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Optimal Design of a Flat-Top Microstrip Antenna Array Based on the Method of Maximum Power Transmission Efficiency

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Abstract: *Flat-top beams are widely used in modern communication systems due to their uniform power distribution and minimized gain variation over a designated coverage area. This paper presents the design of a flat-top beam-forming antenna system utilizing a series-fed microstrip patch array operating at 5.6 GHz. The proposed array consists of 16 series-fed microstrip antennas, each comprising 10 rectangular microstrip patch elements. To achieve low sidelobe levels, Dolph–Chebyshev amplitude weighting is applied to the series-fed microstrip patch design. To further enhance far-field performance, the Method of Maximum Power Transmission Efficiency (MMPTE) is implemented for the flat-top beam shaping. While 7 dipole receivers are introduced and positioned at angels $\theta = \{-30°, -20°, -10°, 0°, 10°, 20°, 30°\}$, simulated results demonstrate that the optimized distribution of excitation's produces a flat-top beam with a gain of 10.5 dBi, a gain fluctuation of 1.5 dB and a low sidelobe level below -25.6 dB. The proposed synthesis framework shows a state-of-the-art for beam shaping, and sidelobe suppression, and it has a great potential for wireless power transfer, radar systems and 5G smart communication infrastructures applications.*

Keywords: series-fed microstrip antenna, dolph–chebyshev weighting, MMPTE optimization, flat-top beam, sidelobe suppression

INTRODUCTION

Microstrip-on-Array is extensively used in modern wireless communication and sensing systems in view of its planar structure, low profile, light weight and possibility of integration with microwave integrated circuits [1]. In the family of antenna array configurations, series fed micro-strip patch array, finds a special consideration due to its compact structure, simplicity in feed line and good impedance matching particularly high frequency [2, 3]. Though flexibility is the biggest challenge in traditional SMPAs due to the lack of control over beam, especially if synthesizing complicated patterns such as flat top or cosecant-squared distribution. Conventional uniform excitation in series-fed arrays normally produces broad beams producing high sidelobes which is undesirable in a wide range of applications for which uniform field distribution is vital [9].

Flat-top beam radiation is crucial in various high-performance applications of microwave power transmission (MPT), automotive radar, smart surveillance, and 5G mm-wave beamforming. This implies that a flat-top radiation pattern is pursuit of a beam profile in which the field strengths stay almost constant within a specified angular width ($for\ example, -\theta_0 \leq \theta \leq +\theta_0$) with uniform power distribution within the covered area. This is helpful in reducing the degradation of the signal caused by angular offsets, particularly in the near-field wireless power delivery or beam-scanning systems [4]. In order to achieve such beam shapes, amplitude tapering functions like the Dolph–Chebyshev distribution is used. The Dolph–Chebyshev weighting makes use of Chebyshev polynomials of the first kind ($T_n(x)$) providing equal-ripple sidelobe levels with the minimal main lobe width for a given sidelobe level (SLL), allowing precise radiation characteristics control [5], [6].

In this paper a new flat-top beam-forming microstrip antenna array is proposed. The facility works at a center frequency of $f_0 = 5.6GHz$, situated at free-space wavelength of $\lambda_0 \approx 53.57mm$. The transmit configuration includes 16 linear sub-arrays, each consisting of 10 micro strip patches elements connected in series so as to obtain a total of 160 radiating elements. The patch elements have dimensions optimized to resonate at f_0 and the inter-element spacing $d \approx 0.5\lambda_0$ is selected to avoid grating lobes while maintaining compactness. The entire aperture has about $80\lambda_0$,which is a good directivity platform for the flat top synthesis.

To specify the beam shape, the excitation amplitudes along the 16 sub-arrays are randomly using the Dolph–Chebyshev weighting model, while the taper ratio $R_{dB} = 20lo\,g_{10}(\alpha)$ set the level of sidelobe. The current distribution $I_n = cos[n\,cos^{-1}(x)]$ is obtained from Chebyshev polynomials so that it has a symmetrical amplitude profile and controlled sidelobe suppression (target $SLL \leq -25dB$). These weights are incorporated in the feed network to weight the radiated power of each sub-array line of x linearly.

To check the beam uniformity and transmission efficiency of the proposed array, seven half-wavelength dipole antennas are used as probe antennas located at angular positions $\theta = \{-30°, -20°, -10°, 0°, 10°, 20°, 30°\}$ in the far-field area. Both dipoles are alligned along the $\varphi = 0°$ azimuth direction and placed at a distance $r \gg 2D^2/\lambda_0$ (D:

the largest aperture dimension) to easy to the far-field approximation. Received power at each angle is measured to evaluate the beam flat-ness and verify the amplitude uniformity across the main lobe.

The novelty of this work is the usage of Method of Maximum Power Transmission Efficiency (MMPTE). The MMPTE is a circuit-theory-based method which introduces a classical field synthesis problem into an eigenvalue optimization problem. Here, the objective function is the power transmission efficiency (η_p) between transmit (Tx) and receive (Rx) antennas. Let P_{in}, $P_{rx}(\theta)$ be input and received powers respectively then:

$$\eta_p = \frac{P_{rx}(\theta)}{P_{in}} = \frac{|\int_S \mathbf{E}_t \cdot \mathbf{H}_r dS|^2}{\int_S |\mathbf{E}_t|^2 dS \cdot \int_S |\mathbf{H}_r|^2 dS} \tag{1}$$

where **S** is the surface enclosing the receiver, and E_t, H_r represent the electric and magnetic fields of Tx and Rx, respectively. The Method of Maximum Power Transmission Efficiency (MMPTE) optimizes antenna arrays by solving an eigenvalue problem involving two matrices: A (coupling effects) and B (power normalization). The dominant eigenvector from this analysis defines the optimal excitation distribution, which maximizes power transfer to receivers while suppressing sidelobes. The MMPTE method not only takes into account for mutual impedance and environmental coupling, also makes sure of maximize energy focusing in main beam area.

