Applications of Fractal and Quasi Fractal Geometries in Slot Antenna Design: A Review

Seevan F. Abdulkareem\textsuperscript{1}, Yaqeen S. Mezaal\textsuperscript{2}

\textsuperscript{1}Computer Technology Engineering Department, Al-Mansour University College, Iraq

\textsuperscript{2}Medical Instrumentation Engineering Department, Al-Esraa University College, Iraq

Corresponding Author Email:yakeen_sbah@yahoo.com

https://doi.org/10.26782/jmcms.2019.08.00018

Abstract

Fractals stand for unique geometries that can be nice-looking for microwave circuit scholars. Latest expansions in wireless communication systems have been caused different experiments to manufacture high-grade diminished components. These experiments motivate microwave circuits and antennas engineers to look for solutions by examining diverse fractal structures. Nonetheless, there are several relevant limits of fractal antennas involving geometric restrictions, low gain, fractal orders and design complexity. These limits are feasibly solved by restructuring methods as in fractal reconfiguration and like pre-fractal structures. These methods have been known as semi or quasi-fractals that can be applied to antenna design without endless scale. Accordingly, quasi-fractal geometry with limited orders or iterations can be exploited for a specific dual/multiband antenna based on a particular fractal iteration.

In this study, the unique properties of fractal geometries will be presented together with the most commonly used fractal geometries applied in the slot antenna design. In this respect, the application of fractal geometries in the slot antenna design can be classified into two categories. In the first category, the fractal geometry is applied directly such that it constitutes the whole slot structure, while in the second one; the fractal geometry is applied indirectly. In this case, there is a slot structure with Euclidean shape, such as triangle, square…etc., and fractal geometry has to replace each line segment in this structure. In addition, slotting processes by fractal or semi fractals in the ground plane of antenna substrates to produce dual or multiband or even wideband response have been discussed in this review paper.

Keywords : fractal geometries, slot antenna design, slot structure, wideband response

I. Introduction

Fractal indicates irregular or broken fragments; the term fractal has been initially presented through Mandelbrot [I] for describing a family of complex shapes which have non-integer dimension and have inherent self-similarity in their geometrical structures. Which is why, there is a necessity for a geometry which is capable of handling such complicated shapes more efficiently compared to the
Euclidean geometry, which has dimensions of integer number, like 1-D line, or 2-D planes...and so on.

Many fields of engineering and science use fractal geometry. A major area of fractal is its use in the antenna design for producing multiband and compact antennas taking advantage of their exceptional features as in self-similarity and space filling [I] [II] [III].

Fractal shaped antennas show certain promising properties, which are associated with their geometrical characteristics. Generally, the fractal structures have manifold copies of themselves at various scales and the fractal’s size is defined through the iteration number and the initiator. The fractal, that is utilized in designing antennas, is typically quasi-fractal or pre-fractal yet not mathematically fractal geometry with unlimited scale. Thus, quasi-fractal of many iterations could be used for certain multi-band antennas. All frequency bands are conforming to a certain fractal’s scale.

Fractal antenna engineering can be defined as a developing field which uses the concepts of fractal to develop novel antenna types with distinguished properties. The self-similarity related to fractal structures cause antenna’s multiband behavior and frequency-selective surfaces. On the other hand, the space-filling properties lead to miniaturized and compact size antennas. Recently, extensive studies were focused on fractal antenna engineering. Fractal methods were utilized to loops, monopoles, patches, dipoles, and slot antennas [III].

Fractal curves can be distinguished through a special feature that, following infinite iterations, their length become infinite even though the whole curve fit into finite area as shown in Figure (1). Such feature could be used for miniaturization of microstrip and printed antennas through increasing the effective electrical length via which current travels. Many applications can benefit from fractal antennas. The continuous expansion in the field of wireless communication has increased the need for compact integrated antennas. Space saving capabilities which are related to fractals to effectively fill a small amount of space provide special benefit of applying integrated fractal antennas over Euclidean geometry [IV].

