



REGULAR ARTICLE

Linear Antenna Array Design with Dolph-Chebyshev Method for High Gain and Side-Lobe Reduction in Wireless Systems

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This paper presents a linear antenna array design employing the Dolph-Chebyshev method to achieve high gain while effectively minimizing side-lobe levels for IoT applications. The proposed approach strikes a balance between key parameters, allowing for the narrowest beam width at a specified side-lobe level and vice versa. Various techniques exist to reduce side-lobe levels, thereby conserving power and enhancing service quality. However, this study focuses on a 7-element array designed using the Dolph-Chebyshev method, offering a structured comparison of radiation patterns at different side-lobe levels. The analysis reveals that increasing directivity and gain does not always correlate with reduced side-lobe levels, emphasizing the trade-offs involved. To validate the approach, a microstrip comb-line antenna array is designed for 5 GHz IoT applications, implemented on a Rogers RO4003C substrate with dimensions of 200 × 50 mm². The array achieves a gain of 13 dBi while maintaining side-lobe levels below -18 dB at 5 GHz. The results demonstrate the suitability of this design for IoT-based wireless communication systems, ensuring efficient radiation characteristics while maintaining a compact form factor. This study highlights the importance of optimizing antenna parameters to achieve the desired performance for modern wireless networks.

Keywords: Dolph-Chebyshev, Fifth Generation (5G), IoT Applications.

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1. INTRODUCTION

The Internet of Things (IoT), a key aspect of 5G technology, enables seamless connectivity among devices using RF sensors and antennas. IoT applications span autonomous vehicles, smart homes, and logistics, but antenna design challenges include compact size, multi-standard support, and cost-effectiveness [1]. Research has focused on microwave and mm-wave bands for wireless standards [2], with shared-aperture antennas offering multiband operation. A notable design in [3] features an S- and X-band antenna with linear and circular polarization, using stacked patches and a parasitic ground. Recent studies also explore compact, multiband IoT antennas for sub-6 GHz applications. They encompass printed monopoles, inverted-F antennas, loop antennas, and patch-based configurations. Monopole-based designs for IoT applications have been detailed in [4], offering versatility across multiple frequency standards. In [5], presented a single-element multiband modified monopole covering frequency bands from 0.697 to 0.991 GHz, 2.38 to 2.5 GHz, 3.07 to 3.35 GHz, and 5.61 to 5.92 GHz. In [6], introduced a compact ultra-wideband monopole antenna operating from 3 to 12 GHz. In [7], discussed multiband monopole-based antennas with features like near-range communication and functions across ultra-high-frequency and microwave frequency ranges, making it apt for IoT applications.

In [8], introduced a compact meandered patch antenna with high fractional bandwidth, operating at the 2.4-GHz ISM band. It employed an inverse S-shaped meander line linked to a slotted rectangular enclosure, incorporating a capacitive load and parasitic element to enhance efficiency and gain compared to conventional designs. Similarly, [9] presented a miniaturized folded patch antenna for below 1 GHz standards, covering bands from 805 to 835 MHz. Achieving a 95% size reduction compared to standard patch antennas, it utilized techniques such as high folding, slots, slits, and inductive loading via vias. Various antennas have been proposed for IoT devices, including inverted-F-shaped antennas, loop antennas, 3D-printed antennas, and glass frame antennas [10]. In [11], a IoT antenna operating at 2.45 GHz was introduced, made from a transparent to ensure visibility.

The antenna's performance was also evaluated amidst adjacent metallic frameworks, showing minimal fluctuations. Additionally, [12] presented a inexpensive energy harvesting device for IoT applications utilizing a rectenna system. This system, comprising a patch antenna, rectifier, and filter designed to operate at 2.4 GHz and was self-operable, making it suitable for IoT applications. Moreover, [13] introduced a tri-band antenna design covering frequency bands of 2.5-2.7 GHz, 3.45-3.8 GHz, and 5.00-5.45 GHz.

