

Educational Model For E And H Patch Octet Antenna Designed Gain Improvement

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Abstract: *The enhancement of directivity and gain remains a critical area of research in the design of antenna arrays. This study presents the design and analysis of highly directive E-octate (E-O) and H-octate (H-O) rectangular microstrip patch antenna arrays (MSPAA) aimed to improve the gain performance at a frequency of 2.4 GHz. The proposed antenna arrays were optimized to attain maximum directivity and gain by carefully adjusting element spacing and substrate dielectric properties. The performance of these arrays was evaluated through electromagnetic simulations, with particular emphasis on radiation patterns, return loss, and impedance matching. The E-O-MSPAA design with optimized spacing has achieved a maximum directivity of 17.7 dBi, which represents an improvement of 3.7 dBi over the original validated E-O-MSPAA design. In comparison, the H-O-MSPAA design outperformed E-O-MSPAA, attaining a directivity of 18.4 dBi along with a narrower beam width. An analysis of return loss indicates a trade-off between bandwidth and minimum return loss for both antenna types. The E-O-MSPAA design exhibits a wider bandwidth with an acceptable return loss, while the H-O-MSPAA features a narrower bandwidth but demonstrates a lower return loss at resonant frequency. In addition, evaluation of active impedance matching reveals that the H-O-MSPAA at higher bandwidth maintains relatively stable impedance characteristics. The proposed optimized E-O-MSPAA design outperforms previous state-of-the-art octet antenna array designs, increasing performance by 3.5 dBi over slotted designs and 0.22 dBi over T-slotted patch designs. These findings highlight the potential of the proposed arrays for applications requiring high directivity and gain, such as satellite communication systems.*

Keywords: *Microstrip patch array antennas, printed circuit board, 5G communication system, HFSS, Octet rectangular patch antennas.*

1. INTRODUCTION-

Owing to their low profile and simplified design, high-directivity microstrip patch antenna arrays are gaining popularity as line-of-sight communication solutions. Several studies have investigated different strategies to improve the directivity and gain of these antennas. The design of a highly directional octate patch antenna for 2.4 GHz applications can be handled by utilizing a variety of strategies and combinations based on existing research. Patch antennas, known for their thin design, ease of manufacture, and adaptability to both flat and curved surfaces, are key components of this array. Because the octate array groups eight patch pieces in a particular configuration, it offers superior directional properties compared with individual patch antennas. The recent study primarily focused on the design and analysis of antenna array performance across a wide operating range. The objective of this research was to assess and compare the gain and directivity characteristics of a highly directional octate E-O-MSPAA antenna array with those of a similar H-shaped H-O-MSPAA array.

The octet patch antenna array is recognized for its exceptional directivity, which has significantly enhanced antenna technology by delivering improved performance across various wireless and space communication applications. The increased directivity and gain of octet patch antenna arrays result in enhanced signal intensity and coverage in specific beam directions. Additionally, the compact design of these arrays makes them particularly suitable for applications with spatial constraints, as they optimize the use of available space. Furthermore, octet arrays contribute to improved signal quality, facilitate higher data rates, and offer greater bandwidth. The electronic beam steering capability of octet arrays allows for

dynamic modifications to the radiation pattern, thereby enhancing directivity and enabling the system to adapt effectively to varying environmental conditions. This adaptability is crucial in optimizing the antenna's performance as it can focus energy in specific directions, leading to improved signal intensity. Additionally, the use of multiple array elements contributes to a superior signal-to-noise ratio and minimizes interference, which further enhances the reliability of communication channels. As a result, these characteristics make octet patch antenna arrays especially advantageous in contemporary wireless communication systems, such as satellite communications, radar applications, and 5G networks, where precise control of radiation patterns and directivity is essential for optimal performance.

The advantages of patch array antennas render them an excellent option for wideband applications. Consequently, leveraging the knowledge of these benefits creates opportunities for the design of octet patch antenna arrays across various frequency ranges. Building upon the inherent strengths of octate arrays, this paper explores targeted design strategies aimed at enhancing gain and directivity specifically at the critical frequency of 2.4 GHz. It is proposed to design and analyse highly directive E and H-patch octet antenna arrays to achieve significant improvements in gain at this frequency. Research has demonstrated that high gain and directivity can indeed be effectively attained through the utilization of spacing between patch antenna arrays.

One such notable contribution within the operational bandwidth is the development of a novel patch antenna featuring two symmetrical slits and closely spaced resonances, which demonstrated a measured gain of up to 19.5 dBi with a fluctuation of approximately 1.2 dB (Boskovic et al., 2018). Adapting this design concept for the 2.4 GHz frequency could facilitate the creation of a highly directional array with improved gain. The performance of patch antenna arrays can be optimized through various strategies. One effective approach involves integrating a differential feeding technique with a parallel-series feed network, which has been shown to enhance both frequency bandwidth and gain simultaneously (Yang et al., 2016). Additionally, another method employs metamaterial structures to increase gain; research indicates that this approach can enhance gain by as much as 5.5 dB within the specified frequency range (Ali et al., 2019). The design of a highly directional E-patch and H-patch octet antenna array operating at 2.4 GHz necessitates the integration of metamaterial structures, differential feeding techniques, and optimization of patch geometry. This combination aims to achieve high gain and directivity while ensuring adequate impedance matching and bandwidth. The application of substrate-integrated waveguide (SIW) technology significantly enhances the feed network design, enabling improved efficiency of the antenna by optimizing power distribution across the array (Ghassemi & Wu, 2012; Mikulasek et al., 2016). Islam et al. (2009b) introduced a broadband inverted E-H-shaped microstrip patch antenna that exhibits a wide bandwidth ranging from 1.76 GHz to 2.38 GHz. This design can be adapted into a 2×4 array configuration to further enhance performance. Notably, the L-probe feeding method presented in this design may facilitate greater bandwidth within the array configuration (Islam et al., 2009b).

Due to their ease of production, low profile, and lightweight characteristics, microstrip patch antennas have gained significant popularity in recent years. However, challenges such as limited gain and bandwidth necessitate innovative design solutions. This study concentrates on the E-shaped octahedral configuration, which integrates the advantages of E-shaped patches with the octet array structure. This innovative design enhances both gain and directivity while retaining the inherent benefits of patch antennas. As a result, the octet patch antenna array is particularly well-suited for applications in satellite communications, radar systems, and 5G networks, all of which require focused beam patterns. The efficiency and effectiveness of this array in modern wireless communication systems stem from its ability to concentrate electromagnetic energy in a specific direction while minimizing radiation in undesired directions. The increasing demand for high-performance antennas in wireless communication systems is being addressed by this study, which analyses highly directive octate E-shaped and H-shaped patch arrays. These arrays are specifically designed to enhance gain performance at 2.4 GHz, a frequency band that plays a crucial role in various applications, including Bluetooth, Wi-Fi, and Internet of Things (IoT) devices. This research focuses on the development of E-patch and H-patch octate antennas, highlighting their efficiency and compact design. A key aspect of this study is the optimization of antenna spacing, which is vital for improving both directivity and gain—particularly important for satellite communication

applications operating at 2.4 GHz. The simulation conducted as part of this study encompasses the design and performance evaluation of the proposed antenna arrays, specifically the E-O-MPSSA and H-O-MPSAA configurations, aimed at enhancing satellite communication systems.

In rest of this study, the antenna design methodology and literature survey are discussed in section 2 and section 3 respectively. Section 4 presented proposed methodology and flow. Section 5 is presented results of E-O-MSPAA antenna simulation including gain, patterns, return losses and impedance characteristics. Finally, section 6 has presented the discussion and sequential conclusion section presented for further understanding and additionally provided future scopes.

2. OCTATE ANTENNA ARRAY CONFIGURATION

Octate antenna arrays are commonly configured as 2×4 or 4×2 array configurations. The arrangement of the antenna elements along the axis has a significant impact on the array's performance. This study presents an E-shaped octate antenna design that incorporates numerous E-shaped patches grouped in an octate pattern. Each patch is designed to resonate at 2.4 GHz, improving the array's performance. The array obtains its peak gain when made of FR4, which has a particular permittivity. The proportions of the E-shaped patches were refined using simulation techniques. Modifying the patch length can aid in achieving the ideal resonance frequency, but increasing the patch width can improve the antenna's gain. Additionally, the placement of the feed point is critical for impedance matching. The recommended octate configuration, which arranges many E-shaped patches in a grid pattern, boosts gain and facilitates constructive interference and high directivity. The distance between these patches is critical for increasing directivity while decreasing mutual coupling. This work focuses on the 2×4 Octate E-O-MSPAA antenna array built with these patch antennas.