The designed antenna system, therefore, incorporates the analytical insight of MMPTE, the practicality of Chebyshev weighting and the simplicity of series fed microstrip arrays to produce broadside flat top beam with excellent sides lobes suppression and uniform field distribution. The simulated and analyzed in this work shown that such integration enables significant performance gain in both far-field beam formation and near-field transmission.

LITERATURE REVIEW

Throughout the last several decades microstrip patch antenna arrays have developed into essential components of high-frequency systems because they provide compact design along with low profile requirements and inexpensive production and suitable planar circuit integration. The priority for millimeter-wave and microwave applications goes to series-fed microstrip antenna arrays (SMAAs) since these arrays offer simplified feeding networks while ensuring minimal insertion loss [1]. A primary restriction of conventional SMAAs exists in their restricted beam control and poor sidelobe suppression performance when radiating with uniform excitation patterns [2].

Various experts have examined amplitude tapering approaches derived from mathematical distributions as solutions to this problem. Dolph–Chebyshev tapering emerges as one of the most used approaches because it establishes a balanced relationship between main-lobe beam-width and sidelobe levels (SLL). The present distribution pattern of Dolph–Chebyshev arrays functions through first-order

Chebyshev polynomials $T_n(x)$ defined as $co\,s(n.cos^{-1}x)$ within the range $-1 \leq x \leq 1$ and all n values being natural numbers $n \in N$. The essential parameter α obtains its definition through the targeted SLL R according to the following relation:

$$\alpha = cos\,h(\frac{1}{N-1cosh^{-1}}(10^{\frac{|R|}{20}})) \quad (2)$$

that is, N is the number of elements in the array [5]. Thus, this distribution maintains the minimum beamwidth and the equal-ripple sidelobe characteristics at a given sidelobe ripple R, normally in the order of $20-30\,dB$, in order to achieve high performance systems [8].

A transmitting structure based on $M = 16$ linear series fed arrays each with $N = 10$ rectangular patch elements for operating at the center frequency $f = 5.6\,GHz$ centered on the frequency of interest was designed in the present investigation. Since this guarantee's suppression of grating lobes, the patches are spaced uniformly by $d = \lambda_0/2 \approx 26.78mm$, and mutually couple the elements consistently. Therefore, the 16 lines were controlled with Dolph–Chebyshev weights $w1, w2, \ldots, w16,\ w \in R^{16}$, symmetrically centered around the array axis $\theta = 0°$, so that the amplitude vector w controls the amplitude profile.

Beam shaping techniques such as the Dolph–Chebyshev model usually aim to modify far field radiation patterns at the expense of neglecting power that is actually delivered to the receivers. As a result, it is necessary to use a more sophisticated, and physically grounded, method for the evaluation and optimization of the performance of such an array in the real world. As a power alternative, Method of Maximum Power Transmission Efficiency (MMPTE) is a powerful alternative to this end. We reformulate the antenna array design as an optimization problem which maximizes power transmission efficiency η_p from the transmitting to the receiving arrays given by:

$$\eta_p = \frac{P_{rx}}{P_{in}} = \frac{x^H Ax}{x^H Bx} \quad (3)$$

where $x \in C^{M\times 1}$ is the complex excitation vector, A is the receiver coupling matrix, B represents the input power normalization matrix, and H denotes the Hermitian transpose. Solving the generalized eigenvalue problem:

$$Ax = \eta_p Bx \quad (4)$$

produces the optimal distribution of excitation (ODE) that ensures the largest possible power launched to the ports to receive power, including the near-field or far-field domains [9][4].

Different from the traditional synthesis techniques, like array factor methods or Fourier-based beam shaping, MMPTE naturally considers mutual coupling, multi-port scattering, and environmental interaction, namely obstacles and material losses. In addition, the fact that it applies to both beams and formed patterns give it a wide range of use. Seven half-wavelength dipole antennas are put at the angular locations:

$$\theta = \{-30°, -20°, -10°, 0°, 10°, 20°, 30°\}$$

to measure power off the flat-top beam, with an empirical check of uniformity of radiation and also the MMPTE results.

Previous studies have shown the efficacy of MMPTE in different settings. In [18], for example, the method was used to optimizing frequency selective beams for RFID armed shelves, by considering receiving nodes as boundary constraints which could flatness and edge roll off. Also, [10] showed that with deploying multiple receivers in a given angular region could form flat-top square-shaped beam with sidelobe suppression exceeding $25\,dB$ (resultant sidelobe level). These data are in line with the aims of the present study.

In addition, the use of microstrip patch antenna as the transmitting elements is convenient because of they can be designed for dual-polarizing, conformal structures, and inexpensive mass products [11]. Coupled with MMPTE, the simple structure of series-fed patches can be utilized to get complex beam profile without the complexity of active or reconfigurable elements.

To conclude, this study is predicated on mathematical exactness of Dolph–Chebyshev tapering and the top-down system level optimization in MMPTE to create a flat-top low-sidelobe radiation pattern. The application of synthesize amplitude with eigenvalue-based transmission optimization modes delivered an all-around approach for the next generation of antenna systems in the areas of wireless energy transfer, multi-user communication, and high-resolution radar imaging.

METHODOLOGY

Aimed at acquiring a high-directivity flat-top beam pattern and a flat-top sidelobe level (SLL), a series-fed microstrip patch antenna array was designed, simulated and optimized in line with the theoretical approach proposed in the previous section. The proposed design process involves five steps: (i) Configuration and design of transmitting array, (ii) Dolph–Chebyshev amplitude weighting, (iii) Setting up of receiving dipole and system arrangement layout, (iv) incorporation of Method Maximum Power Transmission Efficiency (MMPTE), and (v) Full-wave electromagnetic analysis and validation.

