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A Comprehensive Examination of the Current State of the Art in Fractal Array Antennas

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Abstract: Modern astronomical and advanced wireless communication systems necessitate the utilization of array antennas that provide programmable multibeam capabilities, broadband coverage, high-end coverage range, high gain, reduced side-lobe levels with broader side-lobe level angles, enhanced signal-to-noise ratio, and compact dimensions. This has led to many array antenna theories, including fractal array antennas. In order to enhance comprehension of the operational mechanisms of fractal antennas, an introductory exposition on the underlying theoretical principles is provided. This paper provides an in-depth analysis of current developments in fractal array antenna design. To better understand how fractal antenna function, a primer on the theory behind them is presented. In addition, comparative research of the present state-of-the-art in antenna miniaturisation, gain, and Bandwidth augmentation with fractal array are performed.

Keywords: metamaterials, fractal antenna, array antenna, high-gain antenna array, Cantor linear array, circular polarization, side lobe level (SLL)

1. INTRODUCTION

In antenna theory, microstrip antennas are highly active. A thin, grounded dielectric substrate holds a metallic patch for microstrip antennas. Microstrip antennas are portable, compact, cheap, flexible, and easy to integrate with active electronics. Their limitations include low power, bandwidth, polarization purity, and spurious feed radiation [1]. Improved bandwidth and gain are difficult for microstrip antenna design and MIMO communication [2].

In situations where the gain, bandwidth, and power handling capabilities of an individual microstrip antenna element are deemed inadequate, the utilization of an array configuration can be employed to enhance overall performance. In order for the array to operate as an efficient radiator, it is necessary to ensure that each patch within the array is adequately supplied with [3, 4]. The feed arrangement may consist of one or more lines. A network consisting of a solitary feed line is commonly referred to as a series feed network, whereas a network comprising several feed lines is commonly known as a corporate feed network. Corporate feed networks provide the efficient and adaptable transfer of power among various antenna components. The manipulation of the beam's direction within the corporate feed network can be achieved by the introduction of a phase alteration [5].

The use of an array consisting of numerous smaller antennas has the potential to offer equivalent functionality to that of a solitary, cumbersome antenna. Antenna arrays are favored due to their greater directivity and gain, which are essential attributes for numerous applications. The aforementioned categories encompass several domains such as communication systems, radar technology, satellite systems, electronic warfare mechanisms, and the field of radio astronomy. Various geometries, such as linear, rectangular, circular, triangular, and spherical, among others, can be employed to construct an antenna array of identical elements. The electronic scanning of the radiation pattern of a phased array antenna

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is a highly advantageous and innovative capability. The radiation pattern of the array can be electrically controlled and modified in terms of its shape by manipulating the amplitude and phase of the excitation of each radiating component. The resultant electric field generated by the array is obtained by calculating the vector sum of the electric fields created by each individual radiating component. When the constituent fields of the antenna arrays exhibit cooperative behavior, they generate a highly efficient directional pattern. The antenna array holds significant importance in contemporary communication and industrial systems that rely on radio frequency (RF), microwave, or millimeter wave frequencies. In order to address the challenges faced by modern and future communication systems, it is imperative to employ devices that possess the capability to dynamically change the electromagnetic field. Antenna arrays are considered to be the optimal and highly versatile method for facilitating the functionality of these devices

1.1. The Application of Fractal Technology in Antenna Design

A structure characterized by a perpetual absence of termination is referred to as a fractal pattern. The aforementioned structures exhibit patterns that possess unlimited complexity and demonstrate self-similarity across multiple scales [6]. Fractals has the capacity for self-replication, rendering them applicable in diverse domains such as science and engineering. The term "fractal" originates from the Latin term "fractus," denoting a surface characterized by a fragmented or non-uniform arrangement. Several instances of naturally occurring fractals include the shoreline of the ocean, mountain formations, sea shells, snowflakes, leaves, and the intricate pattern of a peacock's plumage. All natural fractals can be categorized as random fractals due to the absence of a deterministic process for their generation and their existence on non-integral surfaces. These structures are also commonly known as "stochastic fractals." Various statistical methodologies are employed in the field of fractal formation. The level of unpredictability exhibited by these fractals varies across different structures and manufacturing techniques. The phenomenon of Brownian motion exhibited by microscopic particles in a fluid might be considered as a prominent example of random fractal activity.

This can be noticed by looking at the diagram. Geometric structures known as deterministic fractals are characterised by their ability to recur at a variety of sizes. In contrast to fractals that are generated at random, these ones have dimensions that have been accurately measured for their development. The construction of deterministic fractals always involves the use of iterated function systems (IFS) and complex number approaches. Scaling, twisting the plan axes, and dislocating the source are the three steps involved in the generation of a fractal structure employing these approaches. The Koch curve, Sierpinski triangle, Julia sets, and Sierpinski square are only a few of the examples of well-known IFS and complex number fractals.