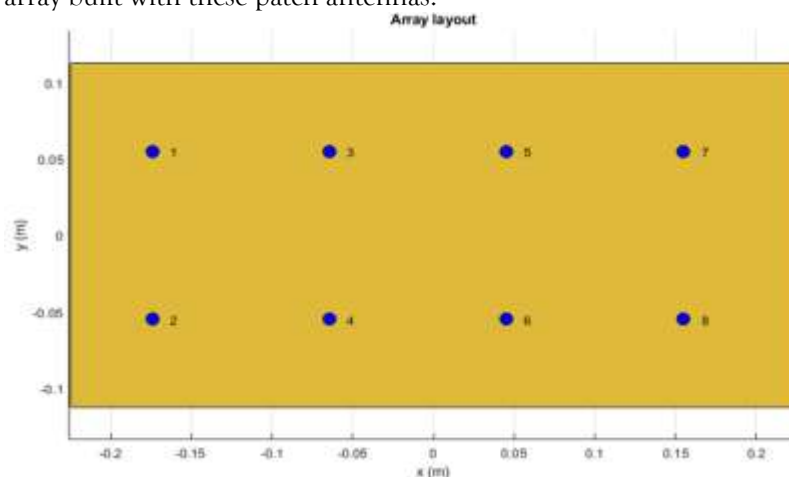


Figure 1 Layout diagram of proposed 2×4 Octate E-O-MSPAA antenna array

Figure 1 displays the Octate antenna array's schematic architecture shows the layout diagram of a proposed 2×4 Octate E-O-MSPAA antenna array. The array is arranged in a rectangular grid. Eight antenna elements are depicted as dark blue circles, numbered 1 through 8 indicating the spatial arrangement of the antenna elements within a-collared rectangular substrate. The top view of the array layout is consistent for both the E-O-MSPAA and H-O-MSPAA patch arrays. Figure 1 depicts the 2.4 GHz array. The array layout top view is the same for both the E-O-MSPAA and H-O-MSPAA patch arrays. Figure 1 depicts the array running at 2.4 GHz.

2.1 E/H-O-MSPAA Octate Design Challenges:

The Figure 2 illustrates the challenges of designing E-O-MPSAA Octate Patch Arrays, including optimizing bandwidth, gap, directivity, element springs, slot dimensions, mutual coupling, achieving an omnidirectional pattern, and considering network design complexity. These challenges require careful control over parameters, minimizing unwanted interactions, and considering intricate interactions between components.



Figure 2 Challenges of designing E-O-MPSAA Octate Patch Arrays

While E-shaped patches can enhance bandwidth, it is crucial to precisely adjust the slot dimensions. Achieving a balance between performance and size reduction is vital for H-shaped patches. In larger arrays, the complexity of feed network design increases in both scenarios, necessitating optimization of power distribution and impedance matching. The bandwidth and efficiency of the antenna are influenced by the substrate; generally, greater radiation quality is produced by substrates with lower dielectric constants. The array structure and element spacing must be carefully considered to reduce grating lobes and provide the best beam characteristics. Furthermore, performance can be significantly affected by fabrication tolerances, especially at higher frequencies, which require exact design methods. The challenges and considerations that must be addressed throughout the design process are illustrated in Figure 2.

2.2 Advantages of Octet antenna array

Octate-patch antenna arrays provide numerous advantages in wireless communication systems. Compared to single-patch antennas, these arrays exhibit higher directivity and gain, resulting in stronger signals and enhanced coverage in specific directions. Their compact design makes octet arrays particularly well-suited for applications with size constraints, allowing for efficient utilization of available space. Additionally, octet arrays offer increased bandwidth, leading to faster data rates and improved signal quality. The capability to electronically steer the beam adds significant flexibility to the system, enabling dynamic adjustments to radiation patterns in response to varying external conditions. Additionally, the incorporation of multiple array elements greatly enhances the signal-to-noise ratio and reduces interference, contributing to more reliable communication links. Given these advantageous characteristics, octet patch antenna arrays are invaluable in contemporary wireless communication systems, such as satellite communications, radar applications, and 5G networks. Their ability to deliver focused and high-quality signals positions them as critical components in the advancement of communication technologies.

3 LITERATURE REVIEW

The primary goal has been to enhance the performance attributes of patch antenna arrays, focusing on aspects such as bandwidth, gain, and efficiency. Researchers have explored a variety of innovative strategies to achieve this, including the use of metamaterials, modifications to substrates, and the introduction of new feeding techniques. These advancements have led to significant improvements in the overall functionality and application of patch antenna arrays within modern communication systems. As

a result, these antennas are now better equipped to meet the demands of today's communication technologies.

3.1 Review of Octate antenna array

Recent studies have explored the effectiveness of octet antenna arrays in milli-meter-wave and 5G communications. Thakur et al. (2022) described an eight-element antenna array designed for 5G applications operating in the LTE 42 band (3.4-3.6 GHz). This array boasts low envelope correlation and impressive isolation, exceeding 14.8 dB. Notably, even with battery installation and user proximity, the side-frame architecture of this array achieves a channel capacity of 41 bps/Hz, allowing multiple antennas to function efficiently within a limited space. Additionally, Palomares-Caballero et al. (2021) presented a 16-element aperture array utilizing glide-symmetric holey gap waveguide technology. This array operates between 68 and 74 GHz and provides a gain of 19 dBi. The combination of performance, compact size, and strong isolation in octet antenna arrays positions them as promising solutions to enhance wireless communication systems. Their innovative design may significantly contribute to the development of more efficient and reliable communication technologies in the future.

3.2 Review of E- patch antenna design

E-shaped patch 2×4 antenna arrays provide a range of benefits in terms of performance and versatility. When compared to standard rectangular patches, E-shaped patches are particularly noted for their enhanced bandwidth and gain. In a recent study, Pauliah Nadar et al. (2023) introduced an E-shaped MSPAA that utilizes an RT/Duroid5880 substrate with a dielectric constant of 2.2 to improve bandwidth. Their research investigated both 2×2 and 3×3 configurations, revealing that the 2×2 array achieved a bandwidth of 0.1 GHz, a gain of 8.9 dBi, and a directivity of 8.95 dBi. The authors propose that a 2×4 configuration could further boost these performance metrics. Additionally, Chung (2013) highlighted the advantages of an H-shaped patch with a 2×4 antenna array for wireless communication applications. This design features an impressive 85% impedance bandwidth, 89% axial-ratio bandwidth, and 80% efficiency, enabling the creation of circularly polarized antenna arrays that perform exceptionally well at 2.5 GHz. By extending this concept to a 2×4 array, it is possible to enhance both gain and directivity while still retaining wideband characteristics. Crucially, the performance of these antenna arrays is significantly influenced by the feeding network, particularly through the use of metamaterial transmission lines (MMLs). These advancements highlight the potential of E-shaped and H-shaped patch antenna arrays in modern wireless communication systems, showcasing their ability to meet the increasing demands for efficient and high-performance antennas.

3.3 Rectangular Patch Array Design

Effective operation of microstrip patch antennas in wireless communication systems necessitates meticulous design and research. Asaduddin et al. (2023) have made significant contributions to the development of efficient antenna structures by proposing a novel design for a microstrip patch antenna array, focusing on performance optimization for microwave applications. In their comparative study, Rastogi et al. (2019) evaluated the advantages and disadvantages of rectangular and E-shaped microstrip patch antenna arrays specifically tailored for X-band applications, providing valuable insights for application-specific antenna selection.

Further emphasizing the critical aspects of gain and bandwidth in modern wireless communication standards, Ramya et al. (2018) conducted a comprehensive design and analysis of a microstrip patch array antenna intended for WLAN applications. Additionally, Sonkar and Thatere (2019) investigated an E-shaped patch antenna array, demonstrating its effectiveness in enhancing overall performance metrics essential for various engineering applications. Collectively, these studies underscore the necessity for continuous innovation and refinement in the design of microstrip patch antennas to propel advancements in wireless communication technologies.