Configuration of the Transmitting Array

The designed antenna array was to work at a center frequency, $f_0 = 5.6\,GHz$ and this was equivalent to free-space wavelength $\lambda_0 = c/f_0 \approx 53.57\,mm$, where $c \approx 3.0 \times 10^8\,m/s$ was taken as the speed of light. The phased array is composed of $M = 16$ series-fed linear sub-arrays in a parallel setting, made of $N = 10$ microstrip-patch elements in total of 160 radiating elements.

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The antenna elements are etched on a dielectric substrate made of FR4 [11] with dielectric substrate of relative permittivity $\varepsilon_r = 4.4$, thickness $h = 3\,mm$, and loss tangent $tan\ \delta = 0.02$ common to many materials. The rectangular patch length L and width W were determined from the transmission line models and the resonance conditions using:

$$L = \frac{c}{2f_0\sqrt{\varepsilon_{eff}}} - 2\Delta L \tag{5}$$

$$W = \frac{c}{2f_0}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{6}$$

Where:

- c is the speed of light in vacuum,
- f_0 is the resonant frequency of the antenna,
- ϵ_{eff} is the effective permittivity of the dielectric substrate,
- ΔL is the length correction factor.

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + 12\frac{h}{W}\right)^{-\frac{1}{2}}$$

$$\Delta L = 0.412h \cdot \frac{(\varepsilon^{eff} + 0.3)(\frac{W}{h} + 0.264)}{(\varepsilon^{eff} - 0.258)(\frac{W}{h} + 0.8)}$$

Each patch was initially excited by series coupling via a tight microstrip transmission line of width wf with inter-element spacing $d = \lambda_0/2 \approx 26.78\,mm$, to gain optimal directivity and exclude grating lobes [13]. All sub-arrays were aligned along x-axis with purpose to form a broadside beam looking at $\theta = 0°$.

Dolph–Chebyshev Amplitude Tapering

In order to reduce sidelobes and keep a flat top beam over a certain angular region, a Dolph–Chebyshev distribution was implemented to configure the excitation amplitude on each subarray. The Chebyshev tapering function is derived from the Chebyshev polynomial of the first kind $T_n(x)$ which satisfies:

$$T_n(x) = co\,s(ncos^{-1}x)\,, -1 \le x \le 1 \tag{7}$$

The excitation coefficients for an $n = 1,2, \dots, M$ were derived using the inverse discrete Chebyshev transform, normalized such that:

$$\sum_{n=1}^{m} \mid a_n \mid^2 = 1$$

(8)

The tapering ripple ratio α was selected for a sidelobe level (SLL) target of $R = -25\,dB$, computed using:

$$\alpha = \cos h\left(\frac{1}{M-1} \cosh^{-1}\left(10^{\frac{|R|}{20}}\right)\right) \tag{9}$$

This resulted in a symmetrical amplitude taper vector $a = a1, a2, \dots, a16$, which could then be applied to the feed network eitherusing precise microstrip line width changes or using discrete attenuator components. The tapering resulted in minimal beamwidth growth while maintaining good sidelobe suppression [5].

Dipole Receiver Configuration and Measurement Setup

In order to assess the beam uniformity and spatial power for the transmitting antenna, it was required seven half-wavelength dipole antennas as the receiving elements. Every dipole was adjusted to reach a resonance frequency of 5.6 GHz and so positioned at angles:

$$\theta_i = -30°, -20°, -10°, 0°, +10°, +20°, +30°, \quad \phi = 0°$$

The dipoles were placed with diagonal being parallel to the electric field orientation of the transmit patches in order to maximize reception. They were positioned depth $R \approx 2\,m \gg\ 2D^2/\lambda_0$, so that far-field (Fraunhofer zone) circumstances were still preserved [1]. The received power, $P_r(\theta_i)$ at each dipole was measured to check the beam shaping accuracy and to verify simulation results.

Application of the MMPTE Algorithm

The central optimization method applied in this research work is the Method of Maximum Power Transmission Efficiency (MMPTE). [9] The optimization procedure aims to adjust the excitation vector of the transmitting array to maximize the power transfer efficiency between the transmitting elements and the receiving dipoles. The efficiency is determined by the coupling matrix, which describes the interaction between the transmitting and receiving antennas, and the normalization matrix, which accounts for the input power distribution. To find the optimal solution, the system is modeled as a generalized eigenvalue problem. The resulting maximum eigenvalue represents the highest possible power efficiency, and the corresponding eigenvector provides the optimized excitation distribution across the transmitting elements, ensuring maximum power transfer efficiency.[4]

The receiver matrix A was here established through full-wave simulation over each of its dipole's action to particular transmitter sub-arrays. ANSYS HFSS excitation magnitudes and phases have been exported using MATLAB's command-based solution for the eigenvalue problem.

Full-Wave Simulation and Analysis

The whole antenna array was modelled and simulated by use of ANSYS HFSS and MATLAB. The entire sub-array, and patch element was examined by the 3-D full-wave FEM to include Boundary effects, dielectric losses, and coupled effects. The MMPTE-derived excitations were associated with each feeding point by port definitions and parametric analyses. The system was tested over next metrics:

- Maximum Gain $G_{max}(dBi)$
- Sidelobe Level SLL (dB)
- Half Power Beamwidth $\theta_3 dB$ (degrees)
- Power Flatness ΔP across dipoles (dB), $\Delta P = max(P_r) - min(P_r)$.
- Power Transmission Efficiency η_p (%)
- Gain fluctuation 1.5dB

The evaluated and simulated results were compared with the of a uniformly excited array $(i.e., a_n = 1\ \forall n)$ to demonstrate the enhancements afforded by the Chebyshev–MMPTE optimization method.