![Figure (1): Space-filling fractals of (a) 3rd iteration Sierpinski carpet, and (b) 3rd iteration Hilbert curve.](image-url)
Self-Similarity

Self-similarity property means that a small part of the structure is a scaled-down copy of the original structure, as displayed in Figure (2). Therefore, antennas can operate at multiple frequency bands. Traditional fractal geometries including Minkowski, Cantor, Koch, Sierpinski, Hilbert, and other fractal curves were efficiently utilized for producing multi and dual band printed slot antennas for many wireless applications [V].

![Figure (2): Self-similar fractals of (a) 3rd iteration Sierpinski gasket, and (b) 3rd iteration Koch curve.](image)

Fractal Dimension

The main feature of fractals is that they have non-integer dimensions dissimilar to the Euclidian which have integer dimensions. The common intuitive concept of dimension is called the topological dimension. A cube, line segment, point and a square, as displayed in Figure (3) have topological dimensions of 0, 1, 2 and 3, respectively. An integer number is always used for expressing the intuitive dimension [VI].

![Figure (3): Euclidean geometries](image)
Fractal dimension is associated to the self-similarity in that the simplest method for creating a figure that has fractal dimension by self-similarity. Then, the fractal dimensions (FD) will be, as given by [VII]:

\[
FD = \frac{\log_{10}(N)}{\log_{10}(1/r)}
\]

(1)

where \(N\) can be defined as the overall number of distinct copies, \(r\) can be defined as the reduction factor value that indicates how will be the new side length regarding the original side length. With the intention of calculating the fractal dimension of any self-similar shape, the shape can be divided into \(N\) parts, where the size of every part is associated with the size of the original one by the reduction factor value. The fractal dimension \(FD\) equals the topological dimension for any Euclidean shape, but \(FD\) can also be evaluated for any non-standard shapes that exhibit self-similarity.

Dimension of some geometrical shapes are listed below in Table (1). The fourth column contains the FD value for each shape, where FD is calculated using equation (1). Figure (4) demonstrates Euclidean geometrical shapes which are split into \(N\) parts by using a reduction factor of \(1/2\) to divide a line segment, square and cube [VII].

**Table (1): Dimensions of geometrical shapes**

| Shape Name       | \(r\) | \(N\) | FD   |
|------------------|-------|-------|------|
| Line             | 1/2   | 2     | 1    |
| Square           | 1/2   | 4     | 2    |
| Cube             | 1/2   | 8     | 3    |
| Cantor Set       | 1/3   | 2     | 0.63 |
| Sierpinski Gasket| 1/2   | 3     | 1.58 |
| Minkowski Island | 1/3   | 5     | 1.46 |

Copyright reserved © J. Mech. Cont.& Math. Sci.
Seevan F. Abulkareem et al.
Features and Limitations of Fractal Geometries in Antenna Design [VII]

**Features:**
- Miniaturization.
- More efficient input impedance matching multi and wide bands (utilizing single antenna rather than several).
- Decreased mutual coupling in the fractal array antennas
- Frequency independent (reliable operation throughout large ranges of frequency).

**Limitations:**
- Complexity (some types are complex to construct).
- Numerical limitations (become less with the continuing advance in computer technologies).
- The benefit begins to diminish after first few iterations.

However, the features offered by the fractal geometries are more than limitations that they have encountered. In addition, the advances in computer technologies and the computational techniques have contributed to make these limitations less important.

**Commonly Used Fractal Geometries in Antenna Design**

Large number of fractal geometries and their variants are reported in the literatures [VII], but very limited number among these were adopted in designing antennas for various applications. In the following subsections, a presentation of the most commonly used fractal types.

**Cantor Set**

Cantor set can be defined as a standard fractal object that displays precise self-similarity through all scales [VII].
Cantor set include infinite set related to the disappearing segments of the line in unit interval. The optimal way for understanding Cantor set fractal is displaying its construction approach, as shown in Figure (5) for the plainest type of Cantor set or triadic Cantor set.

The set will be created via eliminating the middle third of unit line segment (step \( k = 1 \) in figure). From the two segments that remained of the line, every one of which is 1/3 in length, middle thirds will be removed once more (step \( k = 2 \) in the figure). Middle thirds of the 4 of the rest of line segments, every one of which is 1/9 in length, will afterwards be eliminated (\( k = 3 \)) and similarly to infinity. The remaining is considered as a set of infinitely various disappearing segments of the line that lie on unit interval whose combined and individual lengths come close to 0. Such point set is referred to as Cantor dust or Cantor set.

