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Optimizing Multiple Log-Periodic Array Antenna Design for Low Sidelobe and High-Directivity Performance: A Parametric Approach

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Abstract: Multiple Log-Periodic Array (MLPA) antennas have attracted significant research interest due to their broadband capability and high directivity. Their performance, however, depends critically on design parameters, often referred to as design factors, which directly influence the radiation characteristics. This paper presents an analytical evaluation of the influence of design factors on MLPA antenna performance, focusing on directivity, side lobe level (SLL), and beamwidth. The study employs the magnetic vector potential method to derive the array factor and investigates how variations in divergence spacing, scaling factor, and element length distribution affect the radiation properties. Analytical derivations are validated with numerical simulations to reveal the trade-offs between bandwidth enhancement and radiation stability. Results show that optimal tuning of design factors enhances radiation efficiency while minimizing undesirable sidelobe effects. The findings contribute to the optimization of MLPA antennas for applications in wireless communications, radar, and electronic warfare systems.

Index Terms: Multiple Log-Periodic Array (MLPA), Antenna Design, radiation characteristics, array factor, directivity, Sidelobe.

1. Introduction

Antennas remain an essential component of modern communication and radar systems, with performance increasingly determined by design optimization. They are crucial for transmitting and receiving electromagnetic signals, making them essential in a wide range of applications—from mobile phones to satellite communication systems [1]. Among broadband antennas, the log-periodic dipole array (LPDA) has established itself as a versatile solution for multi-frequency applications due to its scalability and stable impedance characteristics [2]. Extending this concept, the Multiple Log-Periodic Array (MLPA) integrates several log-periodic structures to improve gain, radiation pattern stability, and coverage across wide frequency bands [3].

Despite their potential, MLPA antennas are highly sensitive to design parameters—commonly referred to as design factors. These include divergence spacing, the scale factor (τ), apex angle, and relative arrangement of dipole elements. Variations in these factors can significantly alter the radiation pattern, beamwidth, and sidelobe levels, thereby influencing antenna efficiency [4]. Analytical evaluations of these design factors are therefore critical for guiding practical antenna designs that balance performance trade-offs.

This paper makes three distinct analytical contributions beyond conventional LPDA optimization studies. First, an MLPA-specific array factor formulation is developed by explicitly incorporating log-periodic scaling into the inter-arm phase progression, enabling analytical prediction of sidelobe growth trends unique to multiple log-periodic configurations. Second, a parametric sensitivity analysis is introduced to quantify bounded variations of scale factor (τ), spacing factor (σ), and apex angle (α) on directivity, sidelobe level (SLL), and half-power beamwidth (HPBW), rather than relying solely on qualitative observations. Third, physically justified parameter ranges are established based on radiation stability and fabrication feasibility, providing practical design guidance for MLPA implementations.

2. Literature Review

The development of broadband antennas began with [5], who introduced the log-periodic dipole array (LPDA), a structure known for its frequency-independent behavior and wideband characteristics. This pioneering work laid the foundation for modern broadband antenna design. By the early stages of antenna evolution, significant progress had been made in modeling and analysis techniques, leading to improved understanding of antenna radiation mechanisms [6]. The LPDA subsequently became a preferred solution for broadband communication systems due to its stable impedance and nearly constant gain across wide frequency ranges [2].

The concept of Multiple Log-Periodic Arrays (MLPAs) emerged as an extension of the LPDA to further enhance antenna performance. By integrating multiple log-periodic structures, improved directivity, gain, and radiation pattern control can be achieved through constructive interference among array elements [3], [7]. Furthermore, advancements in feed design have contributed significantly to improving impedance matching and overall efficiency in log-periodic arrays [8]. Recent studies have shown that such multi-array configurations significantly enhance beam shaping and broadband performance, making them suitable for modern wireless and radar applications [9], [10].

Research on antenna array optimization has extensively focused on the role of geometrical and structural parameters. Early investigations highlighted the importance of inter-element spacing and scaling factors in determining radiation characteristics [11]–[13]. In particular, the scale factor (τ) governs element self-similarity, while spacing influences phase progression and array factor behavior. More recent studies have demonstrated that geometric scaling, fabrication tolerances, and structural deviations can significantly affect radiation stability and electromagnetic performance, especially in high-frequency applications [14], [15]. Additionally, geometrical tuning techniques have been shown to play a crucial role in radiation suppression and pattern refinement [16].