Within these deterministic fractal structures, the fundamental generator, also known as the seed, duplicates itself indefinitely [7–9].

1.2. Literature Review

When it comes to long-range communication systems, array antennas are a better option than aperture antennas. Since the emission pattern can be fine-tuned with a larger number of antenna components, side lobes are reduced and scanning beams may be made more directed. These basic characteristics [11–14] are what make array antennas so useful in military settings. Traditional array antennas' performance is inadequate for modern wireless communication systems. Due to their new ideas about antenna properties like reconfigurable multi-beams, excellent array factor properties, reduced mutual coupling losses, ultra-wide band, and multiband characteristics, fractal array antennas have recently become a candidate for use in both military and civilian fields [15, 16].

Y. Kim, et al. constructed random fractal array antennas using fractal geometric technology to cut down on unwanted side lobes [17]. Authors presented a technique to combines the best features of both random array antennas and periodic array antennas. For this purpose, the idea of self-similarity is integrated into the theory of random array antennas to control the sidelobe levels. Strong and with a reasonable number of side lobes, fractal random array antennas are an excellent option for large thinning array antennas.

Carles Puente-Baliarda, et al. purposed a Multiband operation and reduced side lobe levels fractal Cantor array antenna [18]. In this article authors also discusses and analyses two approaches to building multi-frequency fractal array antennas. A fractal design of array antennas is introduced, and the relative current distribution function of such a fractal array is derived; in addition, the fractal distance between array components is studied.

L. Dwight, et al. [19] discussed the Cantor array antenna of fractal nature, which had an expansion factor of three for multiband operation and lower side lobe levels than other antennas. This article examines two potential approaches to the fabrication of multi-frequency fractal array antennas and evaluates, compares, and contrasts the benefits offered by each of these approaches. In this study, authors investigate the fractal distance between array components. Additionally, authors introduce a fractal design of array antennas and derive the relative current distribution function of such a fractal array.

D. H. Werner, et al. discusses and designed a methodical strategy for the process of developing linear and planar fractal array antennas [20]. This geometric method, which is based on the concept of sub-array concentric circular rings, may be used to construct any kind of polygon shape imaginable. Cantor linear, Sierpinski triangular, square, and hexagonal fractal array antennas are some types of fractal array antennas that may be designed using this geometric design technique. Other examples include. They demonstrated numerous essential characteristics of fractal array antennas by making use of the recursive structure of fractal geometric technology. Some of these characteristics include multiband behavior, methods for getting lower sidelobe levels, and thinning. Because of the recursive nature of this design process, developing algorithms for it is a very straightforward task.

Douglas H. Werner, et al. [21] purposed a Peano-Gosper fractal array antennas. All of the antenna's elements are arranged in a straight line following a Peano-Gosper curve that allows them to avoid colliding with each other. In comparison to more conventional periodic planar array antennas, which typically have square or rectangular shapes and regular boundary borders, the frequency range of these fractal array antennas is relatively wider, which is just one of the many benefits that come along with using these antennas. These arrays do not display any grating lobes, and this is true even when the distance between antenna components is as close as physically feasible (at least one wavelength apart). Radiation patterns of Peano-Gosper fractal array antennas have been described, along with a well-organized iterative technique that can be used to quickly calculate radiation patterns up to an infinite number of stages of development. This technique can be used to determine the radiation patterns of Peano-Gosper fractal array antennas.

The authors W. Kushirun, et al. [22] offer a concentric circular design process for creating antennas with a fractal array shape, such as a pentagon, an octagon, or a honeycomb, with an expansion factor of 2. Iterative improvements in these arrays' directional performance. The impact of the array's center antenna element has also been studied. The suggested fractal arrays' center element enhanced the behavior of the array's factors. Additionally, a technique for designing conformal fractal array antennas (3D) using concentric spheres is presented. Broadband antenna arrays employing the Menger sponge and Sierpinski gasket conformal fractal designs are created with this 3D design process. Designing such arrays is a difficult task.

Pingjuan L. Werner, et al. [23] have designed a class of antennas they name Peano-Gosper fractal array antennas because of their self-similar structure. In order to prevent the various components of the antenna from coming into contact with one another, they are arranged in a row that follows a Peano-Gosper curve in a straight line. The frequency range of these fractal array antennas is rather extensive in comparison to that of more common periodic planar array antennas, such as those with square or rectangular geometries and regular boundary borders. Fractal array antennas also have regular boundary bounds. Even when the spacing between the antenna components is made as small as is practically possible, these arrays still do not exhibit any symptoms of grating lobes (at least one wavelength apart). We have defined the radiation patterns of Peano-Gosper fractal array antennas and coupled them with a streamlined iterative approach that can be used to rapidly compute radiation patterns up to an infinite number of stages of evolution. This approach will be discussed in more detail in the following section.