**Figure (5): The generation of Cantor set.**

Regarding the Cantor set construction, the preliminary unit line segment \( k = 0 \), is referred to as the set’s initiator. The initial stage, \( k = 1 \), is referred to as the generator or motif, since it is considered as the recurrent iteration related to this stage on the following line segment that result in the set’s creation. It is necessary repeating the generation procedure only via the number of stages needed to deceive the eye, and not countless times (which is considered accurate for every illustration that is related to fractal objects). Yet, the Cantor set is obtained following infinite number of iterations. A set of line segments with a particular measurable length are produced via a finite number of iterations. Such objects created *en route* to fractal object are referred to as pre-fractals[VII].

**Koch Curve**

This construction method is displayed in Figure (6), it is considered as an extra sufficiently documented fractal. Just like the Cantor set, Koch curve is easy to construct through the use of iterative process starting with set’s initiator as the unit line segment (stage \( k = 0 \) in figure). The unit line segment will be separated to thirds, the middle one will be eliminated. After that, the middle third will be substituted by 2 equal parts, they two are 1/3 in length, that create an regular triangle (stage \( k = 1 \)): this stage is the curve generator. In the following stage \( (k = 2) \), the middle third will be eliminated from the 4 segments, every one of which will be substituted by 2 equal
segments. Koch curve will be produced after repeating this procedure for an infinite number of times. Once more, the set’s self-similarity is obvious: all sub-segments are considered as carbon copy of the original curve, as displayed in Figure (6) [VII].

A visible feature of Koch curve is that it apparently has an endless length. Which could be visible from the process of construction. At every stage, \( k \), in its initiation, the length regarding the pre-fractal curve will increase to \( L_{k-1} \), where \( L_{k-1} \) can be defined as the length of the curve in the preceding stage.

It might be visible that Koch curve is efficiently produced from corners, thus, there is no unique tangent happens upon it. Koch curve isn’t a smooth, also it is nowhere-differentiable, as unique tangent, or slope, cannot be gotten upon it. It is a fractal object that possesses a fractal dimension. Every one of the smaller segments of the Koch curve is a precise simulation of the entire curve [VII].

![Figure (6): The generation of Koch curve.](image)

**Figure (6): The generation of Koch curve.**

**Sierpinski Gasket and Carpet**

The construction, which is related to Sierpinski gasket, is displayed in Figure (7). Filled triangle in the plane is the initiator in such case. The middle triangular part will be eliminated from original triangle. After that, the central triangular segments will be eliminated from the rest of the triangular elements etc. Sierpinski gasket is created following an infinite number if iterations. All pre-fractal step in construction are composed of 3 smaller copies of the previous step, every one of the copies is scaled through a factor of 1/2 [VII].
Sierpinski carpet is another variant of Sierpinski gasket, it is displayed in Figure (8). The construction approach for gasket and carpet are similar. In this case, the initiator is a square and the generator will remove the central square, that its side length 1/3 of the original square. With Sierpinski carpet and gasket, the structuring processes cause fractal curves whose area disappears [VIII].
Minkowski Island Fractal

The starting geometry regarding Minkowski island fractal, referred to as initiator, is a Euclidean square. All the 4 straight segments related to the starting structure will be substituted by generator, which has been displayed at the bottom of Figure (9). This iterative generating process will continue for infinite times. The ultimate outcome is a curve with infinitely intricate underlying structure which is not differentiable at any point. The generator will replace all straight segments of geometry. The initiator is square as displayed in the Figure (9) along with the first three construction iterations [VII].

Figure (9): The generation of Minkowski island fractal.

Hilbert Curve

The first four iterations with initiator of Hilbert curves are displayed in Figure (10). It could be noticed that the geometry at a step could be acquired by putting together 4 copies of the preceding iteration, linked to additional line segments. A lot of Hilbert pre-fractal based structures were suggested for producing printed and micro-strip dipole and monopole antennas with miniaturized size and multi-band response for various implementations [IX].
Figure (10): The generation of Hilbert curve.