The design and analysis of microstrip patch antennas have gained increasing significance in wireless communication due to their low profile, lightweight characteristics, and ease of integration. These

antennas are widely utilized across various applications, including satellite communication and mobile devices. Recent studies have primarily focused on tuning these antennas for specific frequency bands and enhancing their performance metrics. For instance, Patil and Patil (2024) introduced a slotted microstrip patch array antenna designed for WLAN applications operating at 2.4 GHz, aiming to improve gain and bandwidth to facilitate more reliable wireless communication. Similarly, Otsap et al. (2023) developed circular patch arrays tailored for industrial sensor networks, demonstrating the adaptability of antenna designs to meet the demands of modern industrial environments. The versatility of microstrip patch antennas is further evidenced by a variety of designs and applications explored in recent literature. Shimu and Ahmed (2016) investigated rectangular microstrip patch antennas operating at 2.45 GHz, providing valuable insights into their performance characteristics. In another study, Muludi and Aswoyo (2017) examined truncated square patch arrays with circular polarization, highlighting the flexibility of microstrip designs in accommodating specific polarization requirements. Additionally, Islam et al. (2019) proposed a modified meander line patch antenna for IoT applications, underscoring the ongoing innovation in antenna design to meet the increasing demand for efficient and compact connectivity solutions. These studies illustrate the continuous efforts to enhance and adapt microstrip patch antennas to address the evolving needs of various wireless communication systems and applications.

Recent years have witnessed significant advancements in the field of microstrip patch antenna design, driven by researchers exploring a diverse array of designs and applications to address the evolving demands of wireless communication technologies. Kaschel and Ahumada (2018) demonstrated how these antennas can be specifically tailored for applications such as wireless body area networks, while Casu et al. (2014) laid the groundwork for understanding the practical aspects of antenna array design.

The continuous evolution of antenna geometry is further exemplified by the work of Muttaqin et al. (2023) and Zafar et al. (2022), who investigated octagonal designs and faulty ground constructions for Wi-Fi and 5G applications, respectively. These studies underscore the critical role of antenna design in keeping pace with rapid advancements in wireless technology. Additional contributions include the research conducted by Al-Gburi et al. (2022), which focused on high-frequency operations for 5G backhaul applications, as well as the innovative approaches of Koesmariyanto et al. (2022) and Gupta et al. (2023), who explored alphabetical and hexagonal configurations, respectively. Together, these studies highlight the diverse array of design options available within microstrip antenna technology and its capacity to effectively address specific communication challenges. Moreover, Rana et al. (2024) illustrated that the application of advanced computational techniques marks a significant breakthrough in antenna design optimization. By leveraging machine learning methodologies, researchers can now explore more complex design spaces, potentially enhancing performance in 5G applications. This trend towards computational design and optimization indicates that antenna engineering is poised to become increasingly interdisciplinary in the future, integrating state-of-the-art data science and artificial intelligence methods with traditional electromagnetic theory.

The enhanced bandwidth and gain characteristics of E-shaped patch antennas can be effectively leveraged in the design of a 2×4 E-shaped patch antenna array. By employing techniques such as array design optimization, feed mechanisms, and substrate selection, it is possible to develop high-performance antenna arrays that are well-suited for various wireless applications. The desired frequency range, polarization, antenna spacing optimization, and efficiency requirements influence the actual design. Future work could involve simulating various 2×4 configurations using these techniques to evaluate their effectiveness in achieving the desired antenna characteristics. Optimization algorithms may also be employed to fine-tune parameters such as element spacing, substrate properties, and feed network geometry. Additionally, prototyping and experimental validation would be essential to confirm simulated performance and ensure practical feasibility. the summary of literature is given in Table 1.

Table 1 Summary of related work and performances comparison

Reference	Antenna Type	Configuration	Gain (dBi)	Size/ Dimensions	Limitations
Thakur et al. (2022)	Octate Array	8-element array for 5G	>14.8	Compact design for limited space	Isolation challenges with user proximity
Palomares-Caballero et al. (2021)	Octate Array	16-element aperture array	19	Glide-symmetric holey gap-waveguide technology	Complexity in manufacturing
Pauliah Nadar et al. (2023)	E-shaped Patch	2x2 configuration	8.9	Standard size	Performance may vary with substrate materials
Chung (2013)	E-shaped Patch	2x4 configuration	Not specified	Standard size	Dependence on feeding network complexity
Asaduddin et al. (2023)	Rectangular Patch	Novel microstrip array	Not specified	Standard size	Generalized findings may not apply to all designs
Rastogi et al. (2019)	Rectangular vs. E-shaped	Comparative study	Varies by design	Standard size	Trade-offs between designs may limit application
Ramya et al. (2018)	Microstrip Patch	WLAN applications	Not specified	Standard size	Limited to WLAN frequency bands
Sonkar & Thatere (2019)	E-shaped Patch	E-shaped patch array	Not specified	Standard size	Potential for high losses in certain configurations
Patil & Patil (2024)	Slotted Microstrip	Array for WLAN	Not specified	Standard size	Limited to WLAN applications
Otsap et al. (2023)	Circular Patch	1x4 and 1x8 configurations	Not specified	Standard size	Focused on specific industrial applications
Shimu & Ahmed (2016)	Rectangular Patch	Standard configuration	Not specified	Standard size	Limited by design complexity
Muludi & Aswoyo (2017)	Truncated Square Patch	2x2 elements	Not specified	Compact size	Polarization issues in certain applications
Shahidul Islam et al. (2019)	Modified Meander Line	IoT applications	Enhanced bandwidth	Compact size	Limited to specific IoT applications

Muttaqin et al [32]	Octagonal Patch Antenna	2x4 Array with T-Slots	10.5	120 mm x 120 mm (approximate)	Large in size comparatively
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Tables have summarized the various literature and their limitations also it is clear that not much research has focussed specifically on gain improvement.

4. PROPOSED DESIGN METHODOLOGY

The antenna array was simulated using electromagnetic simulation software. The simulation includes visualization of the antenna array, its layout, and plots of gain variation with frequency. Details about the simulation workflow, and the information is provided as follows;

Substrate Properties: The simulation uses FR4 as the substrate material. The dielectric constant (ϵ_r) of FR4 is 4.4, and the thickness of the substrate is 0.8 mm.

Array Design and Frequency: The simulation involves a rectangular array design. The array is composed of 2x4 elements, total 8 elements. The simulation appears to cover a frequency range from 2.5 GHz to 7 GHz. The array elements are described as 'patch Microstrip Enotch', which suggests a microstrip patch antenna with an E-shaped notch.

Feed Lines Geometry: FR4 is used as a substrate and typically has a higher loss tangent compared to other RF substrates. This characteristic might influence the choice of feed line length to minimize losses. FR4 is a common and relatively inexpensive substrate material, which might influence the minimum achievable feed line width due to manufacturing limitations. The feed line length in this design is set to 0.1 meters. This length can affect the phase of the signal reaching different elements, potentially impacting the array's radiation pattern. The feed line width is 0.01 meters. The width influences the characteristic impedance of the line, which is crucial for impedance matching and power transfer efficiency. An offset of 0.05 meters is specified. The proposed design flow is given in Figure 3.

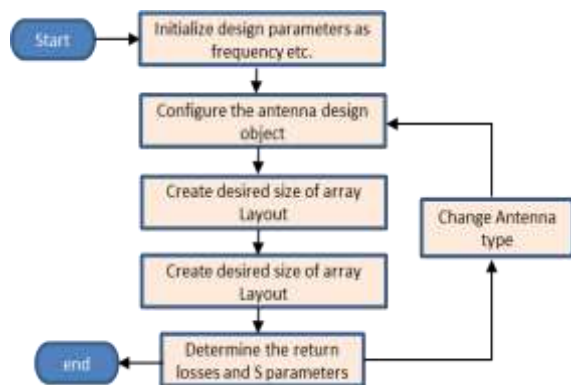


Figure 3 Proposed design flow chart

This offset can affect the symmetry of power distribution and potentially the overall radiation pattern of the array. This geometry may provide power distribution uniformity across the array elements. The dimensions, particularly the width, would be chosen to achieve proper impedance matching with the 50-ohm termination mentioned in the commented-out sections. The feed line dimensions (length of 0.1 m, width of 0.01 m, and offset of 0.05 m) have likely been optimized considering FR4 substrate properties to ensure proper impedance matching, power distribution, and overall antenna performance for this specific 2x4 rectangular array design.

The following performance metrics were evaluated:

4.1 Antenna design performance parameters

The rectangular patch array is evaluated based on gain, return loss and S parameters. An important metric for assessing how well power is transferred from a transmission line to an antenna is return loss.

Return loss: is formulated as;

$$R_L = -20 \log_{10} \left(\left| \frac{(Z - Z_0)}{(Z + Z_0)} \right| \right) \quad (1)$$

Where Z is impedance of array, and Z_0 is characteristic Ref. impedance.

