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Iterative Design and Optimization of a Star-Shaped Fractal Antenna for 5G Applications

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***Abstract*—This study presents the iterative design process of a compact star-shaped fractal antenna tailored for superwide-band (SWB) 5G applications. The antenna design underwent eight evolutionary iterations, starting from a simple rectangular microstrip patch to a sophisticated star-shaped fractal structure. Using the Rogers RT5880 substrate, the final design achieved a frequency range of 20 GHz to 40 GHz with a fractional bandwidth of 165%. The iterative approach optimized critical performance metrics such as the reflection coefficient (S11), Voltage Standing Wave Ratio (VSWR), gain, and radiation patterns. Simulated using CST Microwave Studio, the final antenna exhibited an average gain of 6.4 dBi and a peak gain of 10 dBi. This paper details the step-by-step design process, highlights the improvements achieved across iterations, and discusses the antenna's potential applications in 5G communication systems.**

***Index Terms*—Superwideband (SWB), Microstrip patch antenna, Star shape, VSWR.**

I. Introduction

With the rapid development of wireless communication technologies, high-performance antennas with wide bandwidth, compact size, and high gain are in urgent demand. As 5G networks move into millimeter-wave frequencies, conventional antennas hardly meet the severe requirements of modern communication systems. Fractal geometries, due to their self-similar and space-filling properties, present a very attractive solution by allowing the realization of compact designs with wideband and multiband characteristics.

Since 5G communication is expected to provide transmission speeds 100–1000 times greater than those of earlier wireless technology eras, 5G systems have been proposed to employ larger bandwidths in order to provide these rapid data transfer [1]. The direction of research has recently shifted towards the millimeter wave frequencies in order to increase the capacity and data rates [2]. Thus, it is an expected that the 5G network will work on the frequency above 10GHz [3]. In addition to the several alluring advantages of MSA that were previously highlighted, traditional patch antennas are unable to provide wide bandwith, high gain, and high power handling capability. The greatest solutions for overcoming these deciencies for present and future mobile users may be super wideband (SWB) and ultra wideband (UWB) antennas.

According to the Federal Communications Commission's 2002 recommendation, a UWB antenna performs between 3.1 as well as 10.6 GHz. Its mean EIRP level is 41.2 dBm/MHz, whereas its reflection coefficient is under -10 dB across the entire band [4]. An additional restriction states that an antenna is considered a UWB antenna if its partial bandwidth is higher than 25% and its proportion to capacity is higher than 1.8:1 but does not exceed 10:1. If the range ratio that is, the proportion between the upper cut-off rate to the lesser cut-off rate is greater than 10:1, the antenna is referred to as a super wideband (SWB) antenna. The most commonly utilized method for reaching such broad bandwidths as in SWB is the continuous use of fractal shapes, which permits SWB with no increasing the overall antenna region.

Fractal geometries are characterized by the slow repetition of a similar layout at multiple scales. While fractal geometries' space-filling property results in an extremely tiny antenna, bringing up an identical geometry produces antennas that improved radiation pattern, multiband, and wideband features [5].

In recent years, several antennas have been developed revealed employing fractal patterns to obtain super wideband (SWB). A single of these, [6], recommended two different versions of Sierpinski square slots to create a lightweight hexagonal Sierpinski fractal antenna for SWB usage, obtaining an impedance range from 3.4GHz to 37.4GHz [7]. one more [8], employed hexagonal cycle strand structure to build an inclined super wideband antenna with a reflection coefficient beneath -10db from 1.18GHz to 49.22 GHz. A star-triangular antenna with a star in a circular shape and triangular constructions above it was shown to function in the 20GHz to 40GHz frequency band in [9]. Its total compact size was 20mm20mm1mm. [10] shown how to modify standard antipodal Vivaldi antennas using Chebyshev curved bringing to create an antenna featuring a wide bandwidth ranging from 1GHz to 35GHz.

The proposed paper will develop and optimize a compact star-shaped fractal antenna for 5G applications using an iterative approach. Different from existing works, most of which focused on relatively narrower frequency bands or less complicated geometries, this work applies a careful iterative approach in step-by-step development toward the optimum structure of the antenna. Each iteration addresses specific issues in bandwidth enhancement, gain enhancement, and/or improvement in reflection characteristics. coefficient performance, which yielded a very efficient and compact final design. The contribution of this work is in detailing an iterative design process and showing its effectiveness to obtain a superwideband fractal antenna for 5G applications. This is the first research to utilize the CST Microwave Studio for detailed simulation and analysis at eight iterative stages with optimization of performance metrics S11, VSWR, and gain after each iteration. The iterative approach underlines progressive refinement of Antenna geometry differs this work from other static design focused works. The last design outperforms many antennas in bandwidth and gain while keeping compact form factor. This paper is structured as follows: the design of antenna construction is given in Section II; the simulated result and analysis has been evaluated and discussed in Section III; and finally, the conclusion is given in Section IV.

