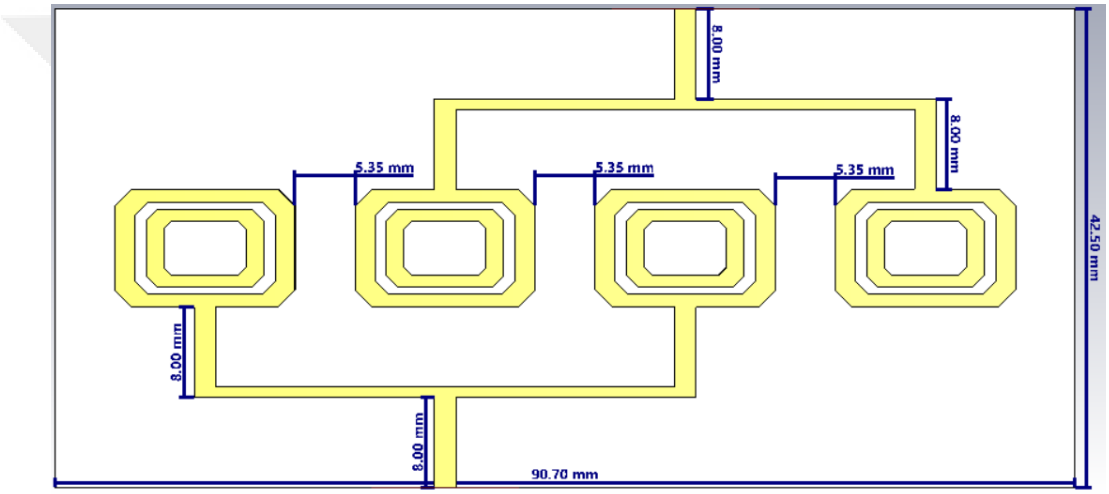

Figure 4.11 : Front and Side view of the 4x1 dual-band fractal MIMO antenna.

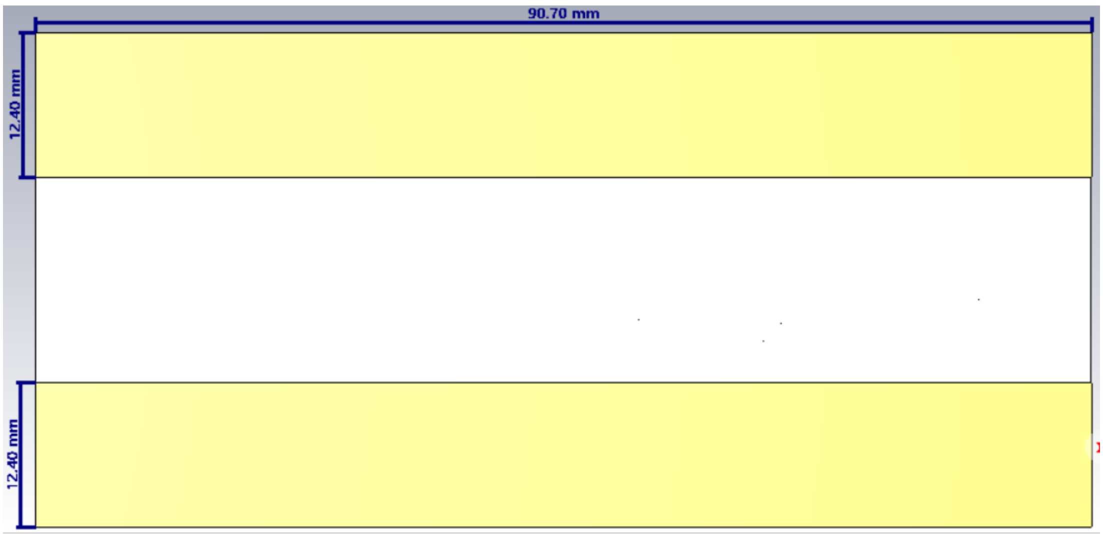

Figure 4.12 : The back view (Ground Layer) of the 4x1 Fractal MIMO Antenna.