Anirban Karmakar, et al. proposed Microstrip fractal planar array antennas using a Sierpinski carpet structure [24] as shown in fig. 1. As a result of their geometrical make-up, the mutual coupling between the antenna components dropped to below -20dB, and low side lobes began to form.

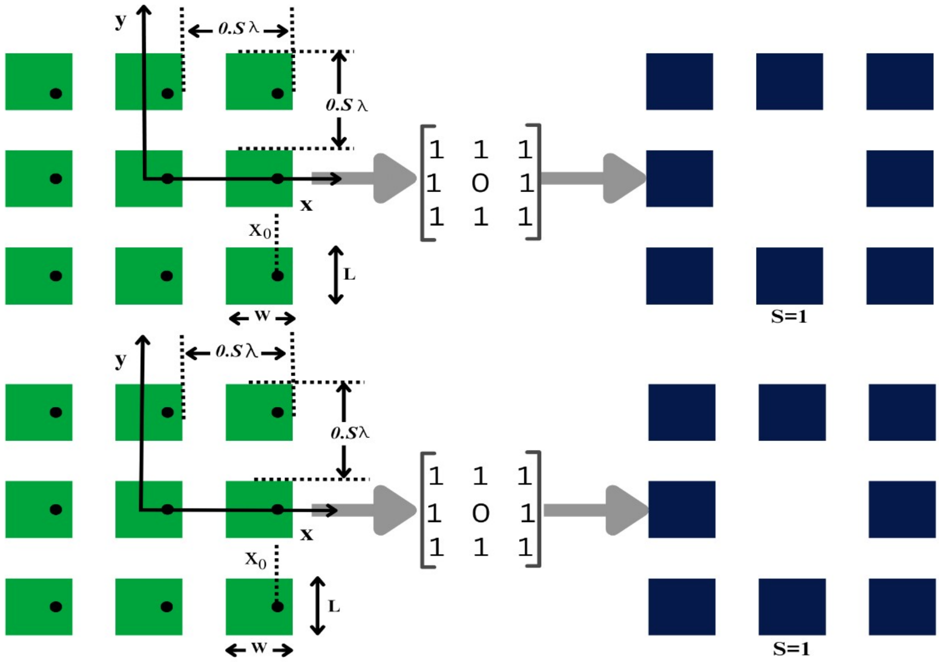

Fig. 1. Illustration of the procedure for converting a 3X3 rectangular microstrip planar array in to a first stage (5'=1) of Sierpinski carpet based thinned array by removing the central element.

The authors A. N. Jabbar, et al. showed off three different forms of new fractal array antennas for use in space and high-tech wireless networks [25]. They outperform the widely-used Uniform Square array, as well as random conventional array antennas and the Sierpinski fractal array antenna. Antenna arrays inspired by Twig, Dragon, and Flap fractal structures are presented.

N. Deepika Rani, et al. compare the Cantor fractal linear array antenna's benefits to those of more traditional arrays [26]. Fractal structures like those used in Cantor linear arrays allow them to outperform more traditional linear array antennas in terms of all of the array factor attributes. Over time, narrower beams and fewer side lobes may be achieved by increasing the expansion factor and iteration count.

V. S. Rao, et al. developed Cantor linear array as a solution to the problem of having an odd number of antenna components [27]. Cantor arrays normally consist of three different components, however at any given moment only two of those elements will be functioning. In this case, the authors suggest making use of four different components, with two of them being in the "on" position and the other two being in the "off" position. Because of this, there is an indirect change in the quality of the array factor as a consequence of the varying distance between the antenna components. The array that is detailed in this paper has obtained greater resolution and side lobes in comparison to both the Cantor fractal array and the standard linear array antenna.

R. T. Hussein, et al. [28] explain the idea of fractal patterns, which are used in antenna arrays to provide multiband behavior. In designing multiband fractal linear array antennas, the Cantor set is a key component shows in Fig. 2. The characteristics of array factors are compared to those of the more common linear array.

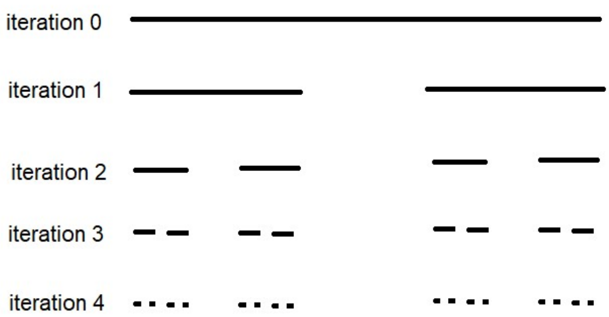

Fig. 2. The first four iterations in the construction of the Cantor set array.