Directivity (D): Refers to an antenna's capability to focus power predominantly in a single direction. It is defined as the ratio of the peak radiation intensity in the intended direction to the average radiation intensity in all other directions. The formula for directivity is:

$$D(\vartheta, \varphi) = 4\pi * U(\vartheta, \varphi) / P_{rad} \quad (2)$$

Where; D is antenna directivity or maximum directive gain.

U is radiation intensity in (ϑ, φ) direction

P_{rad} is radiated power in W

Antenna Array Configuration: Examine a linear antenna array consisting of N elements with a consistent element spacing (dd). The array's overall length is determined by:

$$L = (N - 1) \cdot d \quad (3)$$

Array Gain: An antenna array's gain G_0 can be represented as a function of the gains of its constituent elements and the number of elements N :

$$G = N \cdot G_0 \cdot 1(1 + d\lambda) \quad (4)$$

Where:

- G = Total gain of the array (in dBi)
- G_0 = Gain of a single element (in dBi)
- λ = Wavelength of the operating frequency

Impedance Considerations

The distance between elements in an antenna array can affect its input impedance Z_{in} . Mutual coupling may have an impact on the characteristic impedance Z_0 (50Ω) for elements that are closely spaced. One way to model the input impedance is as follows:

$$Z_{in} = Z_0(1 + R_jX) \quad (5)$$

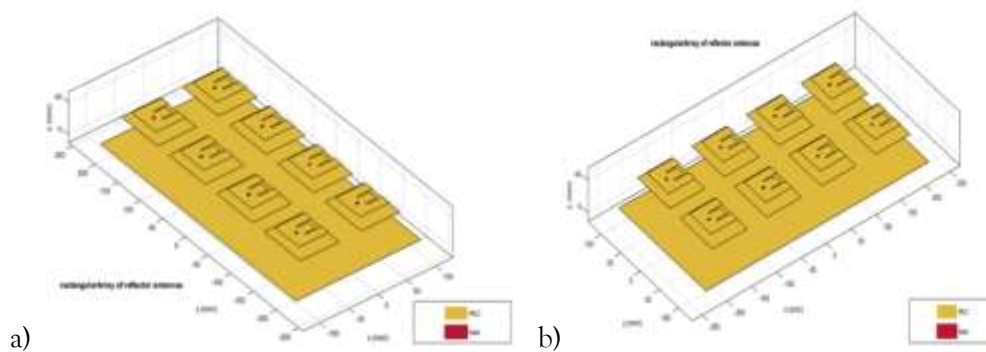
Antenna Spacing: A parametric representation of the relationship between element spacing and gain is possible. Thus, optimizing element spacing can increase the directive gain of antenna. Gain usually rises with increasing dd because of better directivity and fewer side lobes:

$$G(d) = G_0 + 10 \log_{10}(\lambda d) \quad (6)$$

Therefore, in this research it is proposed to optimize the antenna size and element spacing to achieve the higher gain performance.

5. SIMULATION AND EXPERIMENTAL CONSEQUENCES

The results are evaluated to compare the performance of the E-patch and H-patch antennas with the Octate antenna array, focusing on pattern directivity and losses. Simulations were conducted using Matlab. Figure 4 illustrates two 3D configurations of the E-O-MPSAA Octate antenna arrays, each featuring a rectangular ground plane and several E-patch antennas. Figure 4 (a) depicts the 2×4 layout design, whereas Figure 4 (b) shows the 4×2 design. Although the polarization and size are similar, the antenna orientations may differ. Both configurations contain the same number of E-patch antennas; however, their overall dimensions vary to fit different antenna setups. Layout in Figure 4 a) is elongated and narrow, measuring 500×200 nm, whereas layout (b), the 4×2 array, is shorter and wider, measuring 200×500 nm.



a) Figure 4 Layout architecture of E-OMPSAA Octate antenna arrays design
a) For 2x4 E-Patch array, b) for 4x2 E-Patch antenna array

5.1 Three stage Proposed Design

In this paper the three different designs of octate antennas are presented with the sequential improvement in the gain of the antenna. In the first stage the E- patch octate antenna is design is validated using the antenna design tool box, the first initial antenna dimensions are estimated. Then, learning based modified antenna array object is created using improved antenna dimensions aiming to achieve higher directive gain. The spacing between the antennas is optimized using the optimization tool. And finally the performance is compared with designed H-patch octate antennas.

5.2 Validation of E-O-MPSAA antenna Array (Case 1)

The basic antenna design is validated for 2.4 GHz resonant frequency using the antenna dimensions as given in the Table 2. Antenna layout is placed across the plane of 200 b 200 cm.

Table 2 Antenna design Parameters for Validation of E-O-MPSAA

Parameter	Symbol	Range
Size	x,y	[2, 4] and [4, 2]
Row Spacing	Ro_{sp}	0.062457 m
Column Spacing	Co_{sp}	0.062457 m
Lattice	---	Rectangular
Amplitude Taper	V	Set to 1
Phase Shift in degrees	φ	Set to 0
Micro strip Patch	MSP	E- patch
Dielectric	FR4	Permittivity 4.4
Frequency of operation	Fs	2.4 GHz
Array dimensions	Ax, Ay	[200 200] cm

5.3 Proposed Optimized antenna array design (Case 2)

Second design is proposed to incorporate the optimization of the antenna parameters and the spacing between the elements based on experimental learning's. The rectangular plane dimensions are changed in order to improve radiation pattern and directivity of the antenna. Table 3 presented the parameter used during the optimization of antenna array object. The ultimate aim is to optimally design the antenna spacing for maximizing gain.

Table 3 Parametric variations selected during the Optimization of Antenna array design

Parameter	Symbol	Lower Bound	Upper Bounds
Size	x,y	[2, 4] and [4, 2]	
Row Spacing	Ro_{sp}	0.08 m	0.02 m

Column Spacing	$C_{O_{sp}}$	0.08 m	0.02 m
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It is clear from the Table 3 that the optimization design has selected the 0.01 m higher lower bound of spacing and try kipping the upper bound near to maximum limit of 0,02 m.

Parametric optimization: The gain optimization for the optimal element spacing and size of antenna array is illustrated in Figure 6 for the random iteration count or samples for the optimization process

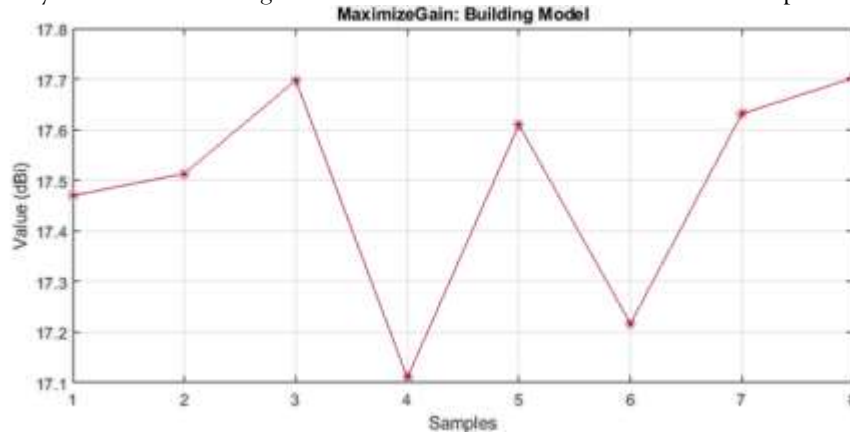


Figure 5 Gain maximization using antenna array optimization via element spacing for E-plane array Case 2.

It can be observed that optimal design achieves the maximum directive gain of 17.7 dBi. Directivity is a measure of how well an antenna converts input power into radio waves headed in a specified direction. It is expressed in decibels (dBi) relative to an isotropic radiator. A directivity of 17.7 dBi indicates a highly focused radiation pattern, which is a characteristic of high-gain antennas. Collinear microstrip arrays are designed to enhance gain by stacking multiple radiating elements in a linear configuration. The purpose of such an array is to achieve constructive interference among the elements, resulting in a higher gain and directivity compared to individual elements. Therefore, achieving a peak directivity as high as 17.7 dBi suggests that the array is effectively focusing energy in a specific direction. Although it is true that this design may also have slightly higher side lobes and is practically difficult to design in real time.

5.3 Radiation Pattern

The radiation pattern exhibits a directional beam, confirming the effectiveness of the octate configuration in enhancing directivity. The E-plane octate of the validation design Case 1 and the proposed optimized design of Case 2 patterns indicate a stable performance across the operating frequency range. In the proposed system the spacing between the elements is optimized and substrate dielectric is considered as FR4 for design of antenna arrays.