Peano Curve

The initiator regarding Peano curve is again specified via a straight line and the correspondent generator include 9 lines one-third of initiator. The first generator’s line runs horizontally, the second turns up 90 degrees, after that, a horizontal segment follows prior to when the curve turns down by 90°. The fifth line move back to the end of the first line with no touching between them. The following part of the curve heads down by 90 degrees, followed by a horizontal part prior to the time where it goes up again. Finally a line located in horizontal position once more forms the last part, as shown in Figure (11). This type is used in antenna design as a modified structure in [X].

Figure (11): The first three iterations levels to construct the Peano pre-fractal curve[X].

Copyright reserved © J. Mech. Cont.& Math. Sci.
Seevan F. Abdulkareem et al.
Some of the Reported Fractal Slot Antennas

As pointed out earlier in study one, in Figure (12), fractal geometries have been widely used to create the structures of slot printed antennas. However, the application of fractals has been adopted in two ways: direct and indirect application. In the following subsections, some of the reported antennas in these categories are highlighted based on the studies reported in [VII].

Fractal Based Slot Antennas: Direct Application

In this classification, direct application of fractals has been adopted. In such a case, the fractal geometries set up the entire antenna slot configurations.

The dual andmultiband behaviors of such antennas have been extracted practically directly without the necessity of any tuning components or slot shape reform. The fractal geometry can be applied to slot structure as well as to the patch structure. Slot antennas based on fractal curves have concerned the scholars to achieve antenna smallness with various resonances.

Sierpinski Gasket Slot Antenna

This fractal has been applied to model a dualband microstrip line fed slot antenna for WLAN uses. The antenna slot structure has the arrangement of Sierpinski gasket of the 1st iteration as shown in Figure (12). The antenna was fed with (50)Ω microstrip transmission line, and the slot structure has printed on the opposite side of the substrate. Simulation fallouts indicate that the resultant antenna shows remarkable dual frequency resonant performance as depicted in Figure (13). This makes the antenna apposite for dualband communication systems involving the dual band WLAN applications.

![Figure (12): The geometry of the proposed 1st iteration Sierpinski gasket printed slot antenna [VII].](image)

Copyright reserved © J. Mech. Cont.& Math. Sci.
Seevan F. Abdulkareem et al.

226
A parametric study has been shown to investigate the most consequences of in effect antenna parameters on its overall performance. The lower resonance was principally attributed by the side length of the slot structure, whereas the length of the feed influences, to definite extents, the position and the matching of the higher resonant frequency.

**Fractal Slot Antenna with Variable $f_2/f_1$**

As a figure of merit of a well designed dual-band antenna is its capability to present a wide range of the two resonant frequency ratio $f_2/f_1$. In the following example, a fractal based slot antenna structure that offers such a feature, as in Figure (14). For this antenna, the feeding and matching structure, which is a dual L-probe, was projected to broaden its bandwidth. The particular goals for such an antenna are specified as tunable dual-band ($f_1, f_2$) operation with orthogonal polarizations as shown in Figure (15), and tunable $f_2/f_1$ ratio as depicted in Figure (16).
In addition, Koch fractal antenna was suggested to create an inverted-L for dual-band WLAN USB dongle application. Fractals produced from several Euclidean structures like circle, triangle and others, were used to construct dualband antennas for various communication applications.

Circular and modified half circular fractal shaped dual band antennas were tested in [VII] for use in dual bands WLAN and C band relevances.

Furthermore, a quasi-fractal based slot structures have been efficaciously used in diversetecnhiques to produce parts (or the full topology) of the ground plane of dual band antenna. Other fractal types applied to microstrip patch antenna to produce dual-band for WLAN applications. In all these works, the dual-band behaviors are obtained without the need for tuning element.
Fractal Based Slot Antennas: Indirect Application

In this classification, the slot structure stands for a grouping of Euclidian structures like square, triangle, rectangle and other polygons, and fractals applied to on these structures, where every line segment is substituted by fractal curve with particular iteration level. In this case, the multiband performance has been reached in diverse methods.

Koch Fractal Based Slot Structures (without tuning stub)

In this case, the use of indirect application of fractal without tuning stub results in a multi-band behavior within the frequency range of interest.