M. Levy, et al. purposed a quick method for smart antenna applications that presents itself via the use of fractal array antenna theory, time and location tag algorithms, and beam shaping algorithms [29-30]. The new techniques that have been suggested continue to enhance the distribution of computational sources for the progression of rapid beams, and the method that has been suggested significantly reduces the amount of time that is required for scheming the array factor. It also considerably reduces the amount of reliance placed on the user's memory.

Levy Mounissamy, et al. presented a conceptual study of fractal array antennas for use in optical communication systems [31-32]. Both the diverging and converging optical fractal antennas, in addition to the non-linear one, are suggested and investigated. The arrays that have been described have great potential for a variety of forthcoming applications, including efficient quantum light sources, nano-scale spectroscopy, and high-speed data transmission systems.

S. Hebib, et al. purposed a Cantor spiral thinning as a way for achieving both lower side lobe levels and narrower main beams simultaneously in a thinned array antenna [33] as shows in fig. 3. Thinner by roughly 10%, this array yet exhibits the same array factor behavior as a standard Cantor circular array antenna.

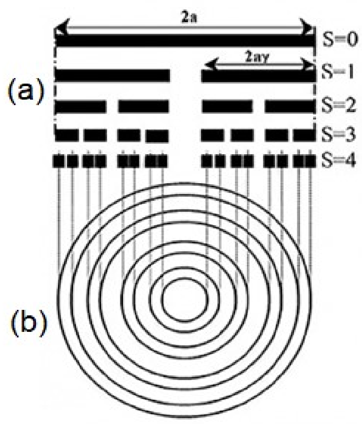

Fig. 3. (a) Symmetric polyadic Cantor set at stage of growth S = 1; 2; 3; and 4.
(b) Resulting concentric rings at stage S = 4.

A novel thinning array antenna form to reduce unwanted side lobes was discussed by Anirban Karmakar, et al. [34]. For the reduction of the side lobes, this paper proposes a new technique using the Sierpinski square design, which is called sequential elimination of components. For the purpose of showing the suggested thinning method, a 99 array with microstrip patch antenna components has been explored.

Carsten Metz, et al. [35] presented effective thinning strategies using non-linear multiplicative processing of array antennas for high resolution digital beam-forming radar applications. These sub-array-based, nonlinear multiplicative thinning processing algorithms show off very promising properties, such as thinning by as much as 80% with very minor sacrifices in picture detail.

Carlo Bencivenni, et al. have presented a novel thinning procedure for linear array antennas used in satellite systems [36]. This technique reduces the size of the array antenna by "Switching off" the antenna components with the lowest weights in the "weight vector" that get the maximum gain. The method's efficacy is validated by comparing it to a precise combinatorial search strategy for finding the best solution for designing irregular array antennas of varying sizes.

Ovidio Mario Bucci, et al. suggested a novel tapering strategies to address the shortcomings of local and global optimization techniques currently employed in satellite communications [37-38]. It turns out that local optimization techniques aren't very useful for huge arrays, and global optimization requires intensive computer procedures. In this paper, one- and two-dimensional tapering strategies, respectively, are presented for linear and circular array antennas. The analytical methods take into account the geometry of the array antenna's central node and the array antenna's components. These approaches are helpful in computing the whole geometry of density tapered linear and concentric circular arrays quickly, iteratively, and deterministically.

K. Ulichny, et al. [39] proposed a thinned array antennas developed by randomly eliminating 22 array antennas (meaning, four neighboring elements) in large aperture arrays, with varying degrees of success. Roughly 5-to-10% of the antenna elements may be thinned in this way without compromising the array factor qualities of the rest of the antenna.

Alessandro Ramalli, et al. developed an antenna with a density tapered array configuration for use in ultrasonic imaging [40]. A method is presented in this article for designing the layout of medium, big, and very large circular array antennas with a minimal number of antenna components that conform to Fermat's spiral seeds, and spiral density that tapers off toward the center. Because of characteristics like aperiodic and deterministic geometry, a special effort is made to guarantee consistent performance throughout a broad range of wheel orientations.

Noor Ainniesafina Zainal, et al. [41] explored antenna for 5G mobile applications with high density tapering. Density tapered arrays of two different forms are shown, one optimized for low side lobes and the other for broad band applications. Instead of turning off certain antenna components, electrical tapering has been employed here by adjusting the space between them.

P. M. N. Keizer, et al. [42] have implemented thin circular arrays on a vast scale, with a wavelength range of 25 to 133, to create a synthesis with a low side lobe. Synthesis of a low-level side lobe by use of amplitude-only taping applied to the "ON" components of a large circularly thinned array antenna.