In [14], introduces a microstrip log-periodic bow-tie

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antenna array, utilizing bow-tie antennas as elements. Three arrays were developed, comprising five, nine, and eleven elements. In [15], a novel log-periodic array approach is presented, featuring square patches fed via an inset feed. Three arrays were developed, with five, seven, and nine elements, each employing a scaling factor of 1.05. These achieved bandwidths of 500 MHz, 800 MHz, and 1.15 GHz, respectively. In IoT antenna design, achieving a low sidelobe level is essential for improving signal quality and reducing interference. Weighting the amplitude along the antenna aperture shapes the beam pattern, often through amplitude tapering, which involves distributing more power in the middle of the array and less towards the ends. This is typically accomplished using coefficients derived from polynomials such as Taylor and binomial series. The Dolph-Chebyshev method, utilizing amplitude tapering, significantly enhances antenna array design. Amplitude tapering optimizes power distribution among array elements, effectively minimizing sidelobe levels and reducing interference in densely populated environments. The method also achieves narrow main lobes, improving directivity and focusing signals on specific targets, which is essential for smart devices and industrial applications. Additionally, its flexibility allows for adaptation to various scenarios, ranging from low-power sensors to high-bandwidth communication systems [16].

In this communication, we propose a comb-line antenna design using Dolph-Chebyshev polynomial method for IoT applications. The amplitude weighting of each radiating element is precisely controlled by adjusting the width of the stub-shaped radiating element. This control mechanism is implemented using polynomials such as Dolph-Chebyshev, ensuring optimal performance. The proposed radiating element's validation is showcased by implementing a linear 7-element array antenna, contrasting it with an array comprising only stub-shaped elements. Both array antennas aim to attain a sidelobe level of -20 dB at 5 GHz. The effectiveness of the proposed element designs is confirmed through the fabrication and testing of antenna prototypes. The observed performance closely mirrors the simulated results concerning return loss, radiation patterns, and sidelobe levels. These findings conforming the proposed radiating element in simplifying and refining design processes, especially concerning amplitude weighting for comb-line array antennas intended for IoT applications.

2. ANTENNA DESIGN

The configuration presented in Fig. 1 illustrates a 90° uniform microstrip comb-line antenna array, where the radiating elements are open-circuited stubs, producing a radiation pattern similar to that of a dipole antenna. The stubs are alternately placed on both sides of the feedline, with the feedline terminated by an open end, creating a standing-wave structure that operates in resonant mode. To achieve broadside radiation, the distance D between adjacent stubs is set to $\lambda/2$, while the stub length L is also chosen to be $\lambda/2$ to ensure proper impedance matching between the feedline and the open termination. A matching line section is incorporated at the input of the structure to ensure impedance matching and minimize reflection losses. The antenna is fed by a

microstrip feedline connected to the central feed of the array, allowing efficient signal transmission and reception. The comb-line stub array is fed in series, gradually distributing energy to each stub along the central feedline. The open-circuited termination of the array results in a resonant structure, with a 180° phase shift between adjacent elements, producing a boresight beam with half-wavelength spacing. The performance of the antenna is significantly influenced by the tapering of the stub widths. For optimal sidelobe control and beamwidth, the Dolph-Chebyshev distribution is employed, offering a balanced trade-off between these parameters. In this design, all stubs are oriented perpendicular to the feedline, ensuring linearly polarized fields at a 90° angle relative to the feedline.

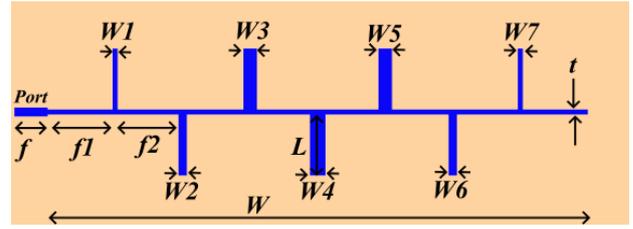


Fig. 1 – Schematic of proposed design

2.1 Dolph-Chebyshev Method

The Dolph-Chebyshev Array Synthesis Principle is a fundamental method in antenna engineering utilized for designing antenna arrays with precise radiation characteristics while minimizing side lobe levels. This principle finds significant application in systems requiring meticulous control over the radiation pattern, such as radar systems or wireless communication networks. At the core of this principle lies the Dolph-Chebyshev window function, enabling the shaping of the amplitude distribution of antenna array elements. Derived from Chebyshev polynomials, this window function facilitates precise control over sidelobe levels within the antenna radiation pattern. The primary objective of Dolph-Chebyshev array synthesis is to determine the excitation coefficients for array elements to minimize the maximum sidelobe level while adhering to specific constraints on the main lobe width and other desired radiation pattern characteristics.