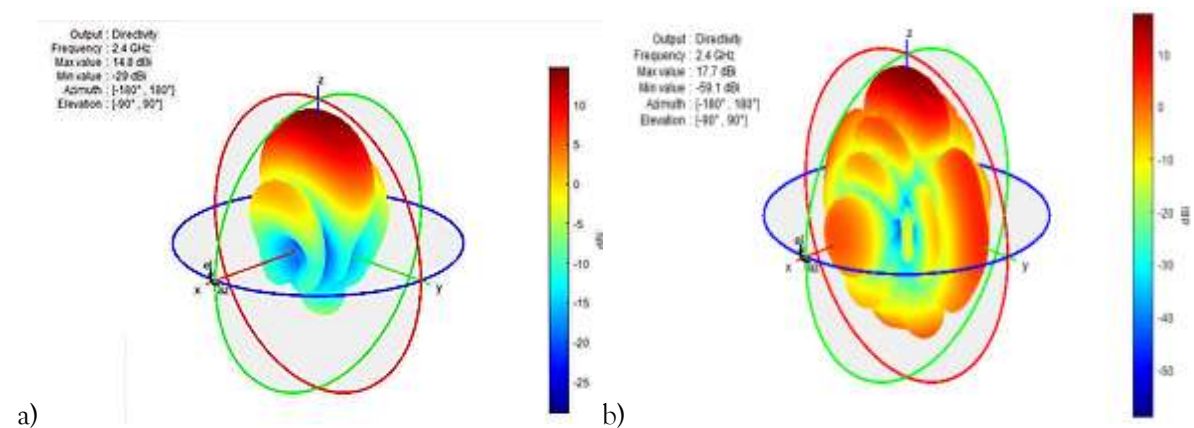


Figure 6 Radiation patterns for Octate E-Patch antenna arrays a) for Case 1 b) for Case 2 proposed array designed

The result comparison of Figure 6 a) and 6 b), focusing on directivity and gain performance for Case 1 and Case 2 of the E-patch design with and without optimization. The performance is compared based on the directivity and gain. It is clear from the Figure 6 a) that Case 1 of validation achieves a maximum directivity of 14 dBi. In comparison to this the proposed optimized design of case 2 has offered maximum directivity is higher at 17.7 dBi.

It can be concluded from the comparison that proposed optimized design of Case 2 Figure 6 b) demonstrates better performance in terms of 3.7 dBi more directivity and overall radiation pattern compared to validated Case 1 of Figure 6 a), The enhanced directivity indicates an improvement in the antenna's capacity to focus radiated power in a particular direction. The narrower main lobe of the radiation pattern in Case 2 confirms this enhanced focus, potentially leading to higher gain and reduced interference. Additionally, the significant decrease in side lobes in Case 2 is beneficial, as it results in less unwanted radiation in undesired directions

The results of azimuth pattern for both case of antenna array design for E-patch are illustrated in the Figure 7.

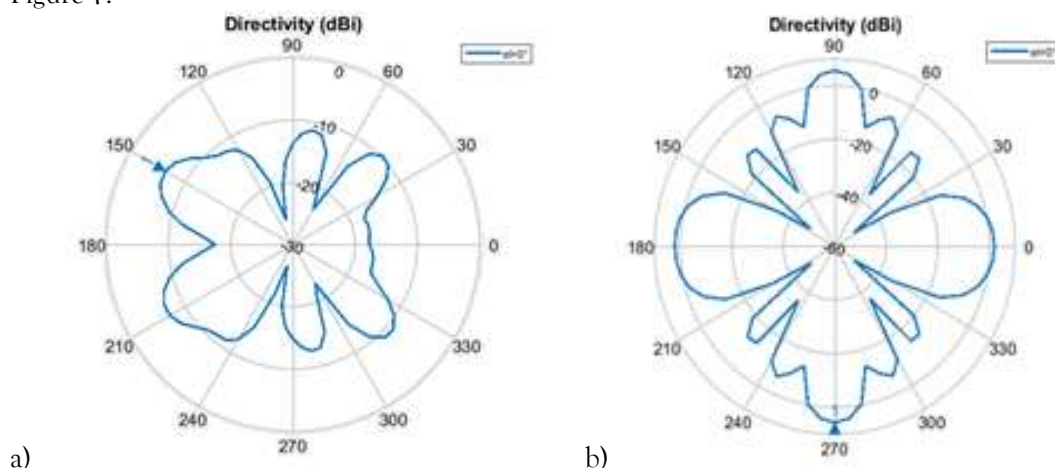


Figure 7 Results of Azimuth Patterns comparison for Octate E-Patch antenna arrays

a) for Case 1 b) for Case 2 proposed array designed

The comparison is based on the directivity and level of side lobes. From the comparison of the azimuth patterns as illustrated in the Figure 7 it can be observed that For Case 1 Figure 7 a) relatively low directivity gain is achievable. The pattern is not sharply focused in any particular direction, indicated by the broad, relatively flat lobes. The peak directivity appears to be around -10 dBi. For Case 2 as shown in Figure 7 b) optimization of design parameters have significantly improved directivity gain compared to Case 1.

The lobes are narrower, resulting in a more focused radiation pattern. The peak directivity is substantially higher than Case 1. The peak directivity appears to be around -17.7 dBi. In terms of the Omini-direction patterns the Case 1 a) radiation pattern is closer to being omnidirectional than Case 2 b) having eight reasonably symmetric lobes of comparable amplitude. However, there are significant nulls between them, suggesting it's far from perfectly omnidirectional. Thus, research suggested that if omnidirectional pattern is required then uses the case 1 design. Else if the directivity is important, as in case of satellite communication then it is suggested using the case 2 design with more directivity.

5.3.1 Comparison of E vs H patch array

Additionally, the Case 3 of the design as H-patch octate array is validated and compared with the performance of Case 2 of our proposed optimum design. This section has compared the performance of

the E-patch octate vs H-patch antenna octate array. The result comparison of Figure 8 a) and Figure 8 b), focusing on directivity and gain performance for Case 2 E-O-MPSAA (with optimization) and Case 3 H-O-MPSAA octate design.

The performance is evaluated based on directivity and gain. Comparing the proposed E-O-MPSAA design (Case 2) with the (Case 3) antenna reveals significant differences in these aspects. Case 2 of the proposed design exhibits a commendable directivity of 17.7 dBi, highlighting its effective focus of radiated energy. However, the H-O-MPSAA antenna slightly outperforms it, achieving a maximum directivity of 18.4 dBi. This marginally superior directivity suggests that the H-O-MPSAA antenna has a more concentrated beam pattern and better radiated power focus than the E-patch array. Further analysis of Figure 8 (b) shows that the H-patch antenna array offers a slight improvement in both directivity and potential gain compared to the E-patch antenna array shown in Figure 8 (a).

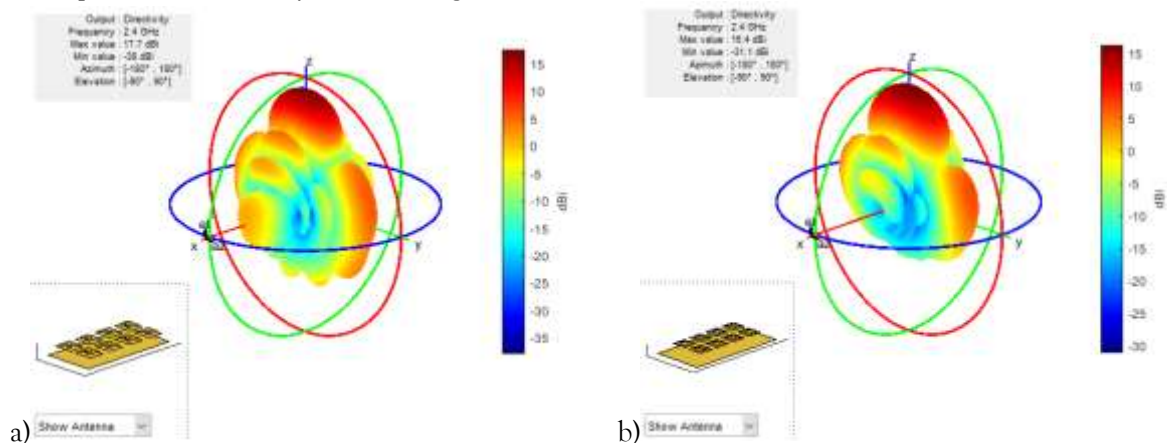


Figure 8 Radiation patterns for Octate 2x4 antenna arrays a) For Case 2 E-O-MPSAA array

b) for Case 3 proposed H-OMPSSAA array design

Additionally, the H-patch array features a narrower beamwidth, indicating enhanced spatial selectivity and potentially improved interference rejection capabilities. These attributes make the H-patch array a promising option for applications requiring precise beam control and high-gain performance, especially in scenarios where directional communication or targeted signal transmission is essential.