Efri Sandi, et al. [43] have presented two new methods for simplifying the design and lowering the price of linear sparse array antennas. The first way is combinatorial, using integer cyclic difference sets to greatly decrease the initial set size. To mitigate the impact of side lobes, the second procedure employs amplitude tapering using a binomial array. This hybrid method considerably reduces the number of antenna components required, the time required for calculation, and the size of the array antennas. Optimizing array antennas is a tried-and-true practice that has been around for at least four or five decades. However, because to the dynamic nature of algorithms, this process of applying optimization strategies to array antennas continues until now. Numerous methods for synthesizing array antennas, including those that optimize the amplitude, phase, and distance between the antenna components, may be found in the literature. In this study, we focused on reducing the size of antenna components by adjusting their amplitude. This article presents the existing literature on amplitude optimization of antenna arrays, as well as fractal array antennas, and highlights the dearth of research into the practical use of optimization methods, notably thinning, in the context of fractal array antennas.

R. L. Haupt, et al. realize the advantages of tiny antenna arrays, was an early user of optimization methods such as genetic algorithms, particle swarm optimizations, and adaptive algorithms. To attain low side lobe levels, a thin array antenna is required, which is a challenging goal to meet. The production of non-uniform arrays via the use of traditional statistical methods is very inefficient. Using conventional techniques of optimization, it is possible to synthesize large arrays of antennas. The person who came up with the genetic algorithm did so because he saw fundamental flaws in the methods that came before it. This approach determines which of an array antenna's components have to be disabled in order to get the fewest amount of side lobes that are feasible. In this paper, both linear and circular antenna arrays are given a more streamlined appearance [44–47].

Rajesh Bera, et al. [48–50] explained the process of thinning concentric hexagonal and cylindrical elliptical array antennas with evenly stimulated isotropic antenna components that are able to provide a directional beam with a low amount of relative side lobes. In order to reduce the size of the array antenna's individual antenna components, the particle swarm and craziness-based particle swarm optimization approaches were used. Because of these optimization approaches, roughly "60%" of the antenna elements were able to become thinner while maintaining the same beam width and reducing the degree of side lobes.

P. Lombardo, et al. discussed the purpose of optimizing the design of a planar thinned array antennas with varying characteristics [51]. The method that has been presented may either function with individual antenna components or with more compact groupings of a variety of subarray kinds that are positioned on a flat surface. The strategy that has been suggested centers on lessening the intensity of the side lobes while also taking into account a fixed number of active antenna components or subarrays. The approach that is being proposed is suitable for a variety of different forms of the output array antenna that is chosen, which makes it possible to achieve the required directivity attributes on the corresponding antenna pattern. In the context of industrial production, the use of subarrays with a limited number of distinct form variants is suitable. This would result in lower costs for both the design and the mechanization of the process. The modularity that is produced as a consequence makes it possible to scale antenna designs to suit a variety of applications.

U. Singh, et al. proposed a biogeography-based optimization approach for the purpose of thinning bulky multiple concentric circular array antennas [52]. The objective is to construct an array antenna with evenly excited current amplitudes using isotropic antenna components in order to produce pencil beams with minimal amounts of side lobes. Because of this optimization, over half of the antenna components have been reduced in thickness while maintaining or improving their array factor behavior.

Urvinder Singh, et al. discussed the Firefly optimization algorithm to the design of thinned concentric circular array antennas [53]. The goal is to build an array antenna consisting of evenly stimulated isotropic components. This kind of antenna is designed to generate a pencil beam pattern with minimal levels of side lobes. Within the scope of this research project, two particular use cases for the suggested technique to thin down concentric circular array antennas were described. The main example uses an inter-element spacing that is uniform and is either fixed at 0.5 microns or one of its multiples, while the secondary case utilizes an inter-element spacing that is either optimal or one of its multiples. Better array factor characteristics have been attained in both of these examples, and the results of this research make it abundantly evident that the firefly method is appropriate and easy to use for any kind of array antennas.

Douglas H. Werner, et al. [54] proposed a synthesis of a fractal radiation pattern was used to describe a combined approach to the design of multiband array antennas. This innovative approach to the design of multi-band array antennas has a number of advantages, including a significant reduction in the amount of mutual coupling losses, the fact that only a minimal amount of element switching is necessary, and the ability to easily realize the design in the form of reconfigurable apertures. Additionally, a thinning procedure that safeguards all of the benefits provided by the band switching architecture was established. This process is predicated on the selection of an appropriate window function. There were several other window functions that were taken into consideration, such as the Blackman–Harris, Kaiser–Bessel, rectangular, and Blackman.

A.N. Bondareako, et al. proposed a new synthesis approach for the creation of various array antennas of Sierpinski gasket nature [55]. This technique is based on the theory of atomic function. A significant advancement may be attributed to the use of this synthesis method to these arrays.

