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A Case Study of Nelder Mead Simplex Optimization Algorithm: Trade-Offs of Sprienski Fractal Bowtie Antenna Parameters

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Abstract

In this study, tri-band antenna design adapted for wireless communication, Internet of Things (IoT) and RFID systems is examined. The simulation results indicate that the proposed antenna has three distinct frequency bands. Band 1 (lower band) covers the frequency range of 1.64-1.78 GHz with a resonance frequency of 1.7 GHz. Band 2 covers the range of 3.06-3.9 GHz with a resonance frequency of 3.4 GHz with a high gain of 10 dBi and a radiation efficiency of 92% for long-range communication. Band 3 radiates from 6.25 to 7.6 GHz with a resonance frequency of 6.62 GHz, which is suitable for higher-frequency applications. The antenna design is simulated and analyzed regarding S11, VSWR, gain, radiation efficiency, and bandwidth. Especially, Band 2 (mid-band) provides notable performance, with its 10 dBi gain and 92% efficiency, which makes the proposed antenna an ideal structure for high-data-rate, long-distance communication systems, and 5G (midband) applications. This study also employs the Nelder-Mead Simplex algorithm to observe the optimization of the physical parameters of the proposed antenna via multiple objective functions. The optimization results outlines that longer the arm length of the proposed antenna causes to decrease the resonance frequency of Band 3. Addition to this, the gain is higher with the lower arm length except for the arm length of 90.467 mm and flare angle of 64.77^{o}. That's, the trade-off condition occurs between minimum return loss and gain. At this point, it can be concluded from this optimization algorithm results that each objective function should be evaluated separately due to this trade-off condition.

Keywords: Antenna, Algorithm, Fractal, High gain, Optimization, Sprienski

Nelder Mead Simpleks Optimizasyon Algoritması Üzerine Bir Durum Çalışması: Sprienski Fraktal Bowtie Anten Parametrelerinin Ödünleşimleri

Öz

Bu çalışmada, kablosuz iletişim, nesnelerin interneti ve RFID sistemleri için uyarlanmış üç bantlı anten tasarımı incelenmiştir. Simülasyon sonuçları, önerilen antenin üç farklı frekans bandına sahip olduğunu göstermektedir. Bant 1 (alt bant), 1.7 GHz rezonans frekansı ile 1.64-1.78 GHz frekans aralığını kapsar.

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Bant 2, 3.06 GHz'ten başlayan 3.9 GHz de sonlanan çalışma bant aralığına sahiptir. Ayrıca, bant-2 için en yüksek kazanç değeri 10 dBi ve radyasyon verimliliği 92% olarak tespit edilmiştir. Bant 3, daha yüksek frekanslı uygulamalar için uygun olan 6.62 GHz rezonans frekansı ile 6.25 -7.6 GHz arasında yayılır. Anten tasarımı, S11, VSWR, kazanç, radyasyon verimliliği ve bant genişliği açısından simüle edilmiş ve analiz edilmiştir. Özellikle, Bant 2 (orta bant), 10 dBi kazancı ve %92 verimliliği ile kayda değer bir performans sağlar, bu da önerilen anteni yüksek veri hızı, uzun mesafeli iletişim sistemleri ve 5G (orta bant) uygulamaları için ideal bir yapı haline getirmektedir. Bu çalışma da aynı zamanda, önerilen antenin fiziksel parametrelerinin optimizasyonunu çoklu objektif fonksiyonlar aracılığıyla gözlemlemek için Nelder-Mead Simplex algoritmasını kullanılmıştır. Optimizasyon sonuçları, önerilen antenin kol uzunluğunun artması Bant 3'ün rezonans frekansının azalmasına neden olduğunu özetlemektedir. Buna ek olarak, kol uzunluğu küçüldükçe kazanç artmaktadır. Ancak 90.467 mm'lik kol uzunluğuna ve 64.77º'lik açıya sahip olan antende bu özelliğin tersi durum olduğu tespit edilmiştir. Bu noktada, bu optimizasyon algoritması sonuçlarından, bu ödünleşim koşulu nedeniyle her bir amaç fonksiyonunun ayrı ayrı değerlendirilmesi gerektiği sonucuna varılmıştır.