The example presented in [VII] is a printed slot antenna proposed for use in the multi-band wireless communication applications. The antenna slot structure has a rectangular shape with its width, from the side of feed, has been modified in the form of Koch fractal curve of the second iteration as shown in Figure (17). The antenna was fed with (50) Ω microstrip transmission line etched on the reverse side of the substrate.

Simulation results show that the resulting antenna exhibits a multi-resonant performance with bandwidths suitable for a wide variety of multi-band wireless communication applications as depicted in Figure (18). These applications include 2.4 GHz WLAN, 2.5 GHz mobile WiMAX, 3.5 GHz mobile WiMAX, U-NII midband and U-NII high-band. Varying the feed line length by –2, 0, 2, and 4 mm with respect to the antenna center, results in the return loss responses shown in Figure (18).

Figure (17): The geometry of Koch based fractal shaped slot antenna [VII]
Koch Fractal Based Slot Antenna (with tuning stub)

The example described here, has been reported in [VII]. A dual wide-band CPW-fed modified Koch fractal printed slot antenna is proposed for WLAN and WiMAX operations, as shown in Figure (19). The design frequency of a triangular slot antenna has dropped by Koch iteration technique resulting in a miniaturized antenna. Investigations about the impedance and radiation characteristics of the projected antenna signpost that are formed Koch fractal slot antenna has an impedance bandwidth under 2.4/5.2/5.8GHz WLAN bands and the 2.5/3.5/5.5 GHz WiMAX bands. As shown in Figure (20). The antenna shows omnidirectional radiation coverage with again higher than 2 dBi in the complete operating band.

The dualband response is extracted as a result of providing the feed line with a tuning stub with embedded slit.
Peano Based Slot Antenna (with rotated slot structure)

In this case, the dualband resonant behavior is obtained by rotating the slot structures around the antenna axis as reported in [VII].

Copyright reserved © J. Mech. Cont.& Math. Sci.

Seevan F. Abdulkareem et al.
In this work, Giusepe Peano fractal geometry has been adopted in the slot antenna, as shown in Figure (21). The Giusepe Peano fractal slot antenna of the second iteration at operating frequency of (4)GHz, as shown in Figure (22), with a bandwidth of (5.9)GHz. The simulations and measurements of a fabricated antenna model have come to an agreement. It is perceived that the case of feed line along the diagonal of fractal square slot offers the finest dualband radiation performance below (7)GHz frequency.

**Figure (21):** Peano based slot antenna with the slot structure rotated by an angle $\alpha$ with respect to the antenna axis as presented in [VII]

**Figure (22):** Simulated return loss responses for several values of angle, $\alpha$, of the antenna depicted in Figure (21) as presented in [VII]

Copyright reserved © J. Mech. Cont.& Math. Sci. Seevan F. Abdulkareem et al.
Commonly Used Tuning Stubs in Slot Antenna

Generally, the tuning stubs are used to regulate coupling between the feed line and the slot structure. Stub loaded feed lines are commonly used in printed slot antenna to control the position of the resonant bands. Furthermore, antennas with stub loaded feed lines are characterized by relatively high gain as compared with those without stubs.

As it is implied in Figure (23), and recall Figure (3), the stubs can be divided into two main categories: Fractals, and non Fractals.

![Application of Fractal Geometry to Dual-band Slot Antenna Structures](image)

**Figure (23): Categories of tuning stubs used in dual-band slot antenna structures.**

Figures from (24 to26) represent some of the recently published works relating to the use of non fractal stubs to extract the resonant behavior of the specified printed slot antennas together with their corresponding return loss responses as depicted in [VII].

![Slot antenna with ring stub](image)  
![Measured and simulated return loss responses](image)

**Figure (24):** (a) Slot antenna with ring stub, (b) Measured and simulated return loss responses.
Figure (25): (a) Circle based fractal slot antenna with circular stub, (b) Measured and simulated return loss responses.

Figure (26): (a) Circle slot antenna with circular ring stub, (b) Measured and simulated return loss responses.