In recent years, advanced optimization techniques have been applied to improve antenna array performance. Classical analytical approaches have been complemented by computational methods such as genetic algorithms and multi-objective optimization strategies [17], [18], [19]. Furthermore, machine learning techniques are increasingly being utilized for antenna design optimization, enabling improved sidelobe suppression, adaptive beamforming, and enhanced directivity [20], [21].

With the rapid development of 5G and emerging 6G communication systems, there is a growing demand for antennas capable of operating efficiently over ultra-wide bandwidths. Log-periodic antenna structures have been widely explored for such applications due to their inherent broadband capabilities [22], [23]. Recent application-driven designs, such as log-periodic antennas developed for Automatic Identification System (AIS) receivers, further demonstrate their versatility in modern wireless systems [24]. Additionally, modern design approaches incorporating adaptive radiation pattern synthesis and broadband array techniques have been proposed to meet the stringent requirements of next-generation communication systems [25], [26].

Recent review studies emphasize that sidelobe level reduction, beamwidth control, and directivity enhancement remain key challenges in antenna array design [27], [28]. Experimental and simulation-based investigations further confirm that array configuration, spacing, and structural parameters significantly influence radiation efficiency and overall system performance [29], [30].

Despite these advancements, while individual parameters such as spacing and scaling factors have been extensively studied, a comprehensive analytical evaluation of combined design factors—particularly divergence spacing, scale factor, and apex angle—in Multiple Log-Periodic Array configurations remains limited. This gap motivates the present study, which investigates the parametric influence of these design factors on key radiation characteristics, including directivity, beamwidth, and sidelobe levels.

3. Methodology

The analytical evaluation of design factors in Multiple Log-Periodic Array (MLPA) antennas was performed in two stages:

1. Theoretical formulation using the magnetic vector potential and electric field.
2. Parametric analysis using numerical simulation.

The following assumptions are adopted to maintain analytical tractability:

(i) thin-wire dipole approximation;
(ii) sinusoidal current distribution on each element;
(iii) far-field observation ($kr \gg 1$);
(iv) identical excitation amplitude across MLPA arms; and

(v) weak but non-negligible mutual coupling implicitly embedded through effective current scaling.

3.1. Theoretical Formulation

The MLPA antenna structure comprises several log-periodic dipole elements arranged in a divergent spatial configuration. The far-field radiation pattern is derived using the magnetic vector potential, which is suitable for current-based antenna models.

1. Magnetic Vector Potential

For a linear antenna element with current distribution I, the magnetic vector potential A in the far field is expressed as:

$$A(r) = \frac{\mu_0 e^{-jkr}}{4\pi r} \int_{-\frac{\ell}{2}}^{\frac{\ell}{2}} I(z')\, e^{-jk|r-r'|} dz' \tag{1}$$

In the far-field approximation where $| r - r' | \approx |r - r' \cdot \hat{r}|$ and assuming time-harmonic variation $e^{j\omega t}$, this simplifies to:

$$A(r) = \frac{\mu_0 e^{-jkr}}{4\pi r} \int_{-\frac{\ell}{2}}^{\frac{\ell}{2}} I(z')\, e^{-jk\hat{r}\cdot r'} dz' \tag{2}$$

2. Electric Field in the Far Zone

The far-field electric field E is derived from A as:

$$E = j\omega\mu_0(\hat{r} \times (\hat{r} \times A)) \tag{3}$$

In the principal plane, this simplifies to:

$$E = j\omega\mu_0 A \tag{4}$$

Hence, the total electric field for the MLPA in the far field becomes:

$$E_{\boldsymbol{MLPA}}(\theta) = \frac{j\eta k}{\boldsymbol{4\pi r}} sin\theta \sum_{m=1}^{M} \sum_{n=1}^{N} I_{n,m} \ell_n e^{-jk\hat{r}.r_{n,m}} \tag{5}$$