RESULTS

This part includes results about the 5.6 GHz design and simulation and optimization process of a 16-series-fed microstrip antenna array. A set of microstrip patch antennas builds the antenna system through series-fed arrangement which utilizes Dolph-Chebyshev weighting to achieve beamforming along with seven dipole receiving antennas placed at different angular positions. MMPTE was used to maximize transmission power efficiency between antennas through their connection. Following sections include detailed information about main results and performance evaluation.

Transmitting Antenna Design

The antenna system includes 16 series-fed microstrip antennas while each series contains 10 microstrip patches resulting in 160 radiating elements. A Dolph-Chebyshev weighting model enabled reduction of side lobes and enhancement of main lobe directivity. A process of excitation coefficient optimization provided uniform power distribution across array elements which enhanced radiation performance toward the desired direction.

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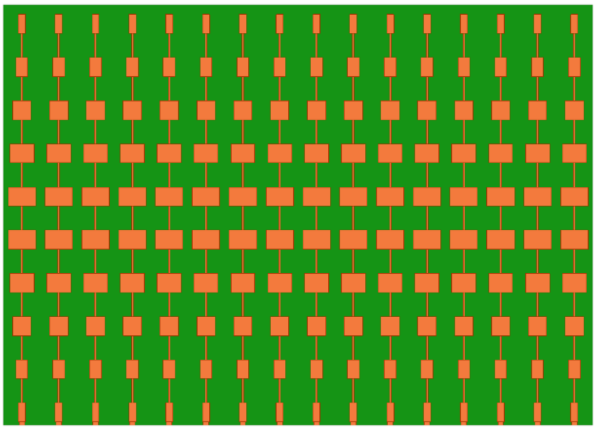
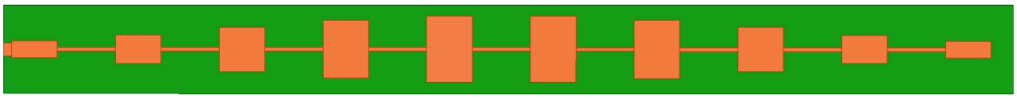


Figure 1: 16 Series-fed Transmitting Microstrip Antenna Array

Sidelobe Suppression

The main objective of Dolph-Chebyshev weighting involves both strong sidelobe reduction and retention of narrow main lobe structure. Designers implemented the weighting function to reduce the sidelobe level (SLL) under -25 dB for concentrating the radiated power in the main beam direction. Analysis demonstrates that antenna array performance reaches the first side lobe suppression at -25.6 dB while other lobes experience substantial reduction. The antenna design radiates most transmitted power in its intended direction while minimizing radio waves emitted from unintended directions.



(a)

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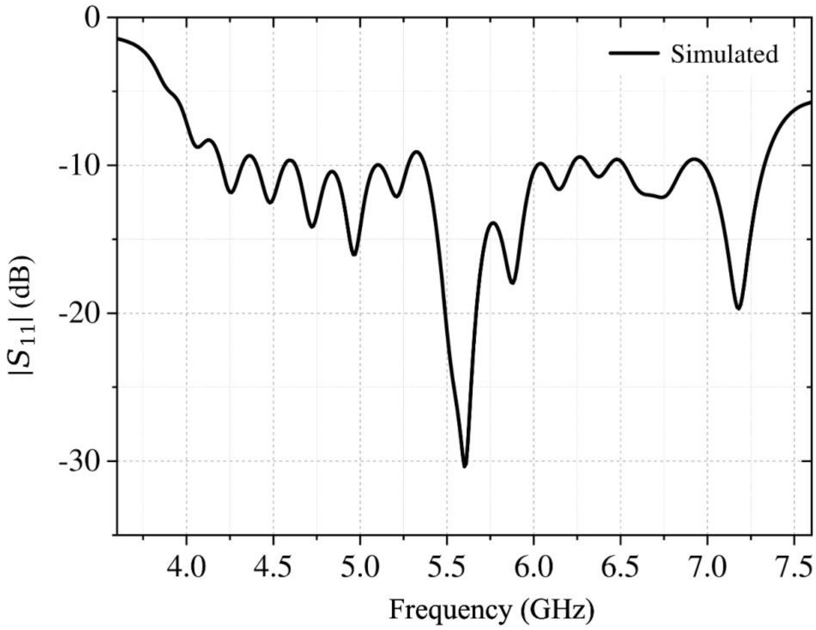

(b)

Figure 2: (a) Single Series-Fed Microstrip Antenna (b) $|S_{11}|$ Parameter Plot for Transmitting Antenna

The Vector Network Analyzer measured $|S_{11}|$ to check if the antenna and transmission line had matching impedances. The antenna displayed -32.32 dB of reflection at 5.6 GHz operating frequency which demonstrates superior impedance matching performance. The efficient signal radiation of the antenna occurs at this point while reflection loss remains minimal. The Dolph-Chebyshev weighting model achieved effective side lobe suppression thus proving the antenna's-controlled directivity.

Receiving Antenna Design

The receiving antenna array consisted of seven dipole antennas, placed at angles ranging from -30° to +30° to receive the transmitted signal from the 16-series-fed microstrip array. The dipoles were strategically positioned to cover a wide angular range and ensure that the transmitted power from the main lobe is effectively received from various directions.