Figures from (27 to 28) represents some of the recently published works relating to the use of fractal stubs to extract the resonant behavior of the specified printed slot antennas together with the corresponding return loss responses as stated in [VII].
Quasi Fractal Antennas

In general, pre fractal geometries or modified fractals or self-similar structures with specified outlines are termed as quasi or semi fractal geometries with specific finite orders. In the literature, dual and multiband semi fractal antennas are reported in [XI] [XII] [XIII] using single layer FR4 substrate and dual via ports. On the other hand, printed slot antenna has been designed based on etched quasi fractal slot in the ground plane of FR4 substrate and single 50 Ohm microstrip feed as stated in [XIV]. The number of bands of printed slot antennas can be inspected by doing parametrical investigations of microstrip feedlength with respect to antenna response by trial and errors. Also, quasi fractal or fractal scaling factor or orientation can be investigated [XIV] [XV].

Wideband Fractal and Quasi-Fractal Antennas

By means of fractal and quasi-fractal structures, wideband frequency responses with bandwidth of several gigahertzes can be realized by using reduced (partial) ground planes as in reported compact antennas using FR4 substrates in [XVI] [XVII] and...
The reduced ground plane can be in any configuration based on realized and intended antenna response by designer. Also, based on above, fractal geometries like Hilbert-zz [XIX], Sierpinski [XX], Hilbert [XXI] [XXII][XXIII], or their modifications (as quasi-fractals), or hybrid fractals [XXIV], can be used in constructing microstrip resonators for wideband antennas with single feed.

Conclusions

Based on this survey, fractal or quasi-fractal slot antennas are mostly verified for dual and multiband antennas. Single band antenna is feasible but it is in less and restricted applications. In addition to substrate specifications, fractal or quasi fractal slot antennas are affected by used feed, slot structure, and the nature of slotting process in upper layer of used substrate or in the ground plane. Quasi or semi fractal antennas stand for antennas with reformed structures based on fractal properties but under limited scales and iterations. Printed slot antennas can be designed by using fractals or quasi-fractals but the slotting process must be in the ground plane and just 50 Ohm microstrip feed can be employed. Wideband microstrip antennas using fractal or quasi-fractal microstrip resonators are feasibly designed with reduced ground plane.

References

I. B. B. Mandelbrot, "The Fractal Geometry of Nature", W. H. Freeman, San Francisco, CA, 1982.
II. Jawad K. Ali, and A. S. A. Jalal, "A Miniaturized Multiband Minkowski-Like Pre-Fractal Patch Antenna for GPS and 3g IMT-2000 Handsets", Asian Journal for Information Technology 6(5), pp. 584-588, 2007.
III. P. S. Addison, "Fractals and Chaos", Institute of Physics Publishing, IOP, Ltd, London, 1997.
IV. Jawad K. Ali, M. T. Yassen, M. R. Hussan, and A. J. Salim, " A Printed Fractal Based Slot Antenna for Multi-band Wireless Communication Applications", Progress In Electromagnetics Research, PIER Proceedings, Moscow, Russia, August 19-23, 2012.
V. K. Falconar, "Fractal Geometry", John Wiley & Sons, Ltd., Baffins Lane, Chichister, 1990.
VI. N. Poprzen, and M. Gacanovic, "Fractal Antennas: Design, Characteristics and Application ", Regular Paper, 2000.
VII. Seevan F. Abdulkareem, Design and Fabrication of Printed Fractal Slot Antennas for Dual-band Communication Applications, M. Sc Thesis, University of Technology, Iraq.
VIII. Y.S. Mezaal, H.T.Eyyuboglu, J.K. Ali, New Dual Band Dual-Mode Microstrip Patch Bandpass Filter Designs Based on Sierpinski Fractal Geometry.In, Proceeding of Advanced Computing and Communication Technologies, Rohtak, India, pp.348-352, 2013.

Copyright reserved © J. Mech. Cont.& Math. Sci.
Seevan F. Abdulkareem et al.

236
IX. Y. S. Mezaal, Jawad K. Ali, and H. T. Eyyuboglu. "Miniaturised microstrip bandpass filters based on Moore fractal geometry." International Journal of Electronics 102.8 (2015): 1306-1319.

