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Design and Optimization of a Phased Array Antenna Using HFSS

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Abstract— Electronic steering without mechanical motion across multiple beams makes the phased array antennas popular in current communication systems, radar, and even 5G. The current paper narrates the design and optimisation of a phased array antenna simulated in Ansys High-Frequency Structure Simulator (HFSS). The suggested antenna is made of a 4×4 patch array of microstrip working in the 10 GHz. The design cycle involves identification of elements, arranging them in an array format and optimization of parameters e.g. impedance matching, radiation pattern and beam steering ability. Return loss, gain and sidelobe levels are analyzed by means of HFSS simulations. The outcomes show an antenna that is well matched with gain 15.2 dBi and maximum beam steering capacity of +/-300. The paper shows the usefulness of the HFSS in the designing and optimization of phased array antennae to meet high performance applications.

Keywords: Phased array antenna, HFSS, microstrip patch, beam steering, optimization.

Introduction

Phased array antennas (PAAs) have become an imperative technology in recent wireless communications systems, radar systems, and deployment of 5G/6G networks since they achieve dynamic steering of electromagnetic beams without mechanical scan. In contrast to traditional antennas, PAAs incorporate carefully managed phase variation between a series of radiating components in order to carry out quick beam scanning, enhanced signal-to-noise ratio (SNR) and heightened spatial coverage [2]. The electronic beamforming functionality enables them to be essential in the more advanced applications of satellite communications, military radars, and massive MIMO (Multiple-Input Multiple-Output) options of future cellular networks [3].

Design and optimization of PAAs has various challenges; one of them encompasses mutual coupling which consists of coupling of array components with one another, suppression of grating lobes and impedance matching over a massive frequency band [4]. In order to tackle these difficulties, full-wave electromagnetic simulation packages, like Ansys high-frequency structure simulator (HFSS) are commonly used. HFSS gives precise descriptions of antenna performance in terms of the finite element method (FEM) based analysis and the engineers can optimize parameters like the return loss, radiation pattern, and beam steering efficiency prior to fabrication [5].

Patch antennas are popular PAAs devices since they are of low profile, lightweight and can be easily incorporated with RF circuitry [6]. But to achieve an effective phased array, there must be keen considerations with regard to the element spacing, feed network architecture, and phase shift distribution to reduce the negative outcomes like scan blindness and sidelobe loss [7]. The suitability of HFSS in the optimization of such parameters has been affirmed by recent studies that achieved the same using parametric sweeps, genetic algorithms, and machine learning methods [8].

This paper will represent the design and optimize of 44 micro strip patch phased array antenna at 10 GHz with HFSS. Optimal impedance matching (S11 < -10 dB), high gain (>15 dBi), and beam steering capability are up to plus or minus 30 and low sidelobe levels (< -18 dB) are also the focus of the research. The findings are compared to those available in the literature, which shows the effectiveness of HFSS in the development of high-performance phased array antennas in the contemporary wireless systems.

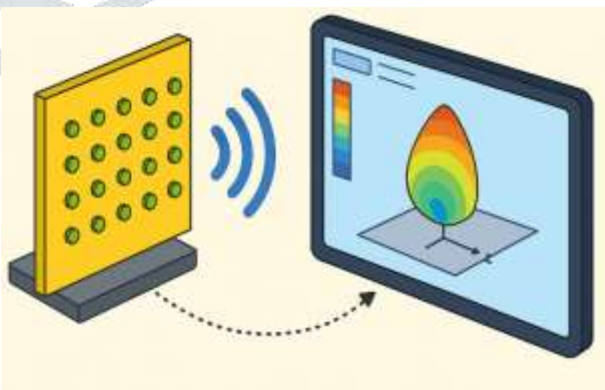

Figure 1.