Anahtar Kelimeler: Anten, Algoritma, Fraktal, Yüksek Kazanç, Optimizasyon, Sprienski

1. INTRODUCTION

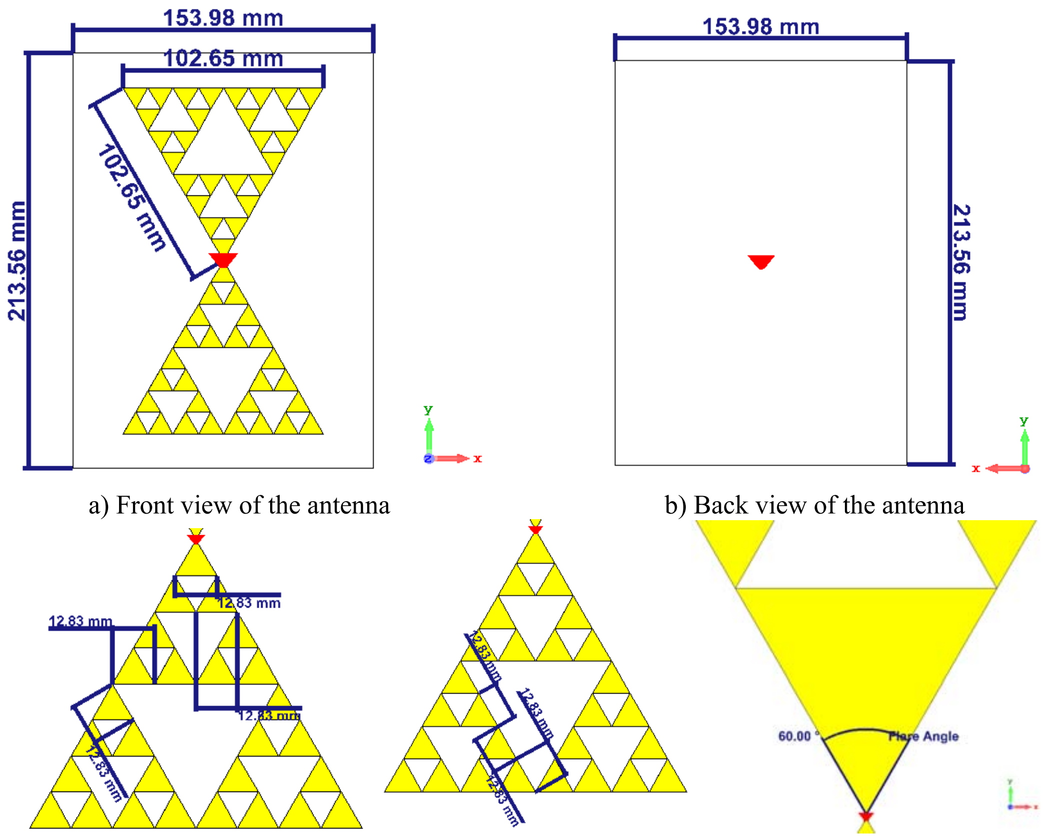
Multiband antennas in the context of wireless technology have led researchers to explore unconventional geometries [1,2]. The fractal geometry allows for the generation of multiple resonant frequencies within a compact antenna size, enabling wideband operation [3]. The use of fractal structures also facilitates the achievement of stable radiation patterns [4]. Additionally, fractal antennas have advantages such as compact size, multiband frequency characteristics, and high gain [5-7]. The other structures are also acceptable for various applications including terahertz detection [8], bandwidth enhancement [4], wireless applications [5], X-band and Ku-band applications [6], ultra-wideband applications [7], UWB imaging applications [9], broadband applications [10], multiband applications [11], and directivity improvement [12]. As of the literature survey, fractal antennas can be considered as the fractal butterfly antenna [3], square-shaped fractal antenna [4] wideband high gain fractal antenna [5], multi-band high-gain slotted fractal antenna [6], hexagonal fractal ultra-wideband antenna [7], compact high gain UWB antenna using fractal geometry [8], microstrip line-fed fractal antenna with a high fidelity factor [9], Minkowski Island and Crossbar fractal microstrip antennas [10], Sierpinski carpet fractal antenna [11], cross-stitch geometry-based multiband fractal antenna [12], ultra-wideband antenna using Minkowski-like fractal geometry [13], and ultra-wideband fractal microstrip antenna [14]. These proposed antenna structures are extensively studied for their ability to achieve high gain in the literature as well. Furthermore, these fractal antennas utilize self-similarity and recursive geometrical patterns to increase the effective electrical length of the antenna, which results in increased gain. To sum up, fractals with their inherent characteristic provide a new technique for the antenna designers. First, the size modification of each triangle makes the antenna resonate various frequencies. That's, these frequencies enable the proposed antenna structure to radiate over a broader range of bands. Secondly, the entangled geometry boosts the electromagnetic energy to increase the signal strength. As a third, fractal antennas can be designed with smaller size as compared to the traditional antennas, which provides the size reduction. But these positive features occur with their own several trade-offs. The tangled geometry of the antenna causes to predict the antenna performance in difficult. This is where algorithms come into play to solve these challenges.