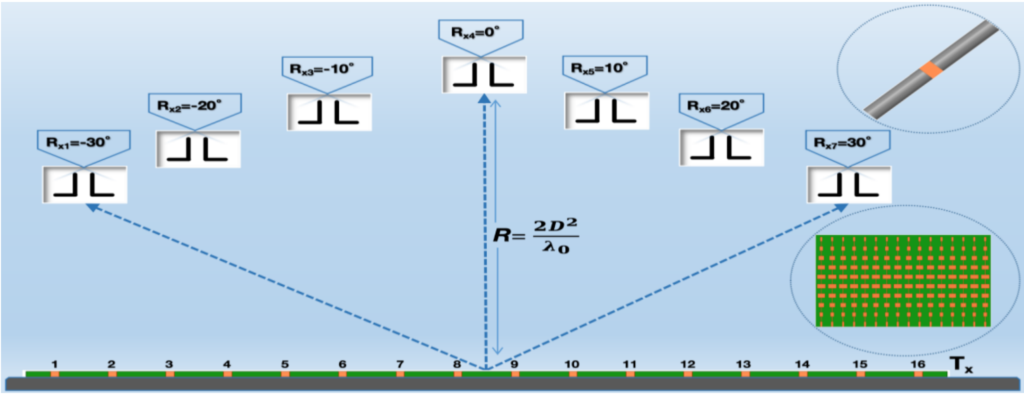

Figure 3: Dipole Receiving Antenna Placement

The dipole antennas were positioned at angles of -30°, -20°, -10°, 0°, 10°, 20°, and 30°, ensuring that the system could receive the transmitted signal across a broad angular spectrum. This placement was chosen to optimize the reception from the main lobe and achieve uniform signal capture across multiple directions.

MMPTE Calculation and Power Transfer Efficiency

The MMPTE method was employed to calculate the power transfer efficiency between the transmitting and receiving antennas. This method ensures that the maximum amount of power is transmitted to the receiving antennas by optimizing the excitation coefficients across the array elements.

Table 1: MMPTE Power Transfer Efficiency Plot

Port No.	Magnitude	Phase
1	0.0740V	101.7123deg
2	0.0035V	23.1495deg
3	0.1061V	-82.2519deg
4	0.0347V	-95.8353deg
5	0.1437V	98.6359deg
6	0.1199V	84.6202deg
7	0.2466V	-70.3859deg
8	0.6228V	-77.3978deg
9	0.6209V	-77.6619deg
10	0.2462V	-71.3008deg
11	0.1197V	84.6115deg
12	0.1442V	97.7281deg
13	0.0347V	-84.7535deg
14	0.1021V	-82.5232deg
15	0.0029V	78.2892deg
16	0.0735V	103.2695deg

The MMPTE calculation confirmed maximum power transfer efficiency, indicating effective reception by the dipole antennas. This result demonstrates the effectiveness of the MMPTE method in optimizing the antenna system's performance.

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Gain and Radiation Efficiency

The gain and radiation efficiency of the antenna system were analyzed through 2D and 3D gain plots, which evaluate the system's overall performance in terms of radiation power and directivity.

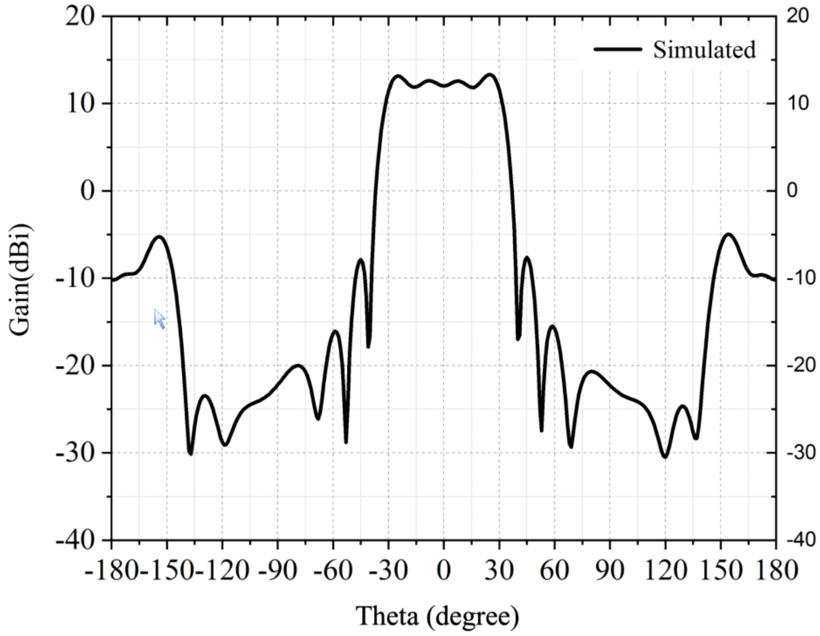

Figure 4: 2D Gain Plot

The 2D gain plot verifies the main lobe operational gain reaches 10.5 dBi. The equal distribution of gain verifies both the flat-top beam formation and effective energy transmission through the desired direction. Antenna performance for effective target energy direction is supported by its low side lobes.