II. Proposed Methodology

A. Antenna Structure

The antenna design started with a simple rectangular microstrip patch. The Rogers RT 5880 substrate was selected with a thickness of 0.787 mm, dielectric constant of 2.2, and loss tangent of 0.0009 because it offers very good performance at high frequencies. The iterative design focused on the transformation of the basic patch into a fractal structure for the desired performance metrics.

TABLE I
Dimensions of Designed Antenna

Parameter	Value
Wg	12.9 mm
Lg	10.7 mm
Wsub	20 mm
Lsub	20 mm
A	8.3 mm
h	0.787 mm
Ls	8.4 mm
R	3.05
Ws	2.8 mm

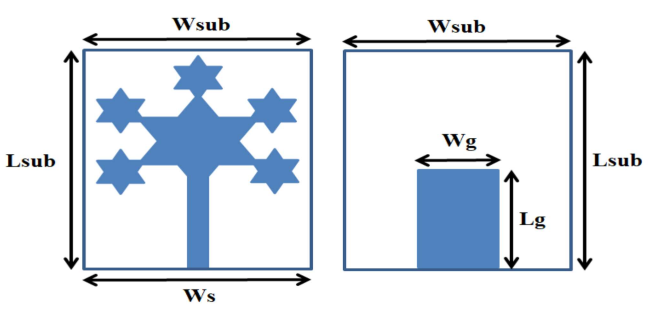

Fig. 1. Final Structure With The Dimensions. (a) Patch(Front View) (b) Ground(Back View).

B. Iterative Design Process

Iteration 1:

- Rectangular patch evolved into a triangular shape.
- Objective: Enhancing the bandwidth by the introduction of more efficient radiating structure.

Iteration 2:

- Triangular structure evolved to star-shaped geometry.
- Objective: To take the advantage of fractal property for enhancing bandwidth and reducing size.

Iteration 3:

- Star-shaped structure at some points of the patch, repeated.
- Objective: Introduce multi-band characteristics with increased geometrical complexity.

Iteration 4:

- Ground plane modified to defected structure.
- Objective: Improve the impedance matching and enhance bandwidth.

Iteration 5-8:

- Minor changes in star-shaped fractal design with focus on:
  - Optimization of dimensions for best S11 performance.
  - Achieving consistent gain across the frequency range.

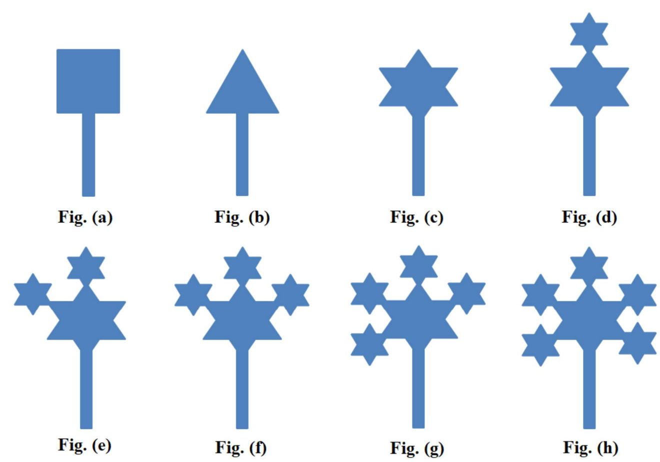

Fig. 2. (a) Antenna-I; (b) Antenna-II; (c) Antenna-III; (d)Antenna-IV; (e) Antenna-V; (f) Antenna-VI; (g) Antenna-VII;(h) Antenna-VIII.

III. Simulated Result & Analysis

All designs were simulated using CST Microwave Studio, a leading tool for electromagnetic design and analysis. Key parameters analyzed included S11, VSWR, gain, and radiation patterns.

A. S-parameter

The S-Parameter, which has been presented by (S11), is also referred to as Reflection Coefficient or return loss. Since in an antenna, the return loss measured is actually the ratio between incident power and reflected power, a good reflection coefficient or return loss should always be more than -10 dB or -15 dB or better for overall good antenna performance. Return loss is 26.921329 dB for 34.54 GHz frequency and -24.627 dB for 28.58 GHz frequency as depicted by Fig. 8.