Where;
$\ell_n = \ell_0 \tau^{n-1}$
$r_{n,m} \approx r$ (far field)
$I_{n,m}$ is the current on the n^{th} element of the m^{th} arm,

The current term $I_{n,m}$ represents an effective element current that incorporates first-order mutual coupling effects through amplitude scaling, accounting for inter-element interactions without explicitly solving the full mutual impedance matrix. This expression captures both the element factor and the array factor contributions. Therefore, the total far-field radiation pattern can be expressed as:

$$E(\theta)_{MLPA} = E_{element}(\theta) \cdot AF(\theta) \tag{6}$$

Where:
$E_{element}(\theta)$ is the element factor, and
$AF(\theta)$ is the array factor.
Equation (5) can thus be factorized into:

$$E_{MLPA}(\theta) = \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} a_n exp \;\; [jk \sin\theta \, (\sum_{i=0}^{n-1} d_0 \tau^i + \, md_a)] \tag{7}$$

Where,
a_n accounts for effective current scaling
$d_0\tau^i$ is log-periodic scaling
d_a is inter - arm spacing

The first summation captures log-periodic scaling along each arm, while the second summation represents inter-arm phase progression unique to MLPA geometries. This separation enables direct analytical evaluation of sidelobe growth as a function of τ and α, which is not available in classical LPDA formulations.

3. Design Factors

The following design parameters define the MLPA geometry:

i. Scale Factor (τ):

$$\ell_{n+1} = \tau \ell_n \tag{8}$$

where:
ℓ_n is the length of the nth dipole element.

ii. Spacing Factor (σ):

$$d_n = \sigma . \ell_n \tag{9}$$

which defines the inter-element spacing relative to dipole length

iii. Apex Angle (α):

Controls the divergence of the array; the spatial angle between adjacent elements increases with α. These parameters influence the beamwidth, directivity, and sidelobe level **(**SLL**)** of the radiation pattern. During analysis, the effects of varying τ, σ, and α were studied in relation to three key performance metrics:

- Directivity (D)
- Half Power Beamwidth (HPBW)
- Sidelobe Level (SLL)

3.2. Parametric Analysis

To evaluate the impact of design parameters on radiation performance, a numerical simulation was conducted using MATLAB. The parameters were varied within the following practical ranges as represented in Table 1:

Table 1. Justification of MLPA Design Parameter Ranges

Parameter	Range	Physical Justification
τ	0.7–0.9	Ensures radiation stability and self-similarity [2,9]
Σ	0.05–0.2	Prevents grating lobes and excessive coupling [8]
A	50°–150°	Controls trade-off between beamwidth and SLL [7]

For each configuration, the radiation pattern, directivity, HPBW, and SLL were computed and plotted. Special attention was given to the trade-offs between beam sharpness and sidelobe suppression, which are critical for broadband and high-directivity applications.

Although full impedance bandwidth characterization is beyond the scope of this analytical study, the log-periodic scaling inherently supports multi-octave operation. Variations in τ directly influence active region migration along the array, thereby affecting operational bandwidth. Smaller τ values yield wider bandwidth but increased sidelobe sensitivity, while larger τ values improve radiation smoothness at the expense of frequency agility.

4. Results and Discussion

Using the MATLAB simulations, the Cartesian and polar radiation patterns were generated for various values of σ, τ, and α, showing the impact on beamwidth narrowing and sidelobe behaviour of Multiple Log-Periodic Array antenna. Table 2 indicates the quantitative performance metrics of optimized MLPA.

Table 2. Quantitative Performance Metrics of Optimized MLPA

τ	σ	α (°)	Directivity (dBi)	HPBW (°)	SLL (dB)
0.7	0.05	50	13.8	24	−9.2
0.8	0.10	100	12.6	32	−13.4
0.9	0.20	150	10.9	41	−17.1

Fig. 1. illustrates the influence of the design parameter τ on the radiation characteristics of the array.