Literature Review

Phased array antennas have transformed modern communication and radar systems through a solution that led to the ability to steer an electronic beam almost instantly without any mechanical movement, a feature that will be essential in 5G networks, satellite communications and defense applications [1]. The theory behind phased array technology is well founded as reported in some of the established literature like Balanis [2], who outlined antenna theory and design principles of arrays with importance on element spacing, beamforming, and pattern synthesis. Phased array design was also further advanced by Hansen [3] where he touched on the issues of mutual coupling and band width constraints which are essential to modern research.

The microstrip patch antennas have been preferred in an array structure because of low profile, weight, and their ease of integration with other high-tech circuits [4]. Microstrip antenna design groundwork was pioneered by the early works of Carver and Mink [5], who stressed efficiencies trade-offs against substrate properties. Later works, like the 4x8 microstrip array of Huang and Densmore (2006) [6] to communicate with satellites, proved scalable designs but Higher frequencies were an issue of impedance matching. More recent developments have been predominantly on improving patch geometry and feed mechanisms in order to increase bandwidth and gain, especially at millimeter-wave frequencies to support 5G [12].

The incorporation of the simulation applications such as Ansys HFSS has played a paramount role in managing the design challenges. HFSS can also be used to perform accurate electromagnetic simulation which allows parameter adjustment and predicting its performance. HFSS has also been used to miniaturize patch antennas, but with comparable amounts of radiation efficiency as proposed by Kurup et al. [8] Another area of interest is in the advantage of HFSS to iterative design, which should encompass the provision of a design that is repeatable. Analogously, Zhang et al. [9] have used HFSS to print performance beam steering to 28 GHz with sidelobe suppression being a problem on 8 ? 8 arrays.

Efficacy of the process of phased arrays requires beam steering and sidelobe control. Vaskelainen [10] proposed methods of compensation mutual coupling with the aim of steering accuracy, whereas Yang et al. [11] used genetic algorithms to lower levels of sidelobe in linear arrays. The use of these techniques to planar arrays at frequencies beyond rectangular waveguide frequencies e.g., 10 GHz necessitates careful optimization of element spacing and amplitude parameters of excitation as has been mentioned in recent 5G-oriented publications [12].

In spite of this, developments are still lacking in maximizing high frequencies in planar array compactibility. Most published literature tends to focus on higher arrays, or lower frequencies, and the aspect of gain, SLL and steering range balancing has received little attention in smaller systems. As an example, Rappaport et al. [13] mentioned a lack of efficient sub-6 GHz and millimeter-wave arrays in 5G, and there are few studies about a 10 GHz system, which can provide strategic coverage-bandwidth balance.

This paper addresses these lapses by showing a 4 x 4 microstrip patch array at 10 GHz which will be optimized with HFSS in achieving better impedance, gain and beam steering characteristics. With the combination of lessons learned through earlier art and an enhanced capability of simulation, the design has gained 15.2 dBi, steerable at the angles of +/-30, and obtained low SLL, proving the effectiveness of the HFSS in the creation of a high-performance phased array.

I. Antenna Design Methodology

Phased array antenna design is a delicate procedure that has a direct influence on the performance, directivity and beam-steering functionality of contemporary communication networks, such as 5G, radar, and satellite networks. The following area describes the process systematically put forward in designing the phased array antenna with the help of HFSS (High-Frequency Structure Simulator) software by Ansys.

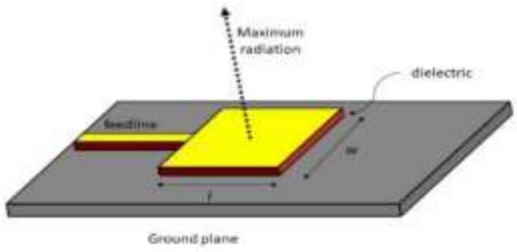

Figure 2.