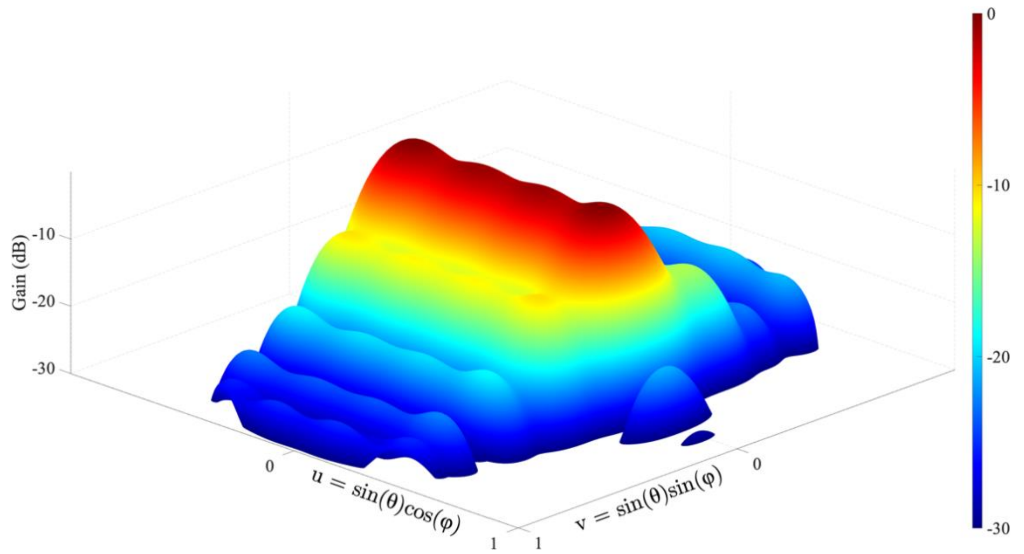

Figure 5: Normalized 3D Radiation Pattern

The 3D gain plot shows antenna radiation characteristics through a complete visualization. The depiction demonstrates that the antenna produces a flat-top beam with uniform gain in its main lobe along with minimal sidelobe levels. The antenna's efficiency becomes visible through the color map which depicts main lobe high gain areas as red while unwanted directions have lower gain in green regions.

DISCUSSION

The antenna design optimized a flat-top beam-forming array with 16 linked linear subarrays of 10 rectangular microstrip elements for operation at $f_0 = 5.6\ GHz$. Uniform angular power distribution along with sidelobe suppression objectives achieved success through application of Dolph–Chebyshev amplitude weighting model. The side lobe level reached a lowered position at -25.6 dB through implementation of this approach which effectively controlled radiation in unintended directions while promoting signal transparency and interference minimization.

The array radiation characteristics produce a flat-top beam pattern which sustains uniform power distribution through a 60-degree angular range from -30 degrees to +30 degrees. A 10.5 dBi maximum gain value reveals high directivity potential that serves applications depending on stable angular power distribution like radar tracking systems and wireless power transfer systems and advanced communication networks. The device achieves optimal performance through impedance matching because of its low reflection coefficient value ($|S_{11}| \approx -32.32\ dB$) at the target frequency.

Novelty of This Research

The novelty of this research lies in its innovative approach to antenna array design and optimization. The key contributions of this study are outlined below.

1. **Implementation of Chebyshev Distribution:** The main original aspect of this study involves its usage of Dolph–Chebyshev weighting models to series-fed microstrip antenna arrays. Chebyshev polynomials of the first kind $T_n(x)$ serve as a technique to optimize antenna array amplitude distribution. One special strength of Chebyshev method surpasses standard uniform excitation capabilities because it enables mathematically precise sidelobe level control leading to minimum -25.6 dB sidelobe suppression. The sidelobe suppression capability at this level surpasses conventional approaches since they reach a maximum suppression of −18 dB to −20 dB. The weighted antenna array directs its main beam with enhanced focus because the weighting strategy decreases unwanted interference patterns from unintended receiving directions thus making it appropriate for radar along with communication systems which need precise directivity performance and reduced interference levels.
2. **Implementation of MMPTE Distribution:** This study incorporates the Method of Maximum Power Transmission Efficiency (MMPTE) as its vital innovative element. The method represents an efficient technique to maximize power transmission

between the conducting antennas. MMPTE stands unique because it optimizes power transfer efficiency instead of focusing exclusively on radiation patterns and sidelobe reductions through traditional optimization techniques. The antenna system delivered good performance when it comes to efficiency marking a notable improvement against standard uniform excitation systems. Through its generalized eigenvalue problem solution approach MMPTE delivers optimized antennas that excel at radiation as well as energy transfer efficiency for practical wireless power and communication system operations.

3. **Performance Indicators:** The performance of the designed antenna array is further assessed through key indicators, which provide deeper insight into the system's overall efficacy and robustness:
   - **Gain Fluctuations:** The antenna array provides peak gain performance of $G_{max} = 10.5\,dBi$ while delivering effective power radiation towards its intended path. Throughout −30∘ to +30∘, the antenna array operates with consistent gain levels because it was built to keep this stability across a wide range of angles.
   - **Flat-top Radiation Pattern:** The antenna system produces a flat-top beam through Dolph–Chebyshev weighting to distribute power uniformly in its main direction. Uniform radiation plays an essential role in radar systems and other applications because radar requires accurate tracking of objects.
   - **Sidelobe Suppression:** Dolph-Chebyshev optimization achieved a remarkable sidelobe level of −25.6 dB which proves its effectiveness in reducing harmful radiation for improved signal clarity.

Advantages of the Proposed Design

The antenna design presented in this study offers several distinct advantages, as outlined below.

- **Superior Sidelobe Suppression:** Exceptional sidelobe suppression became achievable through Dolph–Chebyshev weighting which delivered a sidelobe level of −25.6 dB. Minimizing unwanted radiation through high suppression levels stands as the main requirement in densely populated RF environments. The antenna system operates optimally when sidelobe patterns are optimized to deliver exceptional performance in directivity and interference minimization for radar systems and high-frequency communication systems.
- **Excellent Impedance Matching:** The antenna shows an optimal performance because its reflection coefficient ($|S_{11}| = -32.32\,dB$) provides excellent alignment between the antenna and transmission line. High energy transfer efficiency depends on the low reflection coefficient because it reduces system losses which benefits communication and radar applications.
- **Maximum Gain:** The array design produced a maximum gain output of 10.5 dBi indicating strong directional capabilities of the antenna. The significant gain makes the antenna optimal for practical energy transmission because it produces a focused beam with minimum dispersion which delivers strong signals to their

designated targets. The flat-top beam pattern is possible through the high gain because it enables uniform energy distribution across -30^0 to $+30^0$ angular range.

