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Design of adaptive array using least mean square beamformer

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ABSTRACT

This paper introduces an 8-element linear array designed for adaptive array applications, using least mean square (LMS) algorithm to enhance the directivity of the array. Microstrip antenna has been optimized at 2.3 GHz, a pivotal frequency ranges relevant to 4G and 5G applications. This design is thoughtfully extended to encompass 8-elements, achieved through the art of parameterization using computer simulation technology (CST) microwave studio. This geometry of 8-element exhibits considerable promise, significantly elevating the gain from 6.13 dBi for a single element to an impressive 15.5 dBi for all eight-element array. To further empower the array's adaptability and beam-steering capabilities, the LMS algorithm is simulated. This intelligent algorithm computes complex weights, thoughtfully with various angles, including those for the interested user at 60° and 30°, as well as potential interferers at 10° and 15°, as simulated in MATLAB. These meticulously calculated weights are effectively applied to antenna elements using CST, facilitating beam steering in various directions. During CST simulations, notable peaks in performance emerge at 54° and 28°, strategically aligned with nulls at 10° and 15°. Remarkably, these results exhibit a remarkable degree of concurrence with those obtained through MATLAB simulations, affirming effectiveness of the proposed adaptive array design.

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1. INTRODUCTION

Communication system has evolved into an indispensable facet of modern life, facilitating rapid global connectivity. Among the techniques employed to enhance communication systems, the array of antennas stands out, offering diverse advantages, with interference cancellation being a paramount benefit [1], [2]. Adaptive array antennas are built with the assumption that interested signals and undesirable interference arrive from distinct directions. The array's radiation pattern is meticulously tailored through the amalgamation of signals from multiple antennas, each assigned suitable weighting. This approach not only mitigates co-channel interference but also addresses issues such as fading of signal, complexity of the system, bit error rate (BER), and probability of outage [3], [4]. The significance of adaptive antennas and their controlling algorithms in shaping high-capacity communication systems cannot be overstated. Smart antennas, a type of space-domain technique, have gained prominence for their capacity to harness additional system potential within noise-constrained code division multiple access (CDMA) systems, widely utilized in

3G and 4G standards [5]–[7]. These adaptive antenna systems employ dynamic updates of complex weights to attain maxima in the required direction while establishing nulls in the unwanted interferers directions.

The applications of such arrays span a wide spectrum, including commercial wireless systems such as long-term evolution (LTE) and IEEE 802.16, radar for beam scanning, mobile system, satellite system, and multiple-input multiple-output (MIMO) systems [8]–[10]. The benefits of adopting adaptive antenna array beamforming encompass enhancements in mean square error (MSE), signal to interference plus noise ratio (SINR), interference mitigation, counteraction of multipath fading, and directive gain [11]–[13]. This dynamic system ensures that complex weights for all channels are not pre-defined during the design of the array but are computed on the fly, aligning with the specific objectives. However, challenges persist, particularly in the form of blind areas that manifest between adjacent beams, characterized by a sharp drop in gain from the peak region [14]–[16]. Users traversing these zones may experience signal fading and potential call drops, adding complexity to link budget estimations, a less-than-ideal scenario in system design. The primary interest of this paper lies in the proposition of an adaptive array comprising 8-elements. The design and performance analysis of this array are conducted through the utilization of computer simulation technology (CST) simulation Software and MATLAB. Performance factors including reflection coefficient, voltage standing wave ratio (VSWR), and directivity, are meticulously assessed for arrays consisting of 8-elements. Additionally, the beam-scanning capabilities of the 8-element array are evaluated, with weight computation performed using the least mean square (LMS) algorithm in MATLAB software [17]–[19].

To validate the results, the array system undergoes fabrication and experimentation testing, the results of which closely align with the simulation outcomes. The paper unfolds in several sections, commencing with the presentation of the microstrip patch antenna's design and followed by the geometry simulation of 1, 2, 4, and 8 element arrays using CST microwave studio [20], [21]. The subsequent section details testing of the array prototype and the eight-element array results employing a vector network analyzer (VNA). The paper's penultimate section delves into the LMS algorithm applications to calculate complex weights, considering various angles for interested users and interferers during MATLAB simulations, which are then employed to steer the antenna's beam, as illustrated in Figure 1. Finally, the concluding section encapsulates the key findings and insights derived from this comprehensive exploration [22]–[24].