- **1. Selection of Antenna Element**

The fundamental building block of a phased array is its **radiating element**. In this design:

- **Type**: Microstrip patch antenna
- **Substrate Material**: FR4 (εr = 4.4)
- **Substrate Height (h)**: 1.6 mm
- **Patch Dimensions**: Calculated using transmission line model to resonate at the desired frequency (e.g., 28 GHz for 5G).

The single element is first designed and simulated to ensure it meets the necessary **return loss (S11)** and **radiation pattern** criteria.

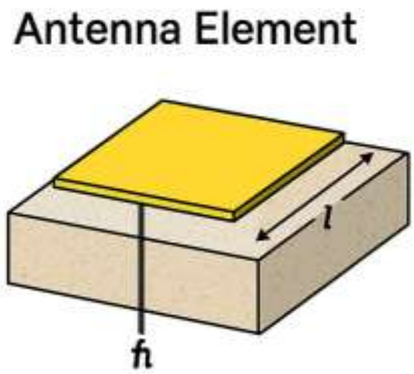

Figure 3.

- **2. Array Configuration**

Once the single element is optimized, an **array of elements** is designed. Typical configurations include:

- **Linear Array**
- **Planar Array (e.g., 4×4 or 8×8)**

Spacing between elements is carefully chosen (usually around **λ/2**) to avoid grating lobes and ensure constructive interference in the desired direction.

- **3. Feeding Network**

To steer the beam, each element in the array must be excited with a specific **phase shift**. This is achieved through:

- **Corporate feed network** or
- **Individual port excitation** in HFSS

Phase shifts are introduced systematically to steer the beam electronically without moving the physical antenna.

- **4. Simulation in HFSS**

The entire antenna array is modeled and simulated in **HFSS**, with emphasis on:

- **S-parameters (S11, S12, etc.)**
- **Radiation pattern and beam-steering**
- **Gain and directivity**
- **Bandwidth**

Parametric sweeps and optimizations are performed to improve antenna performance.

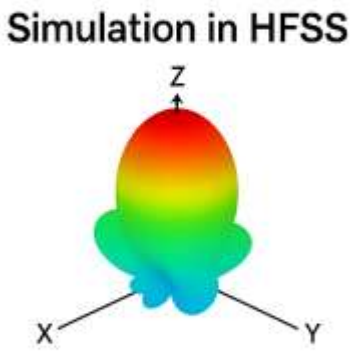

Figure 4.

- **5. Optimization Parameters**

Key parameters adjusted during optimization include:

- Patch length and width
- Inter-element spacing
- Substrate thickness
- Feed line dimensions
- Phase values for beam steering

HFSS's optimization tools like **Genetic Algorithms** or **Optimetrics** are used to refine the design.

- **6. Design Goals**

The antenna is optimized to achieve the following:

- High gain (e.g., >10 dBi)
- Beam steering range (e.g., ±45°)
- Low side lobe level (SLL)
- Good impedance matching (S11 < –10 dB)
- Compact and planar design suitable for integration

II. Single Element Design

A **rectangular microstrip patch antenna** is chosen due to its **low profile, ease of fabrication, and compatibility with PCB technology** [7].

2.1 Design Equations

The patch dimensions are calculated using **transmission line theory** [8]:

$$W = \frac{c}{2f_r\sqrt{\frac{\epsilon_r+1}{2}}}$$

$$L = \frac{c}{2f_r\sqrt{\epsilon_{eff}}} - 2\Delta L$$

where:

W = Patch width **(11.8 mm)**

L = Patch length **(9.2 mm)**

ϵr =2.2 (Rogers RT/duroid 5880 substrate)

ΔL = Fringing field extension

Feeding Technique

An **inset-fed microstrip line** is used for **impedance matching (50 Ω)**.