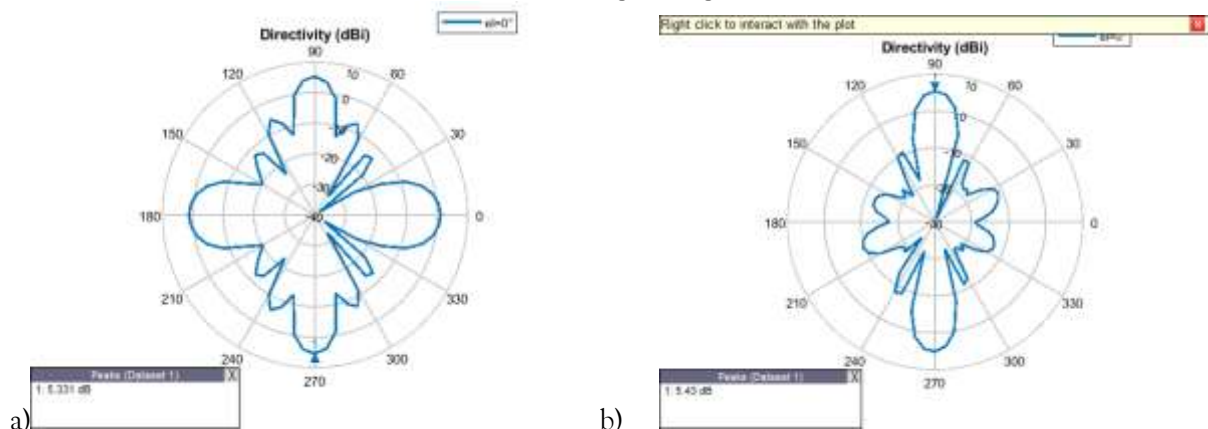


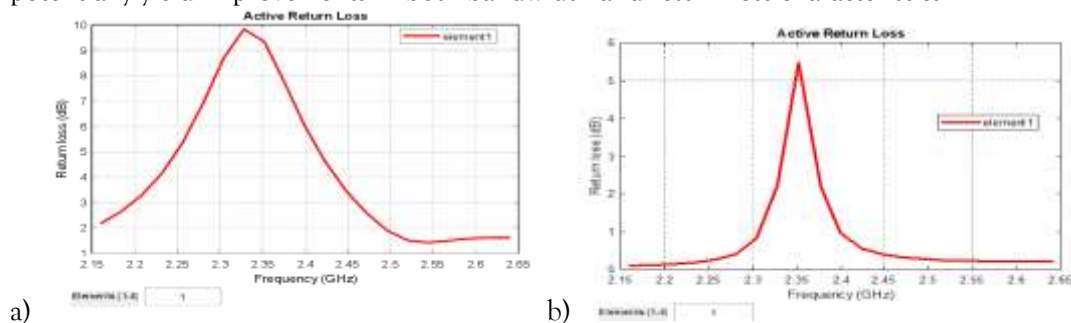
Figure 9 Azimuth patterns comparison for Octate 2x4 antenna arrays a) For Case 2 E-O-MPSAA array b) for Case 3 proposed H-OMPSSAA array design

Figure 9 compares the azimuth patterns of two Octate 2x4 antenna arrays for Case 2 E-O-MPSAA array (Figure 9 a) and the Case 3 of H-OMPSSAA array designs (as in Figure 9 b). It can be clearly observed from Figure that Case 2 design of E-O-MPSAA has much near omni directional pattern with more beam

width. while H-O-MPSAA case 3 of design is proposed to use for the highly directional case of pattern as it offers narrow beamwidth but higher gain comparatively.

5.4 Return Loss Comparison

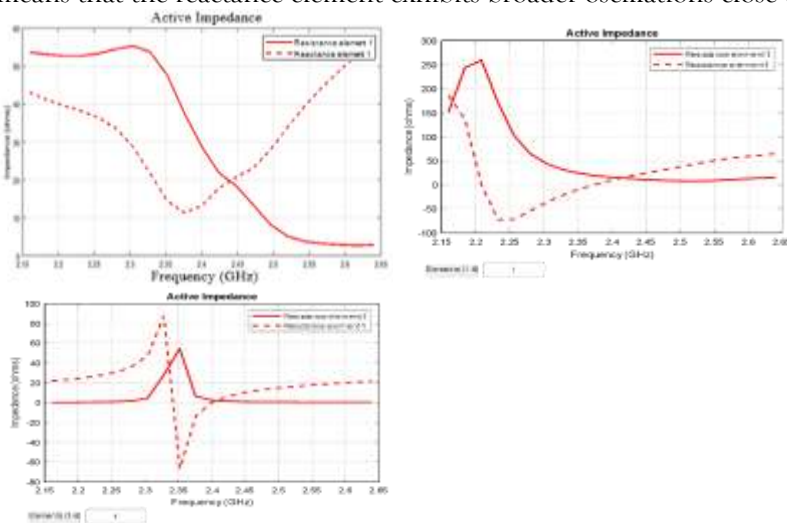
The Figure 10 compares return loss results for two Octate antenna arrays: E-Patch a) and H-Patch b). The E-Patch array has a broader bandwidth with acceptable return loss below a threshold of around 5 dB, while the H-Patch array has a narrower bandwidth with low return loss. At its resonance frequency (approximately 2.35 GHz), the H-patch array produced a smaller return loss than the E-patch array, which performed best at a frequency of approximately 2.3 GHz. In the H-patch array, the minimum return loss was close to 0 dB. For the two antenna types, this comparison shows a trade-off between the bandwidth including minimum return loss. This comparison mainly highlights a trade-off between bandwidth and minimum return loss for the two antenna types. This trade-off is an important consideration when selecting an antenna design for specific applications. The E-Patch array may be more suitable for systems requiring broader frequency coverage, while the H-Patch array could be preferred for applications demanding extremely low return loss at a specific frequency. Further optimization of these designs could potentially yield improvements in both bandwidth and return loss characteristics



a) Figure 10 Results of return losses comparison for Octate antenna arrays a) of E-Patch b) for H-Patch array

5.5 Active Impedance Evaluation

The Figure 11 presents a comparison of active impedance matching for three different 2x4 octate antenna array configurations: Case 1 (E-patch octate), Case 2 (E-O-MPSAA octate), and H-OMPSAA Array. it can be concluded that Case 2 (E-O-MPSAA octate) shows less severe impedance variations and a somewhat larger bandwidth than Case 1. Among the three, the case 3 H-OMPSAA array seems to have the largest bandwidth, with a comparatively constant impedance of 0 ohms throughout a greater frequency range. it means that the reactance element exhibits broader oscillations close to the central frequency, though.



a) for Case 1 E- patch octate b) for Case 2 E-O-MPSAA octate c) for H-OMPSAA Array

Figure 11 Comparison of active impedance matching for 2x4 Octate antenna array

S11 COMPARISON

The Figure 12 presents a comparison of the S parameters for both the E-patch and H-patch arrays. In Figure a), the S parameters for the E-patch array are shown, while Figure b) illustrates those for the H-patch array. The figures reveal that the S parameters of the two arrays exhibit distinct characteristics at different frequencies, likely due to variations in their design and structure. These figures depict the scattering behavior of the antenna arrays over a frequency range from approximately 2.15 GHz to 2.5 GHz. It is noted that the S11 parameter of the E-patch varies from -2 dB to -7 dB over a broader frequency range, whereas the H-patch array starts at -50 dB. Consequently, it is concluded that the H-patch array (Figure 12b) exhibits a much sharper resonance and superior impedance matching at its resonant frequency (around 2.35 GHz) compared to the E-patch array (Figure 12a).