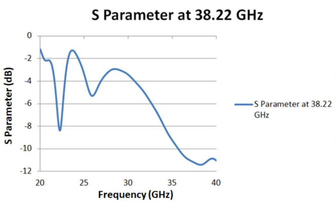

Fig. 3. Antenna III.

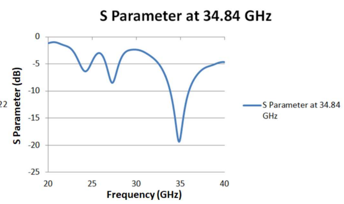

Fig. 4. Antenna IV

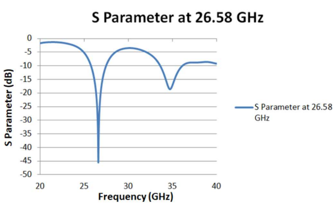

Fig. 5. Antenna V

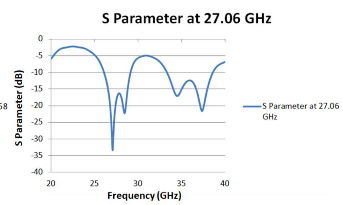

Fig. 6. Antenna VI

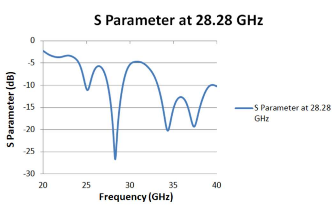

Fig. 7. Antenna VII

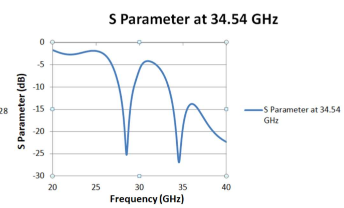

Fig. 8. Antenna VIII

Fig. 9. S Parameter for Different Antennas.

B. Voltage Standing Wave Ratio (VSWR)

The standing wave ratio is another terminology that has been used for the voltage standing wave ratio. The obtained VSWR values for all the microstrip patch antenna designs for 5G applications were below 2 standards. This is an actual and positive value of the ratio. The higher value of VSWR, the higher will be the mismatch. From Fig. 10 the obtained VSWR values in the relevant operating bands are 1.09 and 1.1. The transmission qualities of the antenna are therefore good.

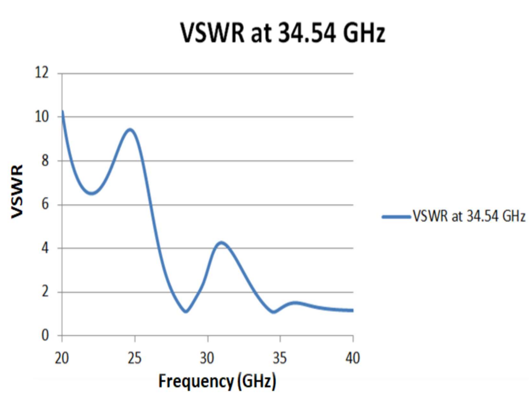

Fig. 10. VSWR of The Antenna-VIII.

C. Radiation Pattern

- **Gain:** Since this form of radiation shows how much energy the antenna is radiating, the gain is one of the key features for WiFi systems. The obtained gain is 7.208 dBi for the lower band and 10.91 dBi for the upper band and. Fig. 11 displays the broadband gain graph.

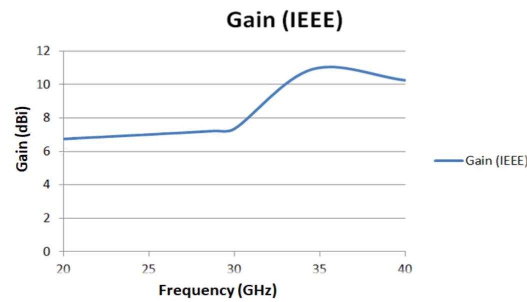

Fig. 11. Gain of The Proposed Antenna-VIII.

- **Directivity:** Another important feature is the directivity because many antennas and optical devices are designed to emit electromagnetic waves in one direction or at small angles. From Fig. 12 and Fig. 13 for the two corresponding frequencies, the obtained directivity was 10.84 dBi and 7.201 dBi respectively.