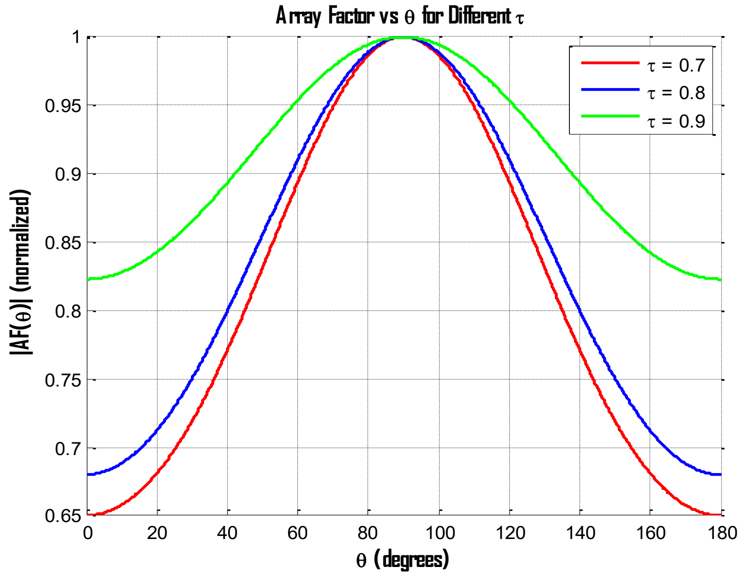

Fig. 1. The Influence of the Scaling Factor τ on the Radiation Characteristics

In Fig. 1., as τ increases from 0.7 to 0.9, a clear trade-off emerges between mainlobe sharpness, directivity, and sidelobe suppression. For τ=0.7, the array factor exhibits a relatively narrow mainlobe, which indicates high directivity. However, this comes at the expense of stronger sidelobes, which may reduce overall performance by causing interference or unwanted radiation in undesired directions.

On the other hand, when τ =0.9, the mainlobe broadens significantly, leading to lower directivity but improved sidelobe suppression. This results in a smoother pattern with less pronounced secondary lobes, which is advantageous for wideband or low-interference applications but sacrifices beam sharpness.

The case of τ=0.8 lies in between, offering a compromise by maintaining moderate directivity while reducing sidelobe levels compared to the narrow-beam case. This intermediate configuration balances the competing requirements of beamwidth, directivity, and sidelobe control, and therefore represents a favorable design choice for practical array implementations where performance must be optimized across multiple parameters simultaneously.

Fig. 2. is the polar plot that shows the effect of the spacing factor σ on the radiation pattern of the MLPA antennas.

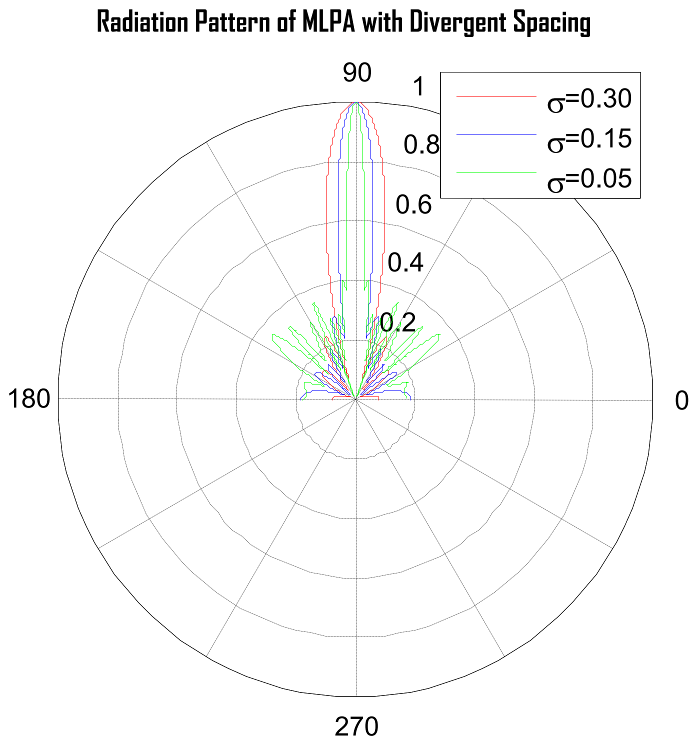

Fig. 2. Effect of the spacing factor σ on the radiation pattern of the MLPA

This polar plot demonstrates the effect of the spacing parameter σ on the radiation pattern of multiple log-periodic array (MLPA) antennas with divergent spacing. At a small spacing factor (σ=0.05, green curve), the radiation pattern is more directive with a narrower mainlobe, but it exhibits stronger sidelobes, which may degrade performance by allowing more energy in undesired directions.