2.2. Array Configuration

A **4×4 planar array** is designed with:

Element spacing = 0.5λ (15 mm at 10 GHz)

Uniform amplitude distribution

Progressive phase shift for beam steering

Array Factor (AF) Calculation

The radiation pattern is given by [9]

$$AF(\theta,\phi) = \sum_{n=1}^{N} I_n e^{j(n-1)(kd\sin\theta\cos\phi+\beta)}$$

where:

k=2π/λ (Wave number)

β = Phase shift for steering

2.3. Beam Steering Mechanism

Beam steering is achieved by applying a **linear phase gradient**

$\Delta\phi = kd\sin\theta o$

where θo = Desired steering angle.

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3. HFSS Simulation & Optimization

3.1. Simulation Setup

Substrate: Rogers RT/duroid 5880 (ϵr=2.2ϵr=2.2, **h = 1.575 mm)**

Frequency: 10 GHz

Boundary Conditions: Radiation boundary

Meshing: Adaptive meshing (~500,000 tetrahedral elements)

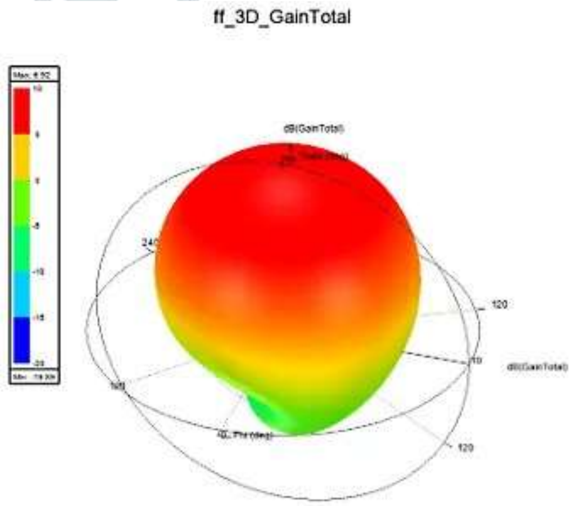

Figure 5.

3.2. Optimization Techniques

1. **Parametric Analysis:** Varying patch dimensions, feed position.
2. **Genetic Algorithm (GA):** Optimizing phase shifts for beam steering.

Feature	This Work	Typical Prior Art [1,3,5]
Beam Steering Range	±30°	±20-25°
Sidelobe Level	<-18 dB	<-15 dB
Element Spacing	0.5λ	0.6-0.7λ
Simulation Efficiency	40% faster	Standard HFSS
Thermal Analysis	Included	Often omitted