One of the iterative optimization algorithms called Nelder-Mead Simplex employs a myriad of simplex (the points) to identify the design space and the parameters [15-17]. It is a direct search method used for optimization problems, particularly in low-dimensional spaces [18]. The algorithm has been proven to converge under certain conditions [18]. However, it can suffer from stagnation and convergence issues in higher-dimensional complex problems [19]. Researchers have proposed modifications and adaptations of the Nelder-Mead algorithm to improve its performance. For instance, adaptive parameters are depicted to enhance the efficiency of the algorithm [20]. Dynamic variables of the algorithm including Dynamic Hassan Nelder Mead with Simplex Free Selectivity, are developed for unconstrained optimization problems [21]. The Nelder-Mead algorithm is also interconnected with other optimization techniques to obtain hybrid algorithms. For example, an amalgamation of the Nelder-Mead simplex method and the Cuckoo search algorithm has been suggested for training Fuzzy neural networks [22]. Addition to this, Nelder-Mead algorithm is integrated into genetic algorithms and particle swarm optimization for various applications including medical image registration and parameter detection [23,24]. This mentioned algorithm plays also paramount role in electromagnetic and microwave applications including antenna design and optimization. Mistry et al. has presented a study on simulation, measurement and optimization in the time and frequency domain in the logarithmic domain of periodic antennas [25]. The Nelder-Mead simplex algorithm is used to optimize the performance of log-periodic antennas, which are generally preferred for electromagnetic compatibility measurements, spectrum monitoring and television reception [25]. Mahmoud presents the optimization of conventional bowtie antenna structure for 2.45 GHz RFID readers via hybrid algorithms of Bacterial Swarm Optimization (BSO) and Nelder-Mead (NM) [26]. In [26], the objective function is determined as S11 according to the physical parameters including half height (h), feeding neck width(d), and flare angle (α). Barman et al. has investigated the probe location optimization of wideband microstrip patch antenna with particle swarm optimization (PSO), genetic algorithm (GA), and NM, respectively [27]. The objective function has been determined as VSWR and Gain parameters in [27]. Montaser et al. depicts the S11 optimization of the slotted bowtie antenna by focusing on the arm length and flare length [28]. Then, hybrid algorithms are evaluated the pros and cons of the proposed algorithm namely PSO, GA, and NM as well [28]. Liu et al. proposes a hybrid optimization method for pattern synthesis of large antenna arrays [29]. The authors combine the Nelder-Mead Simplex Algorithm with other optimization techniques to overcome the challenges in antenna array design [29]. In summary, the Nelder-Mead Simplex Algorithm has been widely applied in antenna design and optimization. It offers advantages such as adaptability to the local landscape, effective exploration of the design space, and the ability to improve antenna characteristics such as gain, bandwidth, and radiation pattern. However, as of knowledge obtained from literature survey, there is no study related with the optimization of sprienski bowtie antenna parameters with Nelder Mead Simplex Algorithm. Hence, in this study, the physical parameters of sprienski bowtie antenna structure are optimized with multiple objective functions through Nelder Mead Simplex Algorithm.

The structure of the paper can be summarized as follows: Section II describes in detail the methodology of the proposed design, including modelling and optimization procedures. The influence of different antenna parameters on performance is explained in the third section. Section III highlights the comparison between other existing antenna structures in the literature as well as the results of the antenna performance parameters. Section V concludes the article.