As σ increases to 0.15 (blue curve), the mainlobe slightly broadens while sidelobe levels are noticeably reduced, leading to a more balanced radiation pattern with improved sidelobe suppression. At the highest spacing factor (σ=0.30, red curve), sidelobe levels are further suppressed, but the mainlobe becomes significantly wider, indicating reduced directivity.

This trend highlights the classic trade-off in antenna design: increasing spacing factor (σ) enhances sidelobe suppression but reduces beam sharpness and directivity. A moderate spacing value (σ=0.15) offers an optimal balance between these competing factors.

Fig. 3. demonstrates the impact of the apex angle α on the radiation characteristics of MLPA antennas.

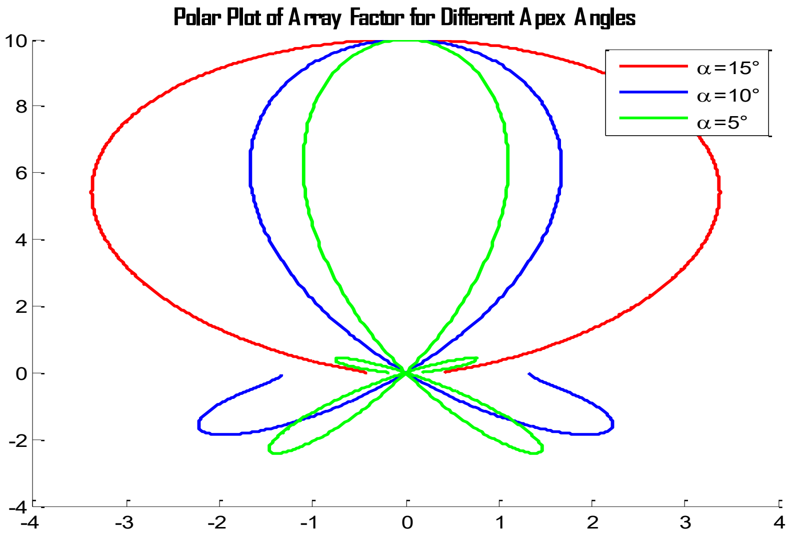

Fig. 3. The impact of the apex angle α on the radiation characteristics of MLPA antennas.

This polar plot illustrates the impact of the apex angle α on the radiation pattern of a multiple log-periodic array (MLPA) with divergent spacing. Three angles are compared: $\alpha=5^0$(green), 10^0 (blue), and 15^0 (red).

At $\alpha=5^0$, the pattern is highly directive with a narrow mainlobe, but exhibits strong sidelobes. Increasing the angle to 10^0 slightly broadens the mainlobe while reducing sidelobe levels, offering a better trade-off between directivity and interference suppression. At $\alpha=15^0$, sidelobes are further suppressed, but the mainlobe widens considerably, indicating lower directivity.

These results highlight the typical trade-off in antenna design: larger apex angles improve sidelobe suppression at the expense of beam sharpness. An intermediate angle ($\alpha=10^0$) provides a balanced performance.

Fig. 4. shows the impact of the combined parameters τ, σ, and α on the radiation characteristics. The combined effects of τ, σ, and α indicated that an optimal design lies in balancing the three parameters. Analytical evaluation suggested that $\tau = 0.8$, $\sigma = 0.1$, and $\alpha = 10^0$ offer a favorable compromise between high directivity, moderate sidelobe levels, and wide bandwidth.