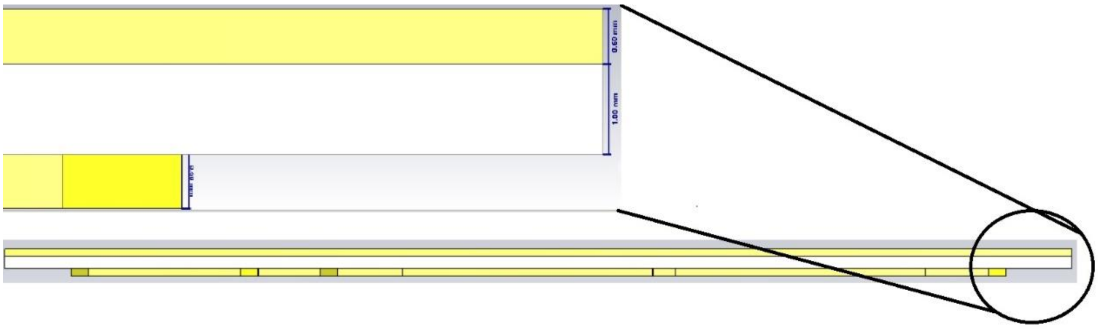

Figure 4.13 : Zoomed top view of the 4x1 double-ring fractal array antenna.

As it can be seen from the front view of the array antenna in figure 4.11 this antenna is quite different than the conventional array antennas, the difference is in the feeding way, this antenna has two ports and each one of these ports is connecting to only two propagating elements via a tree shaped MSL feed, and the other two elements are connected to the other port via another tree-shaped MSL feeding, this type of feeding in the array antenna provides better impedance matching between the four antennas. However, our proposed array antenna as seen from the S_{11} and S22 plots in figures 4.14 and 4.15 respectively propagates at two 5G frequency bands of (2.5 – 3.8) GHz band with resonance frequency at around 3.3 GHz and (5.7 – 7.5) GHz band with resonance frequency around 6.5 GHz, both bands cover important 5G bands, the array has radiation patterns as shown in figures 4.16 and 4.17 for both 3.5 GHz and 7Ghzfor both ports respectively and higher gain compared to the single ring fractal and double ring fractal antennas.

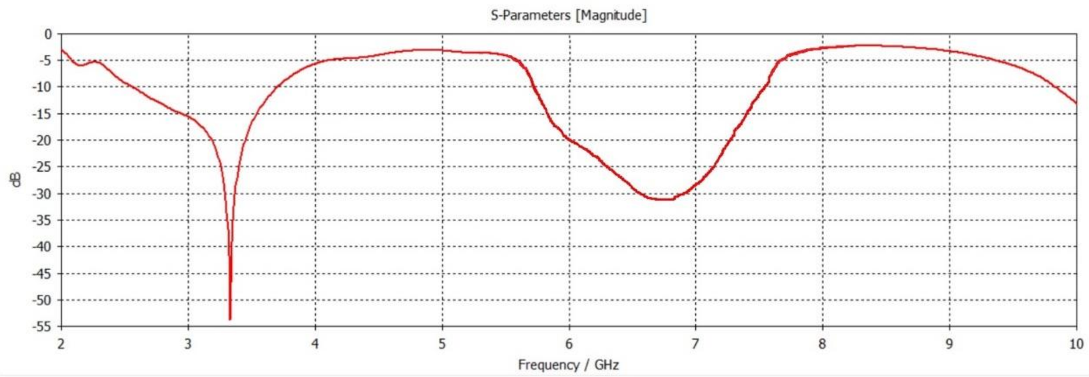

Figure 4.14 : S_{11} of the 4x1 fractal array antenna.

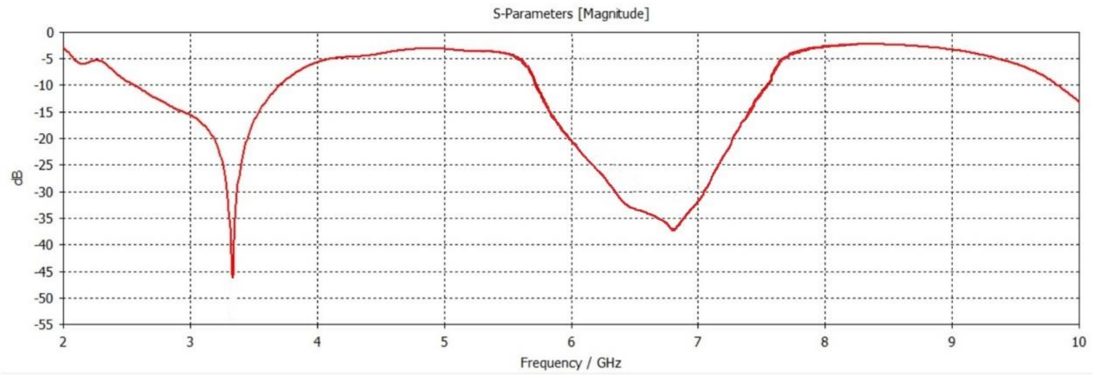

Figure 4.15 : S22 of the fractal 4x1 array.