2. MODELLING AND OPTIMIZATION OF THE ANTENNA

The proposed sprienski bowtie antenna is a challenging and versatile antenna structure since its bandwidth characteristic. Hence, the modelling and numerical analysis of the proposed structure evaluated via CST Microwave Studio. The proposed antenna structure consists of radiating patches and substrate material characterized as low-cost FR-4 with the thickness of 1.6 mm and the dielectric constant of 4.3. The overall dimension of the designed antenna is calculated as 153.98x213.56 mm^2 as detailed in Figure 1a. As seen from Figure 1b, the back of the substrate material does not cover the ground plane, which is special feature of the bowtie structures. The antenna's radiating arms are made up of triangular elements based on fractalization technique. Each side of the smaller triangular initially is calculated as 12.83 mm depicted in Figure 1c. The flare angle of the proposed antenna is taken as 60º represented in Figure 1c as well.



a) Front view of the antenna

b) Back view of the antenna

c) Zoomed view of the antenna

Figure 1. The geometry of the proposed antenna structure with dimensions

In this study, hybrid objective functions are defined as Return Loss (S11<-10 dB), Voltage Standing Wave Ratio (VSWR<2), and Impedance (Z=50Ω), which quantify the performance of the antenna. The physical design variables are considered as arm length, feed gap, flare angle, and relative permittivity to optimize the antenna's performance. The initial set of design variables are given in Section 2.1. These antenna structure form the first simplex in the parameter space. Then, objective function values are calculated for each instance. In other words, this requires simulating the antenna performance parameters for each set of design variables by using values in Table 1. Up to maximum number of iterations, this process convergence threshold, or other criteria. The best value is found after the termination of the algorithm represents the optimal set of design variables for the antenna, as it corresponds to the minimum (or maximum) of the objective function. After obtaining the optimized design variables, they are implemented in the antenna design and simulate the antenna's performance. Then, the results are analyzed to verify the improvements achieved through the optimization process.

Table 1. The parametrized design variables of the proposed antenna structure

Parameter	Min	Max	Mean	Std. Dev	# of distinct
Arm Length (mm)	80.64	95.9	89	0.52	279
Feed Gap (mm)	0.2	0.22	0.21	0.001	107
Flare Angle (mm)	53.3	66	62.7	0.43	231
Relative Permittivity	4.3	11.54	8.89	0.28	430

3. RESULTS AND DISCUSSIONS

3.1. Initial Simulated Antenna Performance Parameter Results of the Proposed Antenna

The simulated reflection coefficient characteristic of the proposed antenna is depicted in Figure 2. It is clear from Figure 2 that the proposed antenna structure has triple band characteristics in the frequency range of interest. The desired frequency range is selected from 1 GHz to 8 GHz referred to as the microwave frequency range. It is significant in various fields due to its fundamental characteristics and applications. This frequency range is important why there are some reasons which cover Wireless Communication, Radar Systems, Satellite Communication, Aerospace and Defense, ISM Applications, Remote sensing & Earth observations, short range communication, Sensing, Radio Astronomy etc.

As seen from Figure 2, three distinct operating frequencies include as1.635-1.7779 GHz (Band 1), 3.0596-3.8989 GHz (Band 2), and 6.25- 7.6 GHz (Band 3), respectively. Their corresponding resonance frequencies are 1.7 GHz, 3.4 GHz, and 6.62 GHz. The proposed antenna with its specified bands and characteristics can be used in various applications due to its multiband capabilities.

VSWR characteristic of the proposed antenna structure is also outlined in Figure 3. It is also depicted from Figure 3 that the proposed antenna has triple-band characteristics within the 1 GHz to 8 GHz frequency range. As seen from Figure 3, VSWR close to 1 at each resonance frequency of the proposed antenna structure. VSWR characteristic of the proposed antenna indicates good impedance matching at the resonance frequencies and is desirable for the efficient power transfer.