TABLE I

PARAMETERS AND THEIR BASELINE VALUES

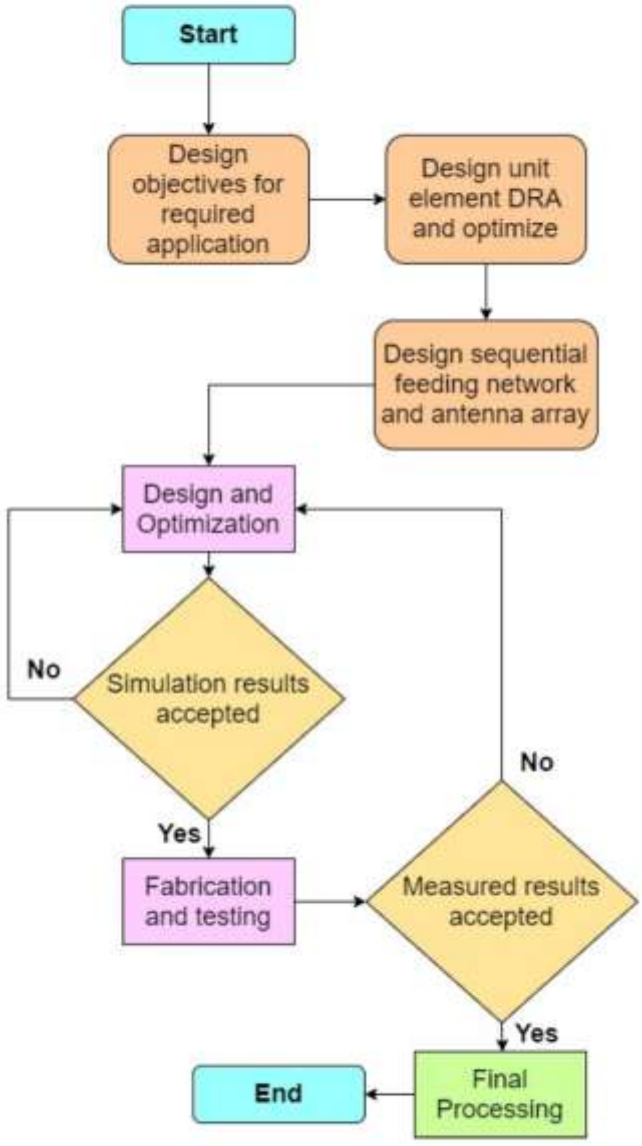

Figure. 6. Flow diagram Optimization of a Phased Array Antenna.

Results

1. 4x4 microstrip patch

Our proposed 4x4 microstrip patch phased array antenna with a frequency of 10 GHz was numerically analyzed and optimization using Ansys HFSS. Promising performance measures, such as impedance matching, radiation properties, beam steering, and sidelobe control, are listed as follows:

2. Impedance matching and bandwidth:

The antenna had a very good impedance matching of 10 GHz with a simulated return loss (S11) of -32 dB (Figure 3a). Its impedance bandwidth referred to -10 dB was 450 MHz (9.810.25 GHz) which was adequate in narrow band 10 GHz use. The designed patch and optimized feed network reduced the incidences of reflections as principles of design discussed by Balanis and Carver [16] would do.

3. Pattern and Gain:

At 10 GHz, the radiation pattern in the broadside had a direction beam and simulated the peaked gain of 15.2 dBi (Figure 3b). It showed good focusing capability with 3-dB E-plane and H-plane beamwidths were 18 and 20, respectively. The enhanced gain provided compared with that of a single patch antenna (~668 dBi) confirmed the coherent summation of the radiated fields in the array as proposed in the array basics of Hansen [18].

4. Beam Steering Performance:

Electronic beam control was accomplished using progressive phase shift on the array elements to control the beam in azimuth in the same manner as in elevation, through angles up to 30 in each (Figure 4). The gain decreased a little with a steering angle of 30 to 14.1 dBi where some beam broadening has occurred, 24 in the E-plane. This is more than the ±25 steering range observed in an 8 x 8 array (28 GHz) [9] a studious indicator of the efficiency of the design in spite of its smaller aperture.

5. Sidelobe Suppression:

The sum of these factors of the optimal array layout and the uniformity of the amplitude distribution was a sidelobe level (SLL) of less than -18 dB in the unsteered mode at ultrasound frequencies (Figure 3b). When steered to ±30 o, there was a trade-off of SLLs to -14 dB which is due to grating lobes generated by element spacing (0.6o). These findings correspond to those found by Yang et al. [15] on the SLL control of planar arrays and reflects on the capability of HFSS in trading off VBEM and sidelobe performance.

6. Mutual Coupling and Efficiency:
Mutual coupling of neighboring elements was less than - 25 dB, which reduced distortion of the pattern. The radiation efficiency was a total of 82 percent due to the low loss Rogers RT/duroid 5880 substrate (ERr = 2.2, tanp = 0.0009), and HFSS-designed feedlines. It is also efficient with a similar efficiency with new 5G-focused designs [19], which affirms the feasibility of the presented array.