The S_{11} performance of this MIMO antenna is much better than the double-ring antenna discussed before, as it can be seen, this antenna has a reflection coefficient value among -45 and -55 dBi for both S_{11} and S22 for the first band at its center frequency. The second bands as well has its S_{11} and S22 performance improved to something around -30 to -35 dBi at its center frequency. In addition, the gain of the propagation bands center frequencies is as shown in table 4.1 below

Table 4.1 : 4x1 fractal-based array gain for the two resonance frequencies.

Frequency	Port 1	Port 2
3.5 GHz	5.643 dBi	5.648 dBi
7 GHz	8.39 dBi	8.4 dBi

The radiation pattern at 3.5 GHz and 7 GHz is shown in figures 4.16 and 4.17 for the first port and the second port, respectively.

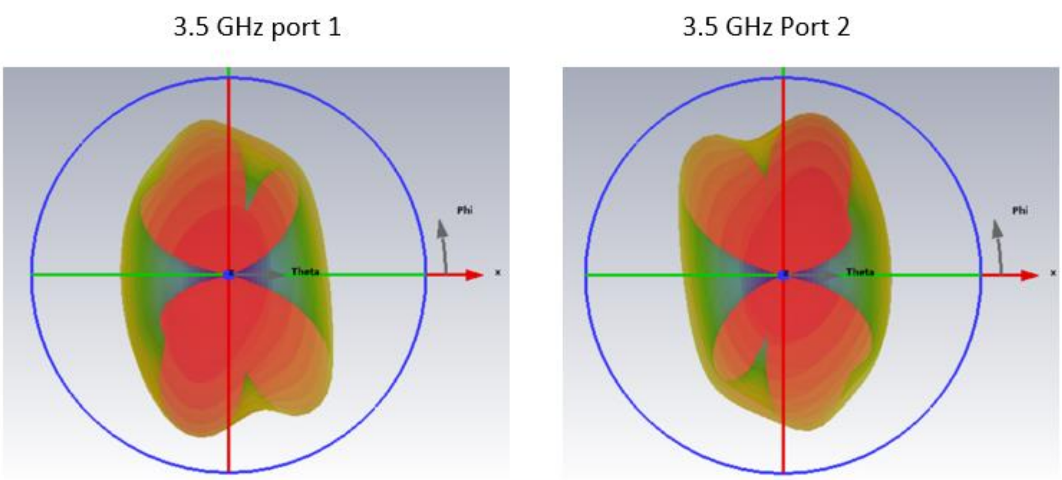

Figure 4.16 : Radiation pattern at 3.5 GHz for ports 1 and 2.