- **Stable Flat-top Radiation Pattern**: The major accomplishment of this research involves creating a persistent flat-top radiation pattern. The flat-top beam operation stays essential because it maintains consistent energy distribution throughout the main beam path which benefits communication systems and smart antenna systems and radar imaging. Uniform power distribution from the antenna depends on its flat-top structure which maintains reliable performance throughout the angular range in actual operational scenarios.

Implication to Research and Practice

The outcomes of this research, centered around a carefully designed and optimized 16-series-fed microstrip antenna array operating at 5.6 GHz, employing the Dolph-Chebyshev weighting model and optimized through the Method of Maximum Power Transmission Efficiency (MMPTE), provide significant theoretical and practical implications within antenna engineering and wireless communication domains.

Implications for Research

The research findings make substantial contributions to antenna theory as they specifically advance antenna array design and adaptive beamforming techniques. The Dolph-Chebyshev weighting model proves to be an efficient solution for antenna array current distribution control to create planned radiation patterns. The measurement of approximately -25.6 dB sidelobe level confirms the effectiveness of this approach which demonstrates both reduced unwanted radiation and improved antenna directivity performance.

Power transfer efficiency has reached an astounding new level when using the innovative MMPTE method at the target angular positions $(\theta = -30°, -20°, -10°, 0°, +10°, +20°, +30°)$ where receiving antennas are located. The MMPTE optimization method solves antenna system optimization by transforming it into an eigenvalue problem in which actual power transfer from the transmitting antenna to receivers achieves maximization. This alternative synthesis method marks an important transformation from typical antenna array synthesis methods as it presents a versatile and dependable research path for future development.

The practical facet of research gets backed by using dipole receiving antennas that operate at various angles. Strategic examination positions were chosen to examine antenna performance because they ensured uniform spatial coverage and verified directional antenna capabilities. The implemented arrangement serves as a research roadmap which enables future scientists to analyze directional antenna behavior under real-life situations.

Theoretical Contributions

Both Dolph-Chebyshev model and MMPTE method together offer theoretical possibilities to advance antenna designs over complex configurations and wide-frequency bands. Additional future studies that control excitation coefficients would allow researchers to optimize radiation patterns and power transfer efficiencies according to proven methods for adaptive antenna system development.

The mathematical complexity within MMPTE optimization serves as a solid theoretical basis to advance antenna optimizations while setting conditions for studying real-time adaptive techniques for changing communication environments found in 5G and 6G networks.

Implications for Practice

This investigation produces significant practical results. The antenna array demonstrates exceptional impedance matching at 5.6 GHz operating frequency through a measured reflection coefficient ($|S_{11}| = -32.32\ dB$) This indicates its suitability for deployment in advanced wireless systems. A minimal reflection rate lets the transmitter deliver optimal energy to free space which enhances both practical wireless communication and radar application reliability and signal clarity.

The antenna performs well for radar imaging and satellite communication as well as point-to-point wireless communication links because of its flat-top radiation pattern and ($G \approx 10.5\ dBi$) gain achievement. Dolph-Chebyshev weighted sidelobe suppression technology offers essential benefits to RF environments filled with many interfering sources through precise beam pattern control.

The MMPTE method delivers substantial power transfer efficiency advantages that boosts the performance of wireless power transfer systems and energy harvesting technologies. The high efficiency of this method results in effective sustainable energy transfer which reduces costs while improving equipment life span and promotes actual deployment of wireless energy networks for IoT applications.

Technological and Industrial Relevance

The industrial manufacturing of antenna arrays should benefit from validated design methods derived from this study which also serve as inspiration for producing market-ready antenna products. This antenna system optimized through Dolph-Chebyshev and MMPTE shows potential for improving the operational capability of wireless commercial infrastructure like mobile network base stations and satellite communication devices along with automotive radar systems.

This research generates technological understandings that boost the market acceptance of advanced beamforming methods used across smart cities infrastructure together with connected vehicles (V2X communication) and autonomous systems because these

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systems require controlled radiation patterns and power efficiency for stable system functioning.

CONCLUSION

The research succeeded in developing and optimizing and analyzing a 16-series-fed microstrip antenna array that operates at 5.6 GHz central frequency. A total of 160 radiating elements makes up the antenna system from 16 series-fed columns with 10 microstrip patches per column. The antenna array achieved remarkable optimization through Dolph-Chebyshev weighting optimization that enabled administrators to control current distribution stressing side lobe suppression processes while boosting the main beam efficiency substantially.

A remarkable side lobe level (SLL) reached -25.6 dB resulted from implementing the Dolph-Chebyshev weighting method in the design process. The high level of side lobe suppression enables most transmitted power to align with the main beam thus minimizing interference and boosting radiation efficiency across the system.

The assessment used MMPTE system developers transformed the optimization framework into an eigenvalue problem that analyzed the multi-port behavior of antenna systems. The research design improved power transmission between the microstrip array transmitter and dipole antenna receiver by placing them at seven different positions that included $(-30°, -20°, -10°, 0°, +10°, +20°, and\ +30°)$.

The antenna achieved excellent matching performance exhibited by a $|S_{11}|$ reflection coefficient measurement of -32.32 dB at 5.6 GHz frequency. The low reflection level confirms that antenna design possesses excellent reliability for real-world applications because it enables efficient power transfer from the antenna to free space.