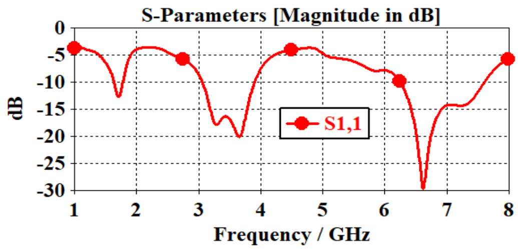


Figure 2. The reflection coefficient characteristic of the proposed antenna structure in the desired frequency

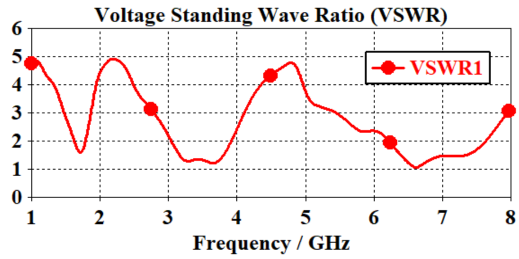


Figure 3. The VSWR characteristic of the proposed antenna structure in the desired frequency

Another crucial antenna performance parameter is of gain to understand the antenna's characteristics and its potential applications. The detailed gain characteristic is given in Figure 4. The gain of 5.8 dBi (at 1.7 GHz) suggests that the antenna has relatively moderate gain in this band, which can be suitable for many wireless communication applications. The gain of 10 dBi (at 3.4 GHz) suggests a higher level of gain, making it suitable for applications requiring increased directional performance. The gain of 6.67 dBi (at 6.62 GHz) suggests moderate gain, making it suitable for applications that require a balance between directivity and wide coverage.

Radiation efficiency and radiation pattern characteristics of the proposed antenna is illustrated in Figure 5 and Figure 6, respectively.

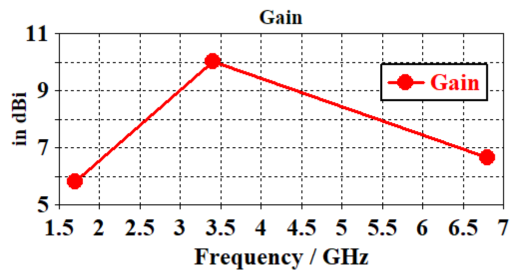


Figure 4. The gain characteristic of the proposed antenna structure in the desired frequency

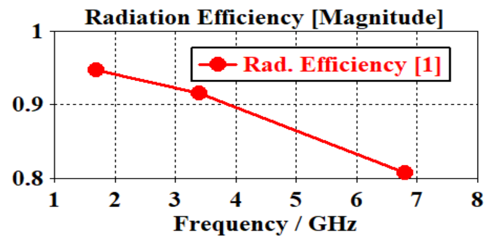
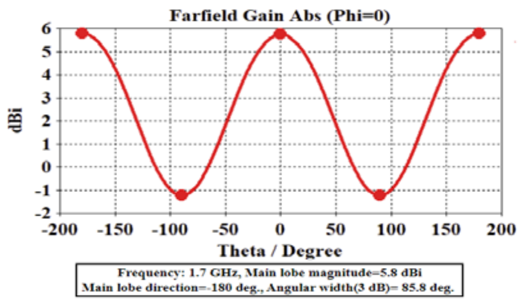
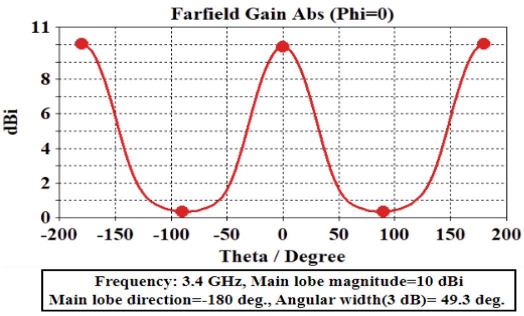