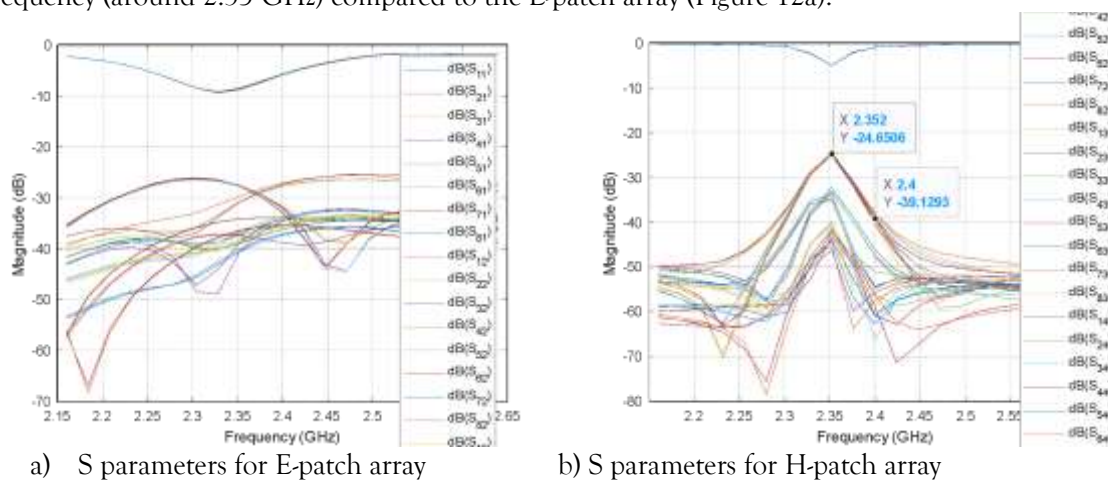


Figure 12 comparison of S parameter for designed cases

However, the E-patch array provides a more consistent, though less optimal, impedance match across a wider frequency range. The decision between the two would depend on the application's priorities: whether a narrowband, high-performance operation is preferred over a wider-band, more moderate performance.

STATE OF ART GAIN PERFORMANCE

The maximum directive gain achieved for the different state of art antenna array are presented in the Table 4.

Table 4 State of art Gain performance comparison.

Parameter	Pauliah Nadar et al. (2023) E-Patch	Thakur et al. (2022) Slotted	Muttaqin et al [32] T slot	Proposed E-Shape
Maximum Gain (dBi)	8.2	>14	17.55	17.7
Size of array	2x2	Octate	Octagonal	Octate

It is clear from Table 4 that the proposed optimum design out performs over the previous mentioned octate antenna array design in terms of directivity. compared to 2x2 patch of Pauliah Nadar et al. (2023) the gain is almost doubled. and over Thakur et al. (2022) the 3.5 dBi increase is offered. and over the T slotted patch Muttaqin et al the 0.22 dBi Improvement is achieved.

6 DISCUSSIONS

The discussion section of this work focuses on several important topics. First, there were notable increases in antenna performance when comparing the E-O-MSPAA and H-O-MSPAA designs. The maximum

directivity of the updated E-O-MSPAA design (Case 2) is 17.7 dBi, which is 3.7 dBi higher than that of the first validated design (Case 1). This demonstrates the effectiveness of the optimization process. The H-O-MSPAA design (Case 3) exhibits a directivity of 18.4 dBi and features a narrower beamwidth, significantly outperforming the E-O-MSPAA design. This indicates that the H-O-MSPAA is well-suited for applications that necessitate precise beam control and higher gain.

Additionally, important trade-offs exist between return loss and bandwidth. The H-O-MSPAA demonstrates a narrower bandwidth but achieves lower return loss at its resonant frequency, whereas the E-O-MSPAA offers a wider bandwidth alongside acceptable return loss. This distinction underscores the necessity of selecting the most appropriate design based on the specific requirements of each application.

Among the three designs evaluated, the H-O-MSPAA provides the largest bandwidth and the most consistent impedance in terms of active impedance matching. This characteristic is advantageous for applications requiring stable performance across a broader frequency range.

Moreover, the proposed optimized E-O-MSPAA design outperforms slotted designs by 3.5 dBi and T-slotted patch designs by 0.22 dBi when compared to leading contemporary designs. This advancement highlights the potential of the proposed arrays for use in applications that demand high gain and directivity. The recommended designs are particularly well-suited for satellite communication systems and other applications requiring focused beam patterns, owing to their enhanced directivity and gain. Furthermore, the availability of both E-patch and H-patch configurations provides greater flexibility in meeting specific performance requirements.

7. CONCLUSIONS AND FUTURE SCOPES

This study presents the design and analysis of highly directional E-shaped and H-shaped octate microstrip patch antenna arrays (E-O-MSPAA and H-O-MSPAA) aimed at enhancing gain at a frequency of 2.4 GHz. The dielectric properties of the substrate and the spacing between elements of the arrays were optimized to maximize directivity and gain. The performance of the arrays was evaluated through electromagnetic simulations, focusing on key parameters such as impedance matching, radiation patterns, and return loss.

- The optimized E-O-MSPAA design surpasses the baseline validated octate design by 3.7 dBi, achieving a maximum directivity of 17.7 dBi.
- The H-O-MSPAA design exhibits superior performance compared to the E-O-MSPAA, characterized by a lower beamwidth and a directivity of 18.4 dBi.
- A comparison of return loss reveals a trade-off between bandwidth and minimal return loss, with the E-O-MSPAA offering a wider bandwidth alongside acceptable return loss, while the H-O-MSPAA features a narrower bandwidth but lower return loss at its resonant frequency.
- In terms of active impedance matching, the H-O-MSPAA demonstrates the largest bandwidth and relatively stable impedance characteristics.
- Notably, the proposed optimized E-O-MSPAA design outperforms previous state-of-the-art octet antenna array designs, providing a 3.5 dBi increase over slotted designs and a 0.22 dBi improvement over T-slotted patch designs.

Finally, in conclusion, the E-Patch array is more suitable for systems that require broader frequency coverage, whereas the H-Patch array may be preferred for applications that necessitate extremely low return loss at a specific frequency.

Future scopes: Future research may involve further optimization of antenna array designs to achieve enhanced gain and directivity. This could entail investigating different substrate materials, feed network setups, and patch shapes. It would be beneficial to fabricate and test a prototype in order to experimentally validate the simulated results. Its potential applications could further be expanded by looking into how well the array performs in various frequency bands and for new wireless applications like 5G and IoT. The capabilities of the array could be improved by incorporating cutting-edge methods like adaptive beamforming with artificial intelligence or metamaterials. Lastly, applications with limited space would benefit from downsizing efforts to lower the overall size while preserving performance.