The Chebyshev polynomial of degree N , denoted by $T_N(x)$, is defined recursively as:

$$T_0(x) = 1,$$

$$T_1(x) = x,$$

$$T_{n+1}(x) = 2xT_n(x) - T_{n-1}(x)$$

The Dolph-Chebyshev window function $W_N(\theta)$ is defined as:

$$W_N(\theta) = \frac{1}{\sqrt{1 + \varepsilon^2 T_N^2(\cos(\theta))}}$$

Where $T_N(x)$ is the Chebyshev polynomial of degree N , ε is the maximum allowable sidelobe level.

The array factor $AF(\theta)$ of the antenna array can be expressed as:

$$AF(\theta) = \sum_{n=1}^N a_n e^{j(n-1)kd \sin(\theta)}$$

Where a_n and θ represents the excitation coefficients for the array elements and angle of radiation.

The Dolph-Chebyshev Array Synthesis Principle, based on these equations, enables to design antenna arrays with specific radiation characteristics while minimizing side lobe levels. This approach provides precise control over the radiation pattern, essential for optimizing antenna performance. By leveraging Chebyshev polynomials, the Dolph-Chebyshev window function facilitates accurate sidelobe level control. The array factor expression captures the combined radiation pattern of antenna elements within the array, allowing for adjustment of excitation coefficients to achieve desired radiation patterns. The antenna was fabricated using Rogers RO4003C substrate with $\epsilon_r = 3.38$ with height of 1.52 mm, and other geometrical dimensions are $f = 7.78$, $f_1 = 15.84$, $f_2 = 15.84$, $t = 1.22$, $L = 14.43$, $W = 190$, $W_1 = 1.74$, $W_2 = 1.22$, $W_3 = 2.09$, $W_4 = 2.86$, $W_5 = 3.37$, $W_6 = 3.56$, and $W_7 = 3.37$ (all dimensions are in mm).

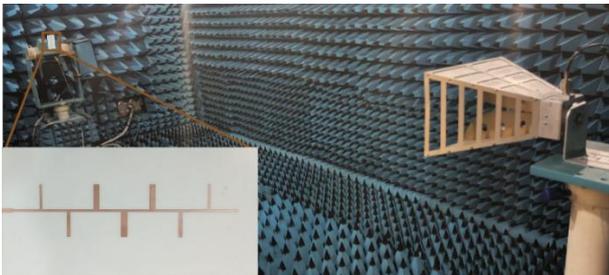


Fig. 2 – Photograph of the fabricated antenna array, with the experimental setup

3. RESULTS AND DISCUSSION

The proposed configuration and experimental setup are shown in Fig. 2. Fig. 3 illustrates the reflection characteristics obtained from measurements and simulations using the proposed Dolph-Chebyshev method for array antennas. At 5 GHz, the measured frequencies demonstrate reflections below the -10 dB criterion for arrays employing the proposed method. Fig. 4 depicts a 3D representation of the antenna radiation pattern at 5 GHz, demonstrating a directional radiation pattern.

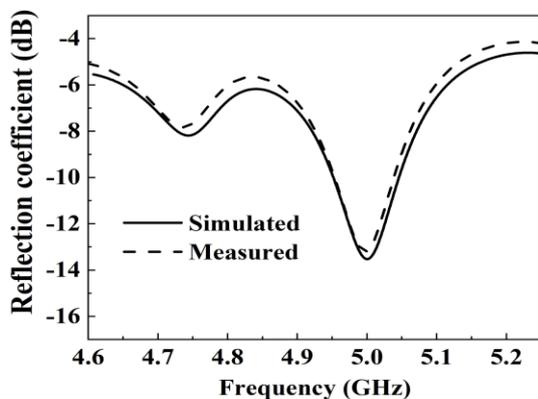


Fig. 3 – Simulated and measured S-parameters of the combine array

From Fig. 5, the 2D radiation pattern at 5 GHz reveals side lobe levels below -18 dB for both simulated and measured values achieved using the proposed Dolph-Chebyshev method. Additionally, a Half-Power Beamwidth of 15° and a realized gain of 13 dBi (as shown in the Fig. 6) were attained. Overall, the results demonstrate the successful implementation of the proposed Dolph-Chebyshev method for array antennas, showcasing favorable reflection characteristics, expected radiation behavior, and desirable radiation patterns at 5 GHz. These findings underscore the effectiveness and practical suitability of the array design methodology, validating its potential for various real-world applications in the field of antenna engineering.