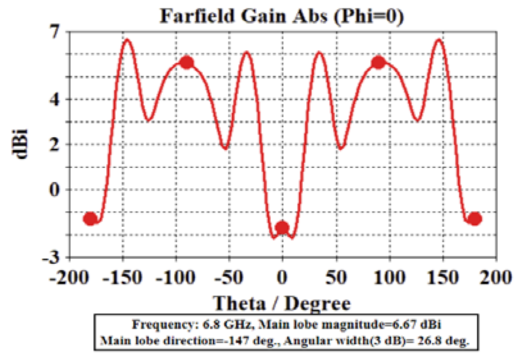
Figure 5. The radiation efficiency characteristic of the proposed antenna structure in the desired frequency



a) The radiation pattern characteristic for the resonance frequency of 1.7 GHz



b) The radiation pattern characteristic for the resonance frequency of 3.4 GHz



c) The radiation pattern characteristic for the resonance frequency of 6.8 GHz

Figure 6. The radiation pattern characteristic of the proposed antenna structure

Table 2 is outlined overall RF performance parameters of the proposed antenna structure. Band 1 exhibits excellent antenna efficiency (95%), indicating that a high percentage of the input power is effectively radiated as electromagnetic waves. High efficiency is desirable for minimizing power loss and ensuring effective signal transmission and reception. Band 2 provides substantial antenna gain (10 dBi), suggesting that it can direct and concentrate radiation in specific directions. High gain is essential for long-range communication and radar applications where signal strength and coverage are critical. Band 3 covers a relatively broad frequency range, making it versatile for applications that require flexibility in frequency selection. The proposed antenna in Band 3 provides a balance between gain and efficiency, making it suitable for applications that require both directional performance and power efficiency.

Table 2. RF performance parameters of the proposed antenna structure

Band	Op. Freq. (GHz)	Res. Freq. (GHz)	Gain (dBi)	Efficiency (%)
1	1.64-1.78	1.7	5.8	95
2	3.06-3.9	3.4	10	92
3	6.25-7.6	6.62	6.67	81

In summary, the proposed antenna exhibits different characteristics and performance levels in each band, allowing it to cater to a wide range of applications:

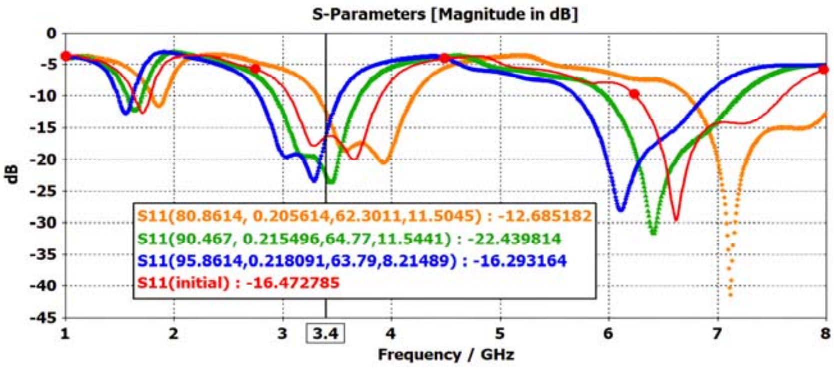
- **Band 1 (1.635-1.7779 GHz):** High efficiency, suitable for efficient power transfer and reliable communication, such as satellite and wireless applications.
- **Band 2 (3.0596-3.8989 GHz):** High gain and good efficiency, ideal for radar, long-range communication, and aerospace applications.
- **Band 3 (6.25-7.6 GHz):** Versatile frequency range, balanced gain and efficiency, making it adaptable for various applications, including satellite communication and wireless LANs.

3.2. Optimized Simulated Antenna Performance Parameter Results of the Proposed Antenna

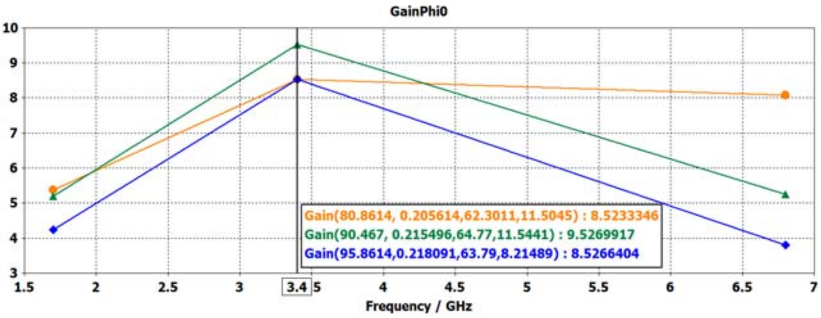
The minimum, maximum, mean, std deviation and how many different values each design parameter to be optimized are given in Table 1. This dataset shows the values obtained because of the Nelder-Mead Simplex algorithm. By increasing the arm length of the proposed antenna, the resonance frequency of Band 3 is decreased as represented in Figure 7a. However, the gain is higher with the lower arm length of the proposed antenna except for the arm length of 90.467 mm and flare angle of 64.77^{o} as depicted in Figure 7b. On the other hand, the trade-off condition occurs between minimum return loss and gain as depicted in Figure 7c and 7d, respectively. At this point, it is deduced from this optimization algorithm results that each objective function should be evaluated separately due to this trade-off condition.