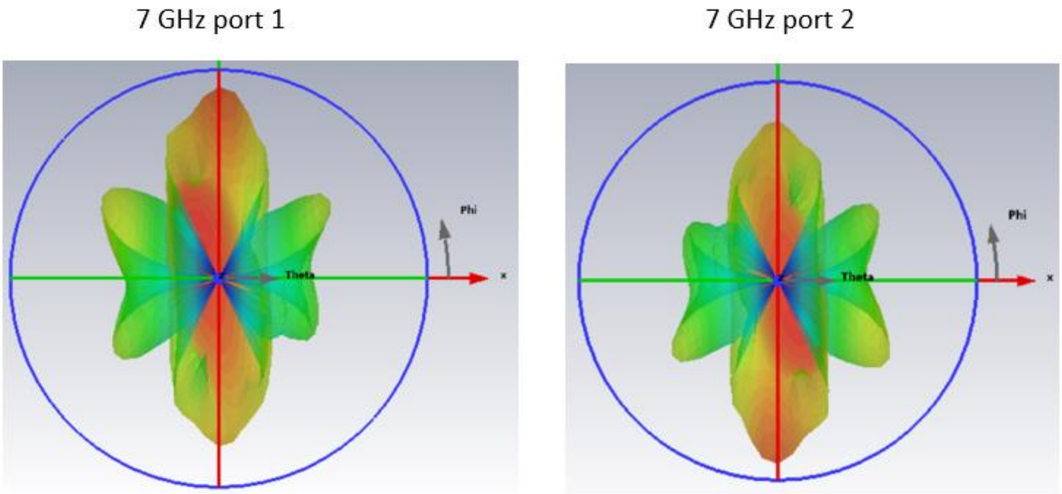

Figure 4.17 : Radiation pattern at 7 GHz for port 1 and port 2.

5. CONCLUSIONS AND RECOMMENDATIONS

In this chapter the conclusions from this thesis are presented and a comparison between the four different fractal-based designs is provided along with some recommendations for future work.

5.1 Conclusion

The spectrum of the fifth generation 5G of the wireless communications is divided into several parts, however, some parts of that spectrum are already being used in some countries around the globe but the development of smaller and more convenient components are still in need. Therefore, in this thesis the design of three different fractal-based antennas were proposed for the 5G applications in the 3.5 GHz and 7GHz centered spectrum bands using CST Microwave studio simulator. The design of the first antenna started by designing a cutted-angles rectangular patch antenna that propagates at 3.5 GHz, then by copying and then scaling-down the same patch and later substracting it from the main patch we got a single ring cutted-angles rectangular patch antenna that propagates at 3.5 GHz with a reflection coefficient of -19 dB and a gain of 2dBi. The second antenna was created by scaling-down the full ring of the first antenna and create a similar inner ring that propagates at 7 GHz center frequency and has a bandwidth between 6.25-8.1 GHz, this antenna is able to propagate at two different 5G frequency bands centered at 3.5 GHZ and 7 GHz respectively. This antenna has a reflection coefficient S_{11} of around -20dB for both resonant frequencies of both bands, and has a gain of 2.29 dBi and 2.51 dBi for the two bands at their center frequency. All these antennas were have a microstrip feeding line with a length of 16 mm which equal to something around $\lambda/4$ of the first band's center frequency, all the antennas have an FR-4 substrate thickness of 1 mm and a width of the feeding line of 1.6 mm so that together they provide a 50 ohm impedance at the input port which assure that most of the input port's waves are being propagated. Finally, in order to increase the gain a 4x1 antenna array was designed to propagate at the same bands, this array has two feeding ports that designed in an inverted way to improve the matching between the array elements, each port is connected to only two propagating elements by a tree shaped λ/4 length microstrip has a reflection coefficient of around -45 dBi and -35 dB for both bands at their center frequencies, respectively. This array antenna has also a gain for the 3.5Ghz centered band of 5.64 dBi for port 1 and 5.648 dBi for port 2, and for the 7 GHz band the gain was equal to 8.39 dBi and 8.4 dBi for port 1 and port 2, respectively. In table 5.1 below we provide a comparison between the four fractal-based designed antennas that focuses on the size, bandwidth, reflection coefficient, and gain.

Table 5.1 : Comparison between the designed antennas.

Antenna	Size (mm)	Feeding	B.W. (GHz)	Gain (dBi)	Reflection coefficient (dB)
Single Ring	27x16x2.2	MSL	3.1 – 4.5	2.0	-19
Double Ring	27x16x2.2	MSL	a) 3.1 – 4.1 b) 6.2 – 8.1	2.29 2.51	-21 -23
Fractal array	90.70x42.5x2.2	2 Tree-shaped MSL	Port1 a) 2.6–3.6 b) 5.8 – 7.5 Port 2 a) 2.6 – 3.75 b) 5.8 – 7.5	Port 1 a) 5.643 b) 5.648 Port 2 a) b)	 -54 -32 -46 -36

5.2 Recommendations For Future Work

As for a future work, these designed antennas can be improved, for example different substrates for the single and double ring antennas, and study the effect of changing the feeding line, However in the case of antenna array, the future work may include increasing the propagating elements, also finding ways improve the gain along with achieving better S_{11} parameters. Also study the effected for the case when antennas for mmWave is needed. Therefore testing whether this design is appropriate for these cases or not.

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