Authors D. H. Werner, et al. addressed nature-based optimization methodologies for the construction of poly fractal antenna arrays, such as the genetic algorithm and the covariance matrix adaptation evolutionary approach [56]. These arrays make use of compact direct techniques, raised power series, and aperiodic tiling. The working frequency bandwidths of poly fractal array antennas may reach up to 30:1 and beyond, and they have no grating lobes and extremely low sidelobe levels.

Sierpinski fractal array antenna optimization utilizing the differential evolutionary method was taken into consideration by Anirban Karmakar, et al. [57]. In a normal situation, fractal array antennas like Sierpinski carpet structures may suffer from an elevated side lobe level, in addition to suffering from complicated array factor calculation, which isolates it from the application of any evolutionary optimization strategy. A novel iterative feed matrix is proposed, and it is based on the Sierpinski carpet array. Its insertion simplifies the computation complexity of the Sierpinski fractal array antenna at different iterations and expansion factors, and it makes them suitable for the application of any evolutionary optimization methods.

Chen W-L, et al. [59] proposed a wide-slot antenna with a fractal-shaped slot for bandwidth improvement. Experimental results show that operating bandwidth can be greatly increased by etching the wide slot as fractal shapes, and that there is a correlation between bandwidth and iteration order (IO). The experimental investigation of the fractal shapes' scale factor (IF) continues. At operating frequencies around 4 GHz, the proposed fractal slot antenna achieves an impedance bandwidth of 2.4 GHz, defined by a 10 dB reflection coefficient. This is roughly 3.5 times that of a conventional microstrip-line-fed printed wide-slot antenna. In addition, it has a 1.59 GHz bandwidth with a 2-dB gain.

M. Shirazi, et al. [70] introduces a slot-ring antenna/array that is capable of reconfiguration and supports dual polarization. The antenna/array can switch between the S and C bands, and it offers a large bandwidth in each operational condition. This configuration is depicted in Fig.4. The reconfiguration of a 2×2 C-band antenna array to an S-band antenna unit cell, and vice versa, can be achieved by simultaneously activating eight PIN diode switches. The integration of fractal shapes inside the antenna structure yields a substantial improvement in bandwidth. The antenna exhibits a fractional bandwidth (FBW) of 69.1% in the S-band working state and 58.3% in the C-band operating state. The measured maximum realized gain is 2.4 dBi in the S-band and 3.1 dBi in the C-band. In the case of the 2×2 C-band array, the inter-element spacing is designed to be smaller than 0.5λ0 over the frequency range. This specific configuration allows for beam scanning without the presence of grating lobes. In addition, a variant of this antenna/array is showcased, exhibiting a front-to-back ratio exceeding 12.0/16.0 dB at frequencies of 3.5/8.0 GHz. The wideband antenna/array has the potential to function as a unit cell inside a larger array, with element spacing equal to half the wavelength at the center frequency of both frequency bands.

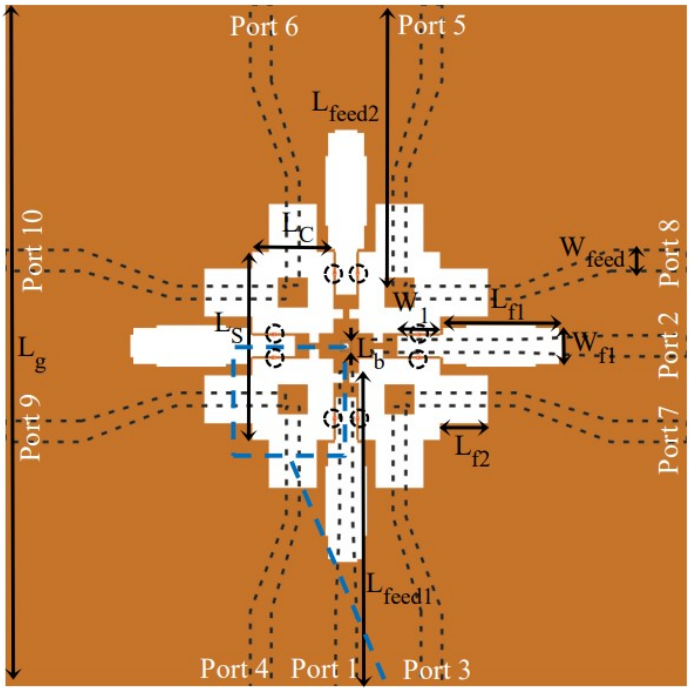

Fig. 4. Configuration of reconfigurable dual- polarized wideband slot ring antenna/array