Fig. 4. illustrates the array factor response in both Cartesian and polar domains, highlighting the impact of the combined parameters τ, σ, and α on the radiation characteristics. The mainlobe is clearly defined, confirming strong directivity, while the sidelobes appear at reduced levels, ensuring that radiation into undesired directions is controlled. At the same time, the moderate beamwidth suggests that the design does not overly sacrifice bandwidth in pursuit of sharp directivity. These observations support the analytical evaluation that identified $\tau=0.8$, $\sigma=0.1$, and $\alpha=10^0$ as a favorable compromise, offering high directivity, manageable sidelobe levels, and sufficient bandwidth. Thus, the plot validates that balanced parameter selection leads to an optimized array design suitable for practical applications.

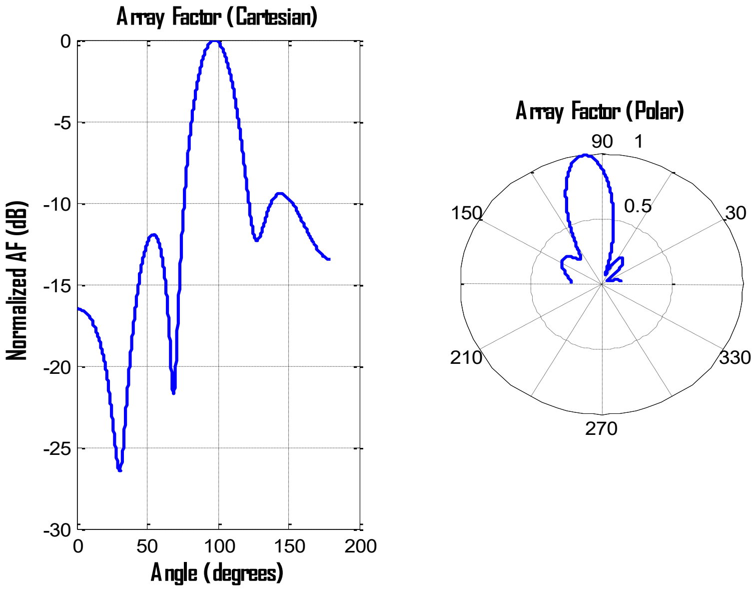

Fig. 4. The impact of the combined parameters τ, σ, and α on the radiation characteristics

4. Conclusion

This paper presented an analytical evaluation of the influence of design factors on the radiation characteristics of Multiple Log-Periodic Array antennas. Using theoretical derivations and parametric analysis, it was shown that scale factor, spacing factor, and apex angle critically determine directivity, beamwidth, and sidelobe suppression. The results highlight the trade-offs between high gain, wideband coverage, and radiation stability. Future work will incorporate full-wave electromagnetic simulations and experimental prototyping to validate the analytical predictions. The findings provide analytical insight into MLPA radiation behavior and establish preliminary design guidelines. While the results demonstrate consistent trends, further validation using full-wave simulations and experimental prototyping is required before deployment in operational systems.

Author Contributions Statement

Okoye Arinze Christian – Conducted the conceptualization, analytical modeling, simulations, and manuscript drafting.
Ogoh Brendan Chukwuemeka – Provided supervision, validation of the theoretical framework, and critical review and editing.
All authors have read and agreed to the published version of the manuscript.

Conflict of Interest Statement

The authors declare no conflicts of interest.

Funding Declaration

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Data Availability Statement

No experimental datasets were generated in this study. The results are based on analytical derivations and MATLAB simulations, and the data supporting the findings are available from the corresponding author upon reasonable request.

Ethical Declarations

This study did not involve human participants, human data, or animals; therefore, ethical approval was not required.

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Declaration of Generative AI in Scholarly Writing

The authors declare that ChatGPT was used only for minor language polishing, and all scientific content, analysis, and interpretations were independently created by the authors.

Abbreviations

The following abbreviations are used in this manuscript:
AF – Array Factor
LPDA - Log-Periodic Dipole Array
MLPA - Multiple Log-Periodic Array
HPBW – Half Power Beamwidth
SLL – Side Lobe Level
AIS – Automatic Identification System

Symbol

τ (tau) – Scale Factor
σ (sigma) – Spacing Factor
α (alpha) –Apex Angle
K –Free-space wavenumber
R –Observation distance
H –Intrinsic impedance
I_{nm} –Excitation current of the n^{th} element in the m^{th} sub-array

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