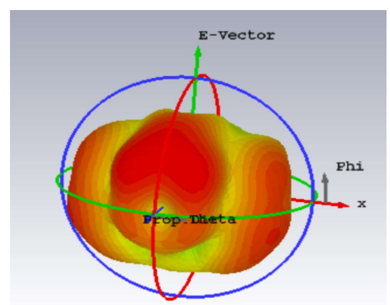

Fig. 12. Directivity at 28.58GHz for Antenna-VIII.

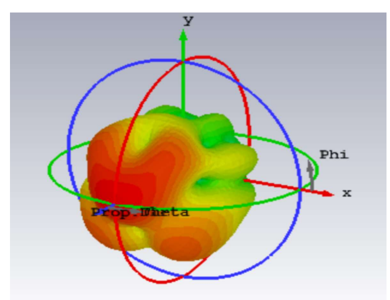

Fig. 13. Directivity at 34.54GHz for Antenna-VIII.

D. Farfield Pattern

Fig. 14 and Fig. 15 are the directional Far-field antenna structure. The 2D radiations structures representative of cross polarisation and Co-polarization at 34.54 GHz and 28.58 GHz are portrayed, respectively, by the theta and phi fields. One can notice that cross polarization is much higher at 6GHz rather than at another frequency. The radiation pattern analysis has also indicated that this antenna possesses very remarkable omni-directional properties: one loop-shaped plane and another is a circular plane, which could be shown on the graph.

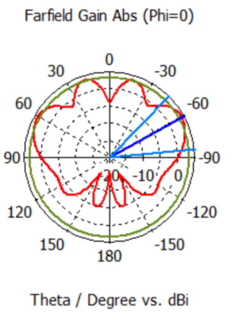

Fig. 14. Farfield Pattern at 28.58GHz for Antenna-VIII.

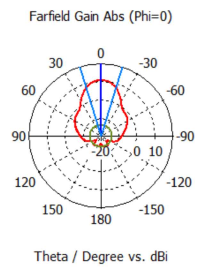

Fig. 15. Farfield Pattern at 34.54 GHz for Antenna-VIII.

E. Comparison with Existing Star Shape Fractal Base Antenna

TABLE II
PERFORMANCE METRICS ACROSS ITERATIONS

Antenna	Frequency (GHz)	S11 (dB)	Gain (dBi)
III	38.22	-11.41	6.03
IV	34.84	-19.35	8.86
V	26.58	-45.50	8.13
VI	27.06	-33.39	5.97
VII	34.33	-20.92	7.38
VIII	34.54	-26.90	10.91

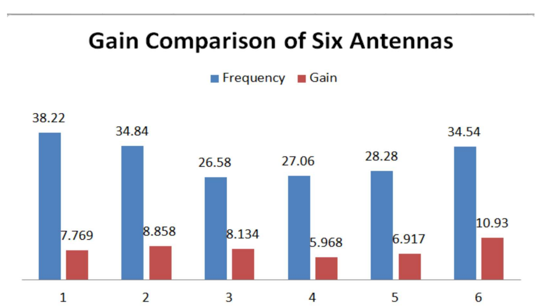

Fig. 16. Displays Simulated Gain at Various Stages.

Table II summarizes the performance parameters of the star-shaped fractal antenna designed for 5G SWB applications at different stages of the iteration process. The resonating frequency ranges from 26.58 GHz to 38.22 GHz, where each iteration was optimized for bandwidth and performance. The value of the reflection coefficient (S11) also showed a significant improvement, with the minimum value of -45.50 dB obtained for iteration V, indicating very good impedance matching. The antenna gain was increased step by step, reaching its maximum at iteration VIII as 10.91 dBi, which verifies its excellent radiation efficiency. The table below assists in revealing how the step-by-step design methodology has optimized the antenna for compactness and high performance to meet the stringent requirements of modern 5G systems.

IV. CONCLUSION

Presently, the development of an iterative process is done in a star-shaped fractal antenna aimed for operation at the 5G super-wideband. Starting with a simple rectangle patch antenna to the best version of an optimized fractal version which outperforms huge improvement for most parameters under bandwidth, gain, and S11. In simulation using CST Microwave Studio, the final design worked for frequency from 20 GHz up to 40 GHz, along with very good impedance matching, with VSWR less than 2, as well as omnidirectional radiation patterns, showing potential in the design for application to 5G communication systems. The study illustrates the potential of fractal geometries and iterative design methodologies to realize compact high-performance antennas. Future efforts will be oriented toward experimental validation and practical integration in 5G systems, which further support the growth of communication technology.

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