M. Shirazi, et al. [71] introduces a modular antenna array that operates in both the S-band and C-band frequencies, offering dual polarization capabilities. The reconfiguration of a 2×2 S-band antenna array to a 4×4 C-band antenna array can be achieved while maintaining the same physical aperture as shows in Fig.5. The implementation of a short ground strip within the slotting antenna serves the purpose of mitigating the mutual coupling between antenna components and minimizing the presence of nulls in the radiation patterns within the C-band array. Furthermore, the implementation of the vertical coax-to-microstrip transition facilitates the feeding of the antenna array from the rear of the ground plane, hence enabling a modular configuration. The achievement of dual polarization capacity is observed in each band. The antenna array exhibits a fractional bandwidth of 64.3% and 66.7% in the Sand C-band working modes, with corresponding gains of 8.4 and 14.3 dBi, respectively. The measurements conducted include the assessment of isolation between various antenna ports, analysis of radiation patterns at different frequency points, and determination of the third-order intercept point (IIP3) of the antenna. The utilization of a triangular lattice is employed in the S-band array in order to decrease the physical separation between the individual antenna elements. This arrangement facilitates the ability to guide the beam towards larger angles.

X. L. Li, et al. [72] presents a wideband vehicular planar inverted F antenna (PIFA) array that incorporates a fractal structure to achieve high isolation. The PIFA antenna components are arranged in a face-to-face configuration, with the inclusion of a decoupling structure (DS) between the elements. This decoupling structure comprises four fractal unit slots and a narrow line slot (LS), which serves the purpose of minimizing the mutual coupling between the antenna elements. The suggested configuration is constructed, and the inhibitory impact of mutual coupling is confirmed by both simulation and measurement techniques. The obtained measurements indicate that the impedance bandwidth spans from 3.02 GHz to 3.96 GHz, encompassing the operational frequency range of 5G. A significant increase in isolation, ranging from 8 to 32 dB, is achieved within the frequency range of 3.17–4.15 GHz when employing a decoupling structure. This improvement is observed when the spacing between two PIFA antenna components is merely 0.17 times the free-space wavelength at the center frequency of 3.5 GHz.

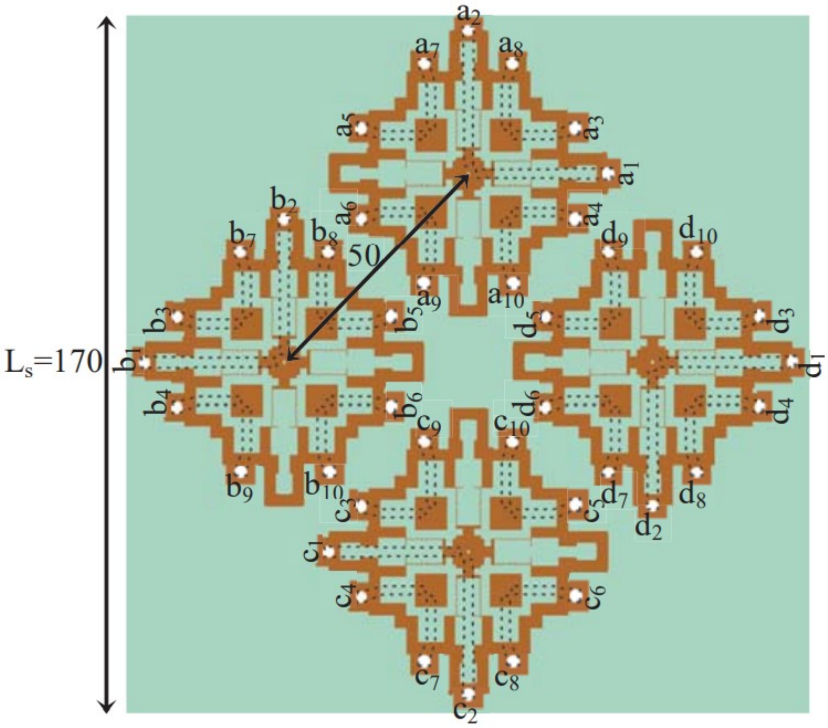

Fig. 5. 2X2 Dual Polarized reconfigurable S-Band array (4X4 C-Band array)

W. T. Li, et al. [73] presents a bandwidth-enhanced, low cost, compact, inkjet-printed multilayer microstrip fractal patch antenna for integration into flexible and conformal devices. The antenna consists of two layers of patches, with the first layer inkjet-printed directly on a 0.125-mm (only 0.005 of the operating wavelength) Kapton polyimide substrate. On top of it, a 0.12-mm-thick SU-8 polymer is covered. To achieve the desired miniaturization and good impedance match, a Minkowski fractal geometry patch is employed as the second layer inkjet-printed on top of the SU-8 polymer. The proposed antenna has compact dimensions of only 22 × 31mm and covers 4.79–5.04-GHz frequency spectrum with $S_{11} < -10$ dB.

Moreover, a 2-bit 1×4 phased array antenna (PAA) is constructed, and its scan ability is estimated to demonstrate its potential application in the true time- delay flexible PAA systems. The prototype is fabricated and tested for impedance and radiation characteristics. The measured and the simulation results show the superiority of the proposed antenna.