REFERENCES

- [1] Ali, W. A. E., Ibrahim, A. A., Hamdalla, M. Z. M., & Mohamed, H. A. (2019). Gain improvement of tunable band-notched UWB antenna using metamaterial lens for high speed wireless communications. *Microsystem Technologies*, 25(11), 4111–4117. <https://doi.org/10.1007/s00542-018-04285-z>
- [2] Boskovic, N., Radovanovic, M., Jokanovic, B., & Doncov, N. S. (2018). Novel *Ku*-Band Series-Fed Patch Antenna Array With Enhanced Impedance and Radiation Bandwidth. *IEEE Transactions on Antennas and Propagation*, 66(12), 7041–7048. <https://doi.org/10.1109/tap.2018.2874515>
- [3] Yang, W., Lim, W. M., Ma, K., & Yeo, K. S. (2016). A Compact High-Performance Patch Antenna Array for 60-GHz Applications. *IEEE Antennas and Wireless Propagation Letters*, 15, 313–316. <https://doi.org/10.1109/lawp.2015.2443054>
- [4] Ghassemi, N., & Wu, K. (2012). High-Efficient Patch Antenna Array for E-Band Gigabyte Point-to-Point Wireless Services. *IEEE Antennas and Wireless Propagation Letters*, 11(11), 1261–1264. <https://doi.org/10.1109/lawp.2012.2224087>
- [5] Mikulasek, T., Puskely, J., Lacik, J., & Raida, Z. (2016). Design of aperture-coupled microstrip patch antenna array fed by SIW for 60 GHz band. *IET Microwaves, Antennas & Propagation*, 10(3), 288–292. <https://doi.org/10.1049/iet-map.2015.0296>
- [6] Islam, M. T., Shakib, M. N., & Misran, N. (2009a). BROADBAND E-H SHAPED MICROSTRIP PATCH ANTENNA FOR WIRELESS SYSTEMS. *Progress In Electromagnetics Research*, 98, 163–173. <https://doi.org/10.2528/pier09082302>
- [7] Palomares-Caballero, A., Alex-Amor, A., Padilla, P., & Valenzuela-Valdes, J. (2021). Millimeter-Wave 3-D-Printed Antenna Array Based on Gap-Waveguide Technology and Split E-Plane Waveguide. *IEEE Transactions on Antennas and Propagation*, 69(1), 164–172. <https://doi.org/10.1109/tap.2020.3008620>
- [8] Thakur, V., Jaglan, N., & Gupta, S. D. (2022). Side edge printed eight-element compact MIMO antenna array for 5G smartphone applications. *Journal of Electromagnetic Waves and Applications*, ahead-of-print(ahead-of-print), 1685–1701. <https://doi.org/10.1080/09205071.2022.2040057>
- [9] Pauliah Nadar, K., Ahmed Jibril, H., Chellappa, A. S., Gopalakrishnan, S., Eswaralingam, A. D., Arul Raj, J. X., Tharcis Mariapushpam, I., Louis, M. T., Muthukutty, R. K., Jeyaprakasam, V., & Vivekanand, C. V. (2023). Design and Analysis of Microstrip Patch Antenna Array and Electronic Beam Steering Linear Phased Antenna Array with High Directivity for Space Applications. *ACS Omega*, 8(45), 43197–43217. <https://doi.org/10.1021/acsomega.3c06691>
- [10] Chung, K. L. (2013). High-Performance Circularly Polarized Antenna Array Using Metamaterial-Line Based Feed Network. *IEEE Transactions on Antennas and Propagation*, 61(12), 6233–6237. <https://doi.org/10.1109/tap.2013.2282296>
- [11] Asaduddin, Mohd & Shah, Shaik & Siddiqui, Mohd. (2023). Design of Microstrip Patch Antenna Array. *International Journal of Wireless and Microwave Technologies*. 13. 39-48. <http://dx.doi.org/10.5815/ijwmt.2023.03.04>
- [12] Rastogi, Alok & Pravin, Gazala & Sharma, Shanu. (2019). Comparative Study of Rectangular and E-Shaped Microstrip Patch Antenna Array for X-Band Applications. http://dx.doi.org/10.1007/978-981-13-0680-8_18
- [13] B. Ramya, C. Supratha and S. Robinson, (2018), Design and Analysis of Microstrip Patch Array Antenna For WLAN Applications, *ICTACT Journal On Microelectronics*, January 2018, Volume: 03, Issue: 04, DOI: 10.21917/ijme.2018.0081
- [14] Priyanka R. Sonkar¹, Prof A.B. Thatere. E Shape Patch Antenna Array. *International Research Journal of Engineering and Technology (IRJET)* Volume: 06 Issue: 04 | Apr 2019 <http://www.irjet.net/>
- [15] Patil, S.V., Patil, V.N. Design and Analysis of Slotted Microstrip Patch Array Antenna at 2.4GHz for WLAN. *Wireless Pers Commun* 138, 2055–2064 (2024). <https://doi.org/10.1007/s11277-024-11430-7>
- [16] Emmanuel Adotse Otsap et al. (2023). Design and Analysis of 1x4 and 1x8 Circular Patch Microstrip Antenna Array for IWSN Application, *Sule Lamido University Journal of Science & Technology* Vol. 6 No. 1&2 [March, 2023], pp. 139-149. <https://doi.org/10.56471/slujst.v6i.365>
- [17] Shimu, N. J., & Ahmed, A. (2016). Design and performance analysis of rectangular microstrip patch antenna at 2.45 GHz. 2, 1062–1066. <https://doi.org/10.1109/iciev.2016.7760161>
- [18] Muludi, Z., & Aswoyo, B. (2017). Truncated microstrip square patch array antenna 2 × 2 elements with circular polarization for S-band microwave frequency. 6, 87–92. <https://doi.org/10.1109/elecsym.2017.8240384>
- [19] Shahidul Islam, M., Kok Beng, G., Amin, N., Misran, N., Islam, M. T., & Ullah, M. A. (2019). A Modified Meander Line Microstrip Patch Antenna With Enhanced Bandwidth for 2.4 GHz ISM-Band Internet of Things (IoT) Applications. *IEEE Access*, 7, 127850–127861. <https://doi.org/10.1109/access.2019.2940049>

- [20] Casu, G., Moraru, C., & Kovacs, A. (2014). Design and implementation of microstrip patch antenna array. 2, 1-4. <https://doi.org/10.1109/iccomm.2014.6866738>
- [21] Kaschel, H., & Ahumada, C. (2018). Design of Rectangular Microstrip Patch Antenna for 2.4 GHz applied a WBAN. 1-6. <https://doi.org/10.1109/ica-acca.2018.8609703>
- [22] Muttaqin, Muhammad & Darmono, Hendro & Koesmarijanto, Koesmarijanto. (2023). Design and Implementation of 2x4 Octagonal Array Patch Microstrip Antennas using T-Slots at 2.4 GHz Frequency for Wifi Applications. *Jurnal Jartel Jurnal Jaringan Telekomunikasi*. 13. 169-176. 10.33795/jartel.v13i2.431.
- [23] Benlakehal, M.E., Hocini, A., Khedrouche, D. et al. Design and simulation of 1×2 , 1×4 and 2×8 microstrip patch antenna arrays based on photonic crystals for improved gain performance in THz. *J Opt* 53, 260-271 (2024). <https://doi.org/10.1007/s12596-023-01513-2>
- [24] Mrs. S. Parameswari A. Ajithkumar , @Design and Simulation of Patch Antenna Array or 5.4GHz Wi-Fi Application@, *International Journal of Engineering Research & Technology (IJERT)* Published by, www.ijert.org NCIECC - Special Issue - 2017 Conference Proceedings
- [25] A D Santoso, F B Cahyono, I Suwondo, Arleiny and B B Harianto, Microstrip Antenna Design with Array Rectangular Patch 2x2 for Ship Radar at 2.2 GHz, *Journal of Physics: Conference Series*, Volume 2117, 3rd International Conference on Advanced Engineering and Technology (ICATECH 2021) 02 October 2021, Surabaya, Indonesia, <https://dx.doi.org/10.1088/1742-6596/2117/1/012019>
- [26] AlGhuri, Ahmed & Zakaria, Zahriladha & Ibrahim, Imran & Halim, Elzameera. (2022). Microstrip Patch Antenna Arrays Design for 5G Wireless Backhaul Application at 3.5 GHz. 10.1007/978-981-16-97814_9.
- [27] Zafar, S., Saxena, V., Baghel, R.K. (2022). Design and Analysis of 2×4 Microstrip Patch Antenna Array with Defected Ground Structure for 5G Mobile Communication. In: Khanna, K., Estrela, V.V., Rodrigues, J.J.P.C. (eds) *Cyber Security and Digital Forensics . Lecture Notes on Data Engineering and Communications Technologies*, vol 73. Springer, Singapore. https://doi.org/10.1007/978-981-16-39616_39
- [28] Koesmarijanto, Koesmarijanto & Alifia, Nur & Darmono, Hendro. (2022). Design and Implementation of 2x4 Element Hexagonal Array Microstrip Antenna with DGS Method in the Shape of Dumbbell Circle Head for 2.4 GHz Frequency Wi-Fi Applications. *Jurnal Jartel Jurnal Jaringan Telekomunikasi*. 12. 232-238. <http://dx.doi.org/10.33795/jartel.v12i4.503> .
- [29] Gupta, S., Chauhan, S., Srivastava, R., Gupta, A. (2023). Comparison of Different Alphabetically Shaped Microstrip Patch Antennas in the S-Band Using HFSS. In: Pundir, A.K.S., Yadav, A., Das, S. (eds) *Recent Trends in Communication and Intelligent Systems. ICRTCIS 2023. Algorithms for Intelligent Systems*. Springer, Singapore. https://doi.org/10.1007/978-981-99-5792-7_16
- [30] Darmono, H., & Koesmarijanto, K. (2023). Design and Implementation of 2x4 Octagonal Array Patch Microstrip Antennas using T-Slots at 2.4 GHz Frequency for Wifi Applications. *Jurnal Jaringan Telekomunikasi*, 13(2), 169-176. <https://doi.org/10.33795/jartel.v13i2.431>
- [31] Md. Sohel Rana, Sheikh Md. Rabiul Islam, Sanjukta Sarker, Machine learning based on patch antenna design and optimization for 5 G applications at 28GHz, *Results in Engineering*, Volume 24, 2024, 103366, <https://doi.org/10.1016/j.rineng.2024.103366>.
- [32] Muttaqin, Muhammad & Darmono, Hendro & Koesmarijanto, Koesmarijanto. (2023). Design and Implementation of 2x4 Octagonal Array Patch Microstrip Antennas using T-Slots at 2.4 GHz Frequency for Wifi Applications. *Jurnal Jartel Jurnal Jaringan Telekomunikasi*. 13. 169-176. 10.33795/jartel.v13i2.431.