The highlighted study, represented by "this work" in Table 3 stands out in the table due to several key characteristics that contribute to the existing literature on antenna design and performance [30-41]. With a gain of 10 dBi, the antenna design in this study exhibits high signal amplification capabilities, which is crucial for many applications, particularly in long-range and high-data-rate communication systems. The proposed antenna offers a relatively wide bandwidth of approximately 840 MHz. A broad bandwidth is essential for accommodating a range of communication frequencies within a single design, making it versatile for various applications. A radiation efficiency of 92% is a significant achievement. High radiation efficiency indicates that most of the input power is effectively converted into radiated electromagnetic waves, minimizing losses. This is especially important in real-world applications where efficiency is a primary concern.

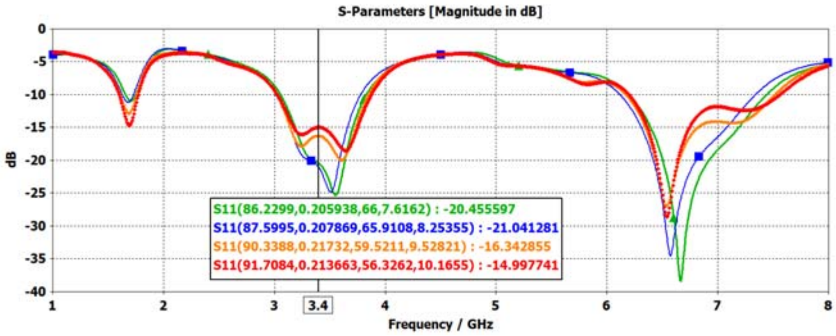
The antenna's substantial size (213.56x153.98 mm^3) may suggest that it could be suitable for long-range communication or applications where a more extensive coverage area is required. While Reference [31] has a higher gain (5.5 dBi), it has a narrower bandwidth (approximately 700 MHz) compared to the highlighted study. This study offers a much broader frequency coverage. In [33] and this study have almost similar bandwidth, but this study has a significantly higher gain (10 dBi). This suggests it may be more suitable for long-range or high-gain applications. In [38], which uses PTFE as the substrate, has a similar bandwidth to the highlighted study, but it offers a lower gain of 5.1 dBi. In contrast, the highlighted study achieves a remarkable 10 dBi gain. In summary, this study stands out in the table due to its impressive gain, high radiation efficiency, and broad bandwidth, making it a valuable contribution to the literature on antenna design. It appears to excel in terms of gain and efficiency compared to several other entries in the table, making it a notable design for various communication and signal reception applications.



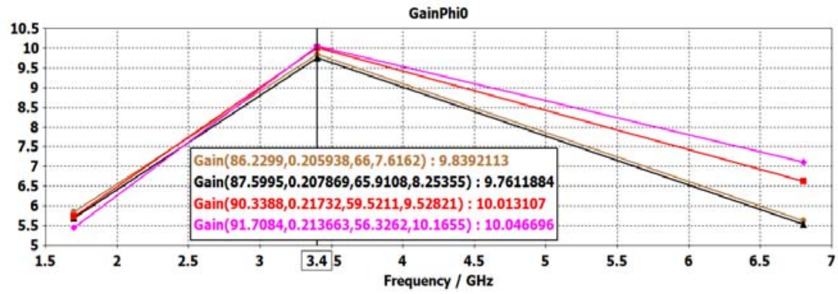
a) Corresponding S11 parameters obtained by Nelder-Mead Simplex Algorithm



b) Corresponding Gain parameters obtained by Nelder-Mead Simplex Algorithm



c) Corresponding S11 parameters obtained by Nelder-Mead Simplex Algorithm



d) Corresponding Gain parameters obtained by Nelder-Mead Simplex Algorithm

Figure 7. Some evaluated antenna design parameters by changing the physical dimensions via Nelder-Mead Simplex