2. RESULTS AND DISCUSSION

Table 2.1 Comparisons between previous related fractal antennas

Ref. No.	BW (GHz)	Gain (dB)	Directivity (dB)	Size (mm)	Efficiency (%)	Array Size	Type	Weak/strong points
[18]		1.1-1.7			30	64 Element	Koch	Not cover all bands, complex geometry
[19]					40	754 Elements	Cantor ring array	Complex geometry,
[20]					60	64 Elements	Sierpinski	Not cover all bands
[21]			21.27		70	19x19 Array	Koch	Large size
[22]			22.5		60	3x3 Array	Koch	Not cover all bands
[23]						1024 Elements	Flap Fractal	Not cover all bands
[24]						9x9	Sierpinski	Gain is improved with SLL (dB) is -18
[55]	2.1-3.2	7					Sierpinski gasket	Gain is not good

[56]	3.2-4.2	10					Sierpinski gasket	Reduce sidelobe levels
[57]	10.25-10.75	5					Sierpinski	Elevated side lobe level
[59]	(2.7–4) (4.3–5.2)	3~5.5		70×70×1.5			Fractal Slot	Large size, LP, does not cover all required bands,
[60]	(2.1–6)	2~5		48×40×1	80–90		Sierpinski	LP, complex design
[61]	(3–12)			31×28×1.6	80–90		Koch	Does not cover 2.4 GHz band, LP, no gain values
[62]	(2.4–2.49)	(1.9~7)		120×120×1.6	-		H-Fractal	Large size, does not cover all required bands, LP,
[63]	(5.1–5.8) (2.4-2.48) (3.4–3.6)	1.1~3.1		100×100×5	50–72		Minkowski	Large size, LP, low efficiency at lower band.
[64]	(5.1–5.8) (1.5–4)	2.2~2.4		80×40×1.58	60–79		Koch- snowflake	LP, does not cover the (5-6) GHz band, complex geometry
[65]	(1.3–20)	−2~10		62×50.8×0.8	20–90		Fern Leaf	LP, low gain and efficiency at lower band
[66]	(2.4–2.5)			35×35×2.5	48–62		Koch	LP, no values of gain, low efficiency values
[67]	(2.5–2.7)			263×164×2.3			Mandelbrot	Large size, LP, does not cover all required bands, no values of gain and efficiency.
[68]	(5.4–14.2)			158×158×3.6			Quasi-Fractal	Large size, LP, does not cover all bands requirement, no values of gain and efficiency.
[69]	(3–25.2)	3~9.8		25×30×1			Hexagonal-Triangular	LP, no efficiency values, does not cover all required frequencies.
[70]	2-8	2.4/3.1	23		61	2x2	slot-ring antenna	Gain is Low, and SLL (dB) is -20
[71]	2-8	8.4/14.3	25		70	2x2 and 4x4	modular antenna array	Gain is Improved
[73]	4.79–5.04		28	22 × 31		1x4	Minkowski fractal geometry	SLL (dB) is -10

3. CONCLUSION

Several of the potential functionalities associated with fractal antenna arrays remain undeveloped, indicating that the technology is still in its nascent stage. The radiation characteristics exhibited by individual elements are characterized by a diffuse nature and possess a relatively low level of directivity, also known as gain. In certain instances, there is a requirement for antennas that possess highly directional characteristics in order to fulfill the demands of long-range communication, resulting in significant gains in signal strength. In order to achieve this objective, it is necessary to augment the electrical dimensions of the antenna. Enlarging the dimensions of an individual component of an antenna sometimes confers it with more authoritative characteristics. One approach to augmenting the overall dimensions of an antenna without enlarging the individual elements involves employing an assemblage of radiating devices that are organized in a specific electrical and geometrical configuration. The newly developed antenna can be classified as an array due to its composition consisting of numerous discrete components. It can be inferred that each element inside the array possesses an equal value to every other element within the same array. While not obligatory, opting for this approach is frequently seen as the most effective utilization of one's time. The constituents of an array possess the capacity to assume various physical manifestations, such as wires, holes, and other forms. This topic serves as a source of inspiration for researchers who want to enhance the performance of implanted antennas through novel approaches. A fractal antenna array is a feasible choice for activities that require high frequency. The utilization of a millimeter wave communication system necessitates the presence of a highly directed and high-gain antenna array. The endeavor to achieve this objective poses a persistent challenge within this particular field. Metamaterials have the potential to enhance the size, gain, and bandwidth of antennas in the field of antenna design. One notable advantage that arises from the usage of metamaterials is the potential for antenna shrinking. In fact, there are now commercially accessible smaller antennas that employ metamaterials. The utilization of fractal antenna arrays has been observed to extend to the field of Multiple-Input Multiple-Output (MIMO) technology as well [74].

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