X. Yaqeen S. Mezaal, Halil T. Eyyuboglu, and Jawad K. Ali. "A new design of dual band microstrip bandpass filter based on Peano fractal geometry: Design and simulation results." 2013 13th Mediterranean Microwave Symposium (MMS). IEEE, 2013.

XI. Y. S. Mezaal, New Compact Microstrip Patch Antennas, Design and Simulation Results. Indian Journal of Science and Technology, 9, 12, 2016.

XII. Yaqeen S. Mezaal, Dalal A. Hammood: New microstrip quasi fractal antennas: Design and simulation results. 2016 IEEE 36th International Conference on Electronics and Nanotechnology (ELNANO); 04/2016, DOI:10.1109/ELNANO.2016.7493014

XIII. Y. S. Mezaal, "New microstrip semi-fractal antenna: Design and simulation results," 2016 24th Signal Processing and Communication Application Conference (SIU), Zonguldak, 2016, pp. 1601-1604. doi: 10.1109/SIU.2016.7496061

XIV. Yaqeen Sabah Mezaal, S. F. Abdulkareem, J. K. Ali: A Dual-Band Printed Slot Antenna for WiMAX and Metrological Wireless Applications. Advanced Electromagnetics 08/2018; 7(3):75-81., DOI:10.7716/aem.v7i3.765

XV. Y. S. Mezaal, and S. A. Hashim . Design and Simulation of Square Based Fractal Slot Antennas for Wireless Applications. Journal of Engineering and Applied Sciences, 13(17), 7266-7270, 2018.

XVI. Yaqeen Sabah Mezaal, Seevan F. Abdulkareem, New microstrip antenna based on quasi-fractal geometry for recent wireless systems, 26th Signal Processing and Communications Applications Conference (SIU), 2018.

XVII. Yaqeen Sabah Mezaal, et al. New Compact Wideband Microstrip Antenna for Wireless Applications. Advanced Electromagnetics 09/2018; 7(4)., DOI:10.7716/aem.v7i4.860

XVIII. Yaqeen Sabah Mezaal, et al. Miniaturized Wideband Microstrip Antenna for Recent Wireless Applications. Advanced Electromagnetics 09/2018; 7(5). DOI:10.7716/aem.v7i5.806.

XIX. Yaqeen Sabah Mezaal, Halil Tanyer Eyyuboglu, Jawad K. Ali: A Novel Design of Two Loosely Coupled Bandpass Filter Based on Hilbert-zz Resonator with Higher Harmonic Suppressions. 3rd International IEEE Conference on Advanced Computing and Communication Technologies (ACCT-2013); 04/2013.

XX. Yaqeen Sabah Mezaal, Halil Tanyer Eyyuboglu, Jawad K.Al: New Dual Band Dual-Mode Microstrip Patch Bandpass Filter Designs Based on Sierpinski Fractal Geometry. 3rd International IEEE Conference on Advanced Computing and Communication Technologies (ACCT-2013); 04/2013.

XXI. Yaqeen Sabah Mezaal, halil T.Eyyuboglu, Jawad K.Ali: Wide Bandpass and Narrow Bandstop Microstrip Filters Based on Hilbert Fractal
Geometry: Design and Simulation Results. PLoS ONE, 12/2014; DOI:10.1371/journal.pone.0115412.

XXII. Yaqeen S. Mezaal, Halil T. Eyyuboglu, Jawad K. Ali: New Microstrip Bandpass Filter Designs Based on Stepped Impedance Hilbert Fractal Resonators. IETE Journal of Research, 07/2014; 60(3):257-264. DOI:10.1080/03772063.2014.922018

XXIII. Yang, Xue-Song, Bing-Zhong Wang, and Yong Zhang. "A reconfigurable Hilbert curve patch antenna." In 2005 IEEE Antennas and Propagation Society International Symposium, vol. 2, pp. 613-616. IEEE, 2005.

XXIV. Y.K. Choukiker, S.K. Sharma, S.K. Behera. Hybrid fractal shape planar monopole antenna covering multiband wireless communications with MIMO implementation for handheld mobile devices. IEEE Transactions on Antennas and Propagation. Dec 17;62(3):1483-8, 2013.