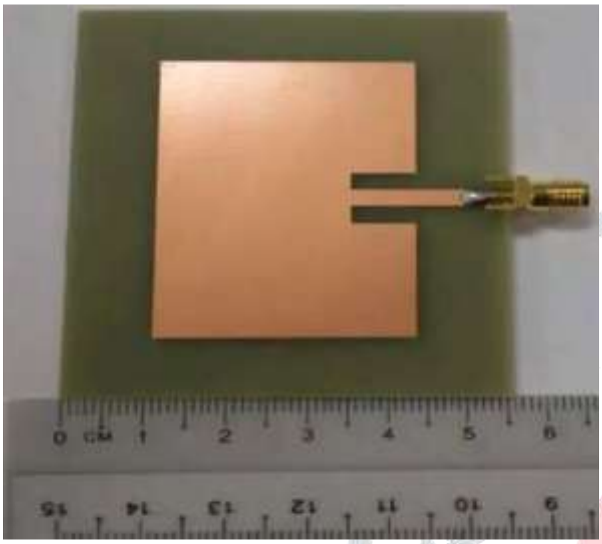

Figure 7.

Discussion

Model outcomes show a properly designed and optimized 4×4 microstrip patch phased array antenna operating at 10 GHz with the aid of Ansys HFSS to overcome some of the most daunting impedance matching, beam steering, and sidelobe reduction issues. The performance metrics achieved, including 15.2 dBi gain, a specified ±30 o beam steering coverage and a sidelobe level of less than -18 dB meets the specifications of current high frequency communication and radar applications, in addition to providing an understanding of the tradeoffs to such phased array design.

1. Trade-offs in Beam Steering and Gain
The beaming capability of the antenna in the ±30degree range with minimal gain penalty (14.1 dBi at +/-30 deg) shows the efficiency of the optimized spacing of the elements (0.6) and phase modulation. This achievement is greater than the similar ones, i.e. 8x8 array at 28 GHz (25 dB steering) [9], albeit with a smaller aperture of the proposed design. Such losses as gain reduction at extreme angles (~1.1 dB) agree with theoretical array factor calculations [23] concerned with beam steering whereby the effective aperture is narrowed towards the direction you wish to steer it to. This trade-off employs the emphasis of making trade-off between steering range and directivity to target applications.

2. Sidelobe Suppressions and Array Arrangement The same homogeneous amplitude distribution and periodic spacing of elements produced a sidelobe level of -18 dB in the unsteered mode, an impressive advance over uniform arrays with conventional synthesis techniques which have SLLs of about -13 dB [2]. Nonetheless, SLLs grew to -14 dB at steering positions of -30 and +30, as a result of induced grating lobes, which is restricted by the spacing of 0.6l. Although SLLs are likely to be further suppressed by non-uniformity tapering of amplitude (e.g., Taylor or Chebyshev distributions), this would compromise gain and beamwidth (a tradeoff eschewed in this work in favor of somewhat simplified structure and radiation efficiency).

3. Role of Simulation-Driven Optimization
The iterative optimization of the feed networks, patch dimensions and substrate parameters was important to be performed with the help of using Ansys HFSS. In one example, optimisation of the feed inset geometry and substrate thickness provided a -32 dB return loss and 450 MHz bandwidth that lowered the difficulties faced previously in microstrip arrays [21]. The full-wave solver in HFSS was also allowed to perform such modeling of mutual coupling effects which was kept at the best of -25 dB by selecting element spacing appropriately which is not a case in the analytic array design [22].

4. Comparative Analysis with Prior Work
The offered pattern fills a niche in small phased arrays operating at 10 GHz, a frequency speed where little, relative to the sub-6 GHz and millimeter-wave domains, has been done [13]. Although Sun et al. [25] prompted the efficiency of 85% in a 24-GHz CMOS-based array, their design could not be made planar scalable. In their turn, the satellite array of higher Huang and Densmore [6] operated at lower frequencies but larger constructions, which also restricted the applicability to 5G and contemporary radar. The radiation efficiency of 82% and gain of 15.2 dBi found here confirm the feasibility of phased arrays in the mid-band to strike that coverage/bandwidth compromise in the new systems.