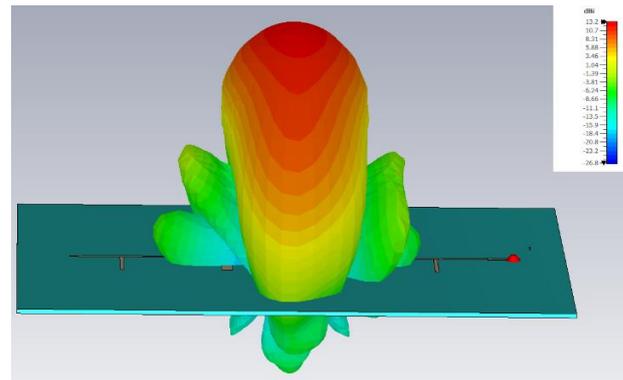


Fig. 4 – Simulated 3D radiation pattern at 5 GHz

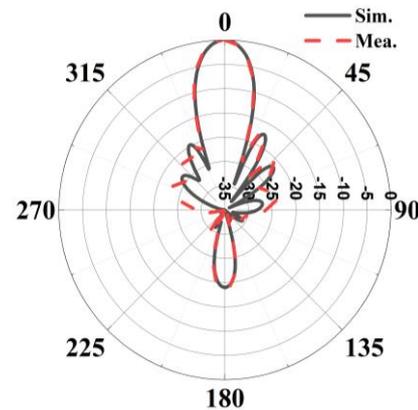


Fig. 5 – Radiation pattern antenna array at 5 GHz

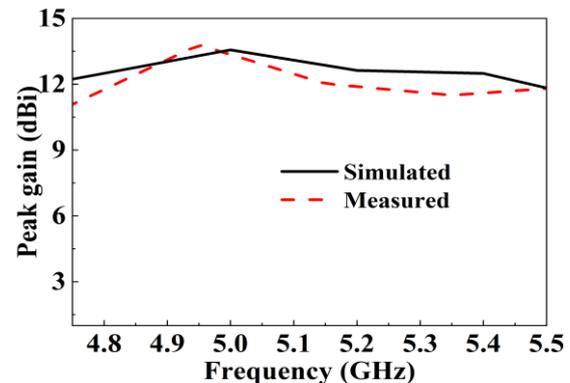


Fig. 6 – Simulated and measured gain

Table 1 – Comparison of the proposed antenna with some other published works

Ref.	[17]	[18]	[19]	[20]	This Work
Ant. Size mm ³	3.18 × 4.84 × 0.308	9 × 11 × 0.25	5 × 20.5 × 1.59	4 × 5.8 × 0.16	200 × 50 × 1.6
Freq GHz	60.09	60	60	59.95	5
S11 dB	– 39.27	– 33	– 16	– 36.41	– 14
Gain dBi	8.4	4.8	5.90	9.2	14

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Проектування лінійної антенної решітки методом Дольфа-Чебишева для високого коефіцієнта посилення та зменшення бічних пелюсток у бездротових системах

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У цій статті представлено конструкцію лінійної антенної решітки з використанням методу Дольфа-Чебишева для досягнення високого коефіцієнта посилення та ефективної мінімізації рівнів бічних пелюсток для застосувань Інтернету речей. Запропонований підхід забезпечує баланс між ключовими параметрами, дозволяючи досягти найвужчої ширини променя на заданому рівні бічних пелюсток і навпаки. Існують різні методи для зменшення рівнів бічних пелюсток, тим самим зберігаючи енергію та підвищуючи якість обслуговування. Однак це дослідження зосереджується на 7-елементній решітці, розробленій з використанням методу Дольфа-Чебишева, що пропонує структуроване порівняння діаграм спрямованості на різних рівнях бічних пелюсток. Аналіз показує, що збільшення спрямованості та коефіцієнта посилення не завжди корелює зі зниженням рівнів бічних пелюсток, що підкреслює необхідні компроміси. Для перевірки підходу розроблено мікросмужкову гребінчасту антенну решітку для застосувань Інтернету речей на частоті 5 ГГц, реалізовану на підкладці Rogers RO4003C з розмірами 200 × 50 мм². Решітка досягає коефіцієнта посилення 13 дБі, зберігаючи при цьому рівні бічних пелюсток нижче –18 дБ на частоті 5 ГГц. Результати демонструють придатність цієї конструкції для систем бездротового зв'язку на основі Інтернету речей, забезпечуючи ефективні характеристики випромінювання при збереженні компактного форм-фактора. Це дослідження підкреслює важливість оптимізації параметрів антени для досягнення бажаної продуктивності сучасних бездротових мереж.

Ключові слова: Дольф-Чебишев, П'яте покоління (5G), Застосування Інтернету речей.