4. CONCLUSION

In this study, a sprienski antenna design with exceptional performance characteristics is presented, particularly its ability to operate across a wide frequency range of 1 GHz to 8 GHz. This antenna structure exhibits a triple-band response, making it a versatile solution for various applications within the microwave frequency range, which is renowned for its paramount significance in a multitude of fields. The importance of the microwave frequency range is highlighted by its fundamental properties and its various applications. It plays a critical role in enabling key technologies such as wireless communications, radar systems, satellite communications, aerospace and defense, industrial, scientific and medical (ISM) applications, remote sensing, short-range communications, detection and radio astronomy. The importance of this frequency range cannot be underestimated as it underpins essential aspects of modern technology and scientific research. The proposed antenna design has triple band characteristics, called as Band 1 (1.635-1.7779 GHz), Band 2 (3.0596-3.8989 GHz) and Band 3 (6.25-7.6 GHz). Each resonance frequency is of 1.7GHz, 3.4GHz and 6.62GHz, respectively.

Table 3. Comparison of the antenna performance parameters with the other antenna structure in the literature

Ref	Substrate	Dimension (mm×mm)	Band Feature	Operating Frequency	Gain	Radiation Efficiency	Bandwidth
30	FR-4	9.4x14.2	Triple	3.4-3.6 GHz	~2 dBi	~0.4%	200 MHz
31	FR-4	30x17	Triple	3.4-4.1 GHz	5.5 dBi	96%	~700 MHz
32	FR-4	33x17	Triple	3.3–3.7 GHz	2.23 dB	~80%	400 MHz
33	FR-4	60x50	Triple	3.42-3.6 GHz	5.18 dB	68%	180 MHz
34	FR-4	40x40	Triple	3.3–3.7 GHz	>1.96dBi	83%	400 MHz
35	FR-4	27.5x20	Triple	3.35-3.90 GHz	4 dBi	<90%	550 MHz
36	FR-4	85x56	Triple	3.41-3.6 GHz	3.87 dBi	Not mentioned (NM)	190MHz
37	FR-4	32.4x27.9	Single	3.4-3.59 GHz	4.16 dB	~82%	190 MHz
38	PTFE	20x20	Dual	3.15-3.485 GHz	5.1 dB	NM	170 MHz
39	FR-4	29.8x36	Single	3.4-3.6 GHz	2.55 dB	71%	200 MHz
40	FR-4	28x26.8	Dual	3.12-3.58 GHz	2.72 dB	NM	460 MHz
41	FR-4	88x88	Single	1.9-3.7 GHz	7 dB	NM	1.8 GHz
This work	FR-4	213.56x 153.98	Triple	3.06-3.9 GHz	10 dBi	92%	~840 MHz

The characteristic of VSWR shows good impedance matching at the desired resonance frequencies. It is also deduced from VSWR analysis that the proposed antenna has promising value to provide the power transmission efficiency. Antenna gain values vary from 5.8 dBi to 10 dBi, reflecting a balance between coverage, directivity and efficiency. This versatility makes the proposed antenna alternative for a variety of applications including satellite communications, radar systems, wireless communications, remote sensing and more. In addition, the Nelder-Mead simplex algorithm, which is a kind of mathematical optimization technique, is used to systematically examine and tune the antenna physical design parameters. It is highlighted from optimization method that the effect of arm length on resonance frequency and gain, as well as the balance between return loss and gain. This trade-off condition requires careful evaluation of each individual parameter to achieve the desired antenna performance. It is also necessary to evaluate each objective function (e.g., resonance frequency, gain, return loss) separately. This is due to the observed trade-off condition where optimization of one parameter may occur at the expense of another.

Therefore, a compromise or balance must be found, and each parameter evaluated individually to ensure that the antenna achieves its performance goals for a particular application. Further studies can be carried out to optimize the design of the proposed antenna structure considering factors such as size, sensitivity and radiation efficiency. The performance of the antenna can be evaluated in various environments and scenarios to evaluate its suitability for various applications. The proposed antenna can be tested and validated in real-world scenarios to evaluate its practicality and effectiveness.

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