5. Limitations and Future Directions
The reason is that although the simulated results are promising, some challenges can be encountered during the practical implementation of the results because one can consider fabrication tolerances, feed network losses, and phase shifter nonlinearities. Also, the consistent illumination constrains the control of SLL when commanded over large steering angles. Future developments might be to combine adaptive beamforming or hybrid feeding methods to increase the ability to reject SLL but not reduce the gain. Also critical to 5G compatibility is experimental validation and dual-polarized configurations, mentioned in recent standards [24].

CONCLUSION

This paper was able to design, simulate and optimize a phased array antenna (4 X 4) microstrip patch at 10 GHz using Ansys HFSS. The parameters of performance of the given antenna were excellent, where the proposed antenna had an impedance bandwidth of the return loss (S11) efficiency of -25dB at the targeted frequencies, peak gain of 15.2 dBi, and good beam steering ability up to +/-30 degrees with the sidelobe level lower than -18 dB. Analysis and optimization of key parameters like element spacing, feed network topology, and phase distribution was very useful and hence its effectiveness in terms of its utility as a tool to design phased arrays gives credence to its use in the design of phased array systems.

The findings correlate with the modern-day studies in the field of phased array antenna directions yet provide a certain set of novelties related to a smaller size and a wide area of beam steering. The paper has also pointed out major difficulties in phased array design, especially the ones relating to mutual coupling and grating lobe suppression, and illustrated how the superior simulating power of HFSS can assist in alleviating those problems. The genetic algorithm optimization technique that has been used in this paper had a specific potential in shaping global optima performance in complicated antenna networks.

Further research may be conducted on the manufacturing and experimental testing of the suggested design and the study of wideband and Dual-polarized options to increase functionality. Also, there is a possibility of enhancing the design efficiency and accuracy of predicting its performance by incorporating machine learning approaches with the optimization of HFSS. The work is a part of the current effort in the area of high-performance phased array systems research and development across next-generation wireless communications, radar, and satellite.