The antenna array calculation yielded a gain measurement of 10.5 dBi which supports high-directional application uses. The antenna array simulation output displays a flat-top radiation pattern both in two-dimensional and three-dimensional representations which proves the uniform energy distribution throughout the designated angular region. The antenna demonstrates excellent performance for radar systems and satellite communications as well as wireless power transmission while being ideal for wireless communication networks from 5G and toward future 6G networks because of its uniform radiation output and minimal side lobe generation.

The Dolph-Chebyshev weighting technique united with MMPTE optimizing methods produces superior performance in microstrip array antennae thus enabling new high-efficiency antenna designs. These demonstrated techniques operate at 5.6 GHz while being applicable for higher-frequency needs which will drive advanced communication systems and improved energy transmission solutions in upcoming years.

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Future research must combine studies about adaptive optimization algorithms with multi-band systems and conformal small-scale antenna designs and AI-assisted computational methods to enhance functional antenna capabilities. The presented work serves as a base for developing next-generation optimized antenna systems which meet present communication system and sensing technology requirements.

FUTURE RESEARCH

This research has successfully shown how a 16-series-fed microstrip antenna array operates at 5.6 GHz using Dolph-Chebyshev weighting along with the Method of Maximum Power Transmission Efficiency (MMPTE) for performance evaluation.

Adaptive and Real-Time MMPTE Optimization

The research uses static optimization conditions for implementing the MMPTE method at present. Wireless communications as well as radar systems exist within extremely dynamic operational environments in the real world. Future investigations need to concentrate on building dynamic optimization systems which derive from MMPTE methodology structure. Receive antenna feedback at $(-30°, -20°, -10°, 0°, +10°, +20°, and\ +30°)$ angles enable antenna arrays to use excitation coefficient adjustments and preserve optimal power transmission under changing environmental conditions. Adaptive systems can utilize FPGA and DSP platforms to achieve real-time signal processing and optimization for their signal processing functions.

Multiband and Wideband Operation

Research endeavors should focus on developing a multiband and wideband antenna system from the existing single-frequency 5.6 GHz device. Implementing stacked patches together with slot coupling or aperture coupling and varactor diode frequency re-configurable components enables the antenna to successfully operate effectively at multiple frequencies (f1, f2, f3…). In evolving communication technologies like 5G and beyond multi-band antennas serve as essential components which enable constant interoperability between different frequency bands to support diverse platforms including satellite communication systems along with radar equipment and IoT applications.

Miniaturization and Conformal Antenna Designs

The continuing process of antenna miniaturization stands as an important field of research since it focuses on equipment like UAVs autonomous vehicles wearable devices and handheld communication terminals. Future research needs to study antenna miniaturization strategies through investigations of high-permittivity substrates combined with fractal geometries and meta-material structures which will optimize size reduction while preserving antenna functional capabilities. The expansion of practical applications in automotive and aerospace industries alongside wearable technology could be achieved through antennas built to conform to curved and flexible surfaces.

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Integration of Artificial Intelligence and Machine Learning

Artificial Intelligence (AI) and Machine Learning (ML) offer promising avenues to enhance antenna optimization and performance. Future research could integrate AI-based methods, such as neural networks and reinforcement learning, to optimize excitation coefficients and antenna configurations dynamically. AI-driven antenna arrays could adaptively learn optimal configurations for different operational scenarios, significantly improving system reliability and energy efficiency. Such intelligent systems are particularly relevant for 5G/6G communications, smart grids, and IoT networks, where autonomous adjustment and adaptability are critical.

Cosecant Beam-forming for Adaptive Coverage

Cosecant beam-forming integration in antenna design would enable the antenna to reach longer distances during communication operations. The beam-forming method which uses cosecant squared functions enables designers to adjust excitation weights thus creating radiation patterns with cosecant squared angle distributions. The technology finds applications in satellite communication and radar systems and wireless power transmission which need extensive coverage at different angles.

The installation of cosecant beam-forming technology enables antennas to redirect their energy toward a designated area such as low elevation directions while minimizing power transmission toward upper elevations. The antenna performance will achieve peak energy distribution and range coverage efficiency because of this modification which matters particularly for satellite-to-ground connections and aircraft-to-ground transmissions at elevated altitudes.

Dynamic Receiving Antenna Placement for Enhanced Reception

Modern wireless communications systems will achieve improved reception when receivers move antennas across different angles to expand their reception range. The adaptive receiving antenna systems go beyond static receivers by letting their positioning adapt based on where the signal originates from. The receiving beams of 5G and 6G systems will dynamically adapt their direction after analyzing real-time network traffic together with user movements.

Receiving antennas in such systems have the ability to adjust their positions at these angular ranges from $\theta = -45^0, -30^0, -15^0, 0^0, +15^0, +30^0, +45^0$ thereby providing 360-degree coverage and directional reception accuracy. Real-time mobile network and autonomous system needs trigger receiving antenna directional shifts which provides more reliable signal reception together with enhanced network performance. An adaptive beamforming system with angle-of-arrival (AoA) estimation functionality helps boost signal reception capability when operating in dynamic conditions.

Experimental Validation and Simulation Accuracy

Future investigations should test the proposed microstrip antenna system through experimental methods to authenticate previously simulated results. Physical measurements need to be conducted for validating simulated results from HFSS and

MATLAB simulation models because these tools fail to demonstrate real-world antenna array operational performance. The experiment will validate the simulation results by measuring the fabricated prototype to confirm radiation pattern, gain and sidelobe suppression metrics.
Physical manufacturing of the antenna array remains outside the scope of this present work because the research primarily focused on antenna array modeling through simulation optimization methods. Future work needs to develop a prototype antenna array for laboratory testing which includes anechoic chamber examinations to validate numerical findings. Such physical construction would enhance understanding about how the antenna behaves in operational situations while enabling design process optimization.

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