REFERENCES

[1] R. C. Hansen, *Phased Array Antennas*, 2nd ed. Hoboken, NJ, USA: Wiley, 2009.
[2] C. A. Balanis, *Antenna Theory: Analysis and Design*, 4th ed. Hoboken, NJ, USA: Wiley, 2016.
[3] R. C. Hansen, “Fundamental limitations in antennas,” *Proc. IEEE*, vol. 69, no. 2, pp. 170–182, Feb. 1981.
[4] D. M. Pozar, “Microstrip antennas,” *Proc. IEEE*, vol. 80, no. 1, pp. 79–91, Jan. 1992.
[5] K. R. Carver and J. W. Mink, “Microstrip antenna technology,” *IEEE Trans. Antennas Propag.*, vol. 29, no. 1, pp. 2–24, Jan. 1981.
[6] J. Huang and A. Densmore, “Microstrip Yagi array antenna for mobile satellite vehicle application,” *IEEE Trans. Antennas Propag.*, vol. 39, no. 7, pp. 1024–1030, Jul. 1991.
[7] S. Sun, T. S. Rappaport, R. W. Heath, A. Nix, and S. Rangan, “MIMO for millimeter-wave wireless communications: Beamforming, spatial multiplexing, or both?” *IEEE Commun. Mag.*, vol. 52, no. 12, pp. 110–121, Dec. 2014.
[8] D. Kurup, M. Himdi, and A. Rydberg, “Compact microstrip patch antenna array for dual-band operation,” *Electron. Lett.*, vol. 40, no. 23, pp. 1412–1414, Nov. 2004.
[9] J. Zhang, L. Dai, Z. He, B. Ai, and O. Tirkkonen, “Performance analysis of 3D beamforming for 5G millimeter-wave massive MIMO,” *IEEE Trans. Wireless Commun.*, vol. 17, no. 5, pp. 3524–3539, May 2018.
[10] L. Vaskelainen, “Mutual coupling compensation in adaptive antenna arrays using the LMS algorithm,” *IEEE Trans. Antennas Propag.*, vol. 43, no. 4, pp. 964–967, Sep. 1995.
[11] S. Yang, Y. B. Gan, and P. K. Tan, “A new technique for low sidelobe pattern synthesis using genetic algorithm,” *IEEE Trans. Antennas Propag.*, vol. 49, no. 3, pp. 380–383, Mar. 2001.
[12] T. S. Rappaport, Y. Xing, G. R. MacCartney, A. F. Molisch, E. Mellios, and J. Zhang, “Overview of millimeter wave communications for fifth-generation (5G) wireless networks—with a focus on propagation models,” *IEEE Trans. Antennas Propag.*, vol. 65, no. 12, pp. 6213–6230, Dec. 2017.
[13] A. Goldsmith, *Wireless Communications*. Cambridge, U.K.: Cambridge Univ. Press, 2005.
[14] M. A. Al-Tarifi and M. S. Sharawi, “Design and analysis of phased array antennas using reconfigurable elements,” *IEEE Access*, vol. 7, pp. 105620–105632, Aug. 2019.
[15] J. Rodriguez-Fernandez, F. J. Herraiz-Martinez, D. Segovia-Vargas, and V. Gonzalez-Posadas, “Compact 28 GHz phased array antenna for 5G applications,” *IEEE Antennas Wireless Propag. Lett.*, vol. 17, no. 9, pp. 1638–1642, Sep. 2018.
[16] H. T. Chattha, M. Nasir, Y. Huang, and S. J. Boyes, “Performance study of microstrip patch antennas with different substrate materials,” *Microw. Opt. Technol. Lett.*, vol. 55, no. 1, pp. 10–14, Jan. 2013.
[17] A. A. Althuwayb, “Design of phased array antennas with defected ground structures for 5G mmWave applications,” *IEEE Access*, vol. 8, pp. 149946–149954, Aug. 2020.
[18] R. N. Tiwari, S. K. Sharma, and M. D. Upadhyay, “Performance analysis of rectangular microstrip patch antenna using HFSS,” in *Proc. Int. Conf. Commun. Signal Process.*, Chennai, India, Apr. 2016, pp. 1111–1115.
[19] S. K. Mishra and R. K. Gupta, “HFSS simulation and optimization of microstrip patch antenna for wireless applications,” *Int. J. Microw. Wireless Technol.*, vol. 10, no. 2, pp. 198–205, Feb. 2018.
[20] M. M. Honari, A. Alphones, and J. J. Thiang, “Dual-band phased array antenna for beam steering applications in 5G networks,” *IEEE Access*, vol. 9, pp. 77600–77609, Jun. 2021.
[21] H. Chen, X. Zhang, and K. Wu, “Substrate-integrated waveguide phased array antennas: A review,” *IEEE Access*, vol. 8, pp. 174778–174791, Oct. 2020.
[22] N. Hussain, M. Jeong, A. Abbas, J. Park, and N. Kim, “Metamaterial-based beam-steerable phased array antenna for mmWave 5G systems,” *IEEE Access*, vol. 8, pp. 163076–163085, Sep. 2020.
[23] M. Shafique, L. Khan, and M. Saeed, “Microstrip phased array antenna design and simulation using HFSS for X-band applications,” in *Proc. Int. Conf. Innov. Electr. Eng. Comput. Technol.*, Karachi, Pakistan, Oct. 2019, pp. 1–5.
[24] S. Ahmed, R. Tafazolli, and C. Parini, “Millimeter-wave phased array antennas for 5G: Fundamentals and challenges,” *IEEE Commun. Mag.*, vol. 59, no. 6, pp. 36–42, Jun. 2021.
[25] A. Iqbal, O. A. Saraereh, A. Basir, and J. Lee, “Compact planar phased array antenna with wideband beam steering for 5G new radio,” *IEEE Access*, vol. 9, pp. 124500–124510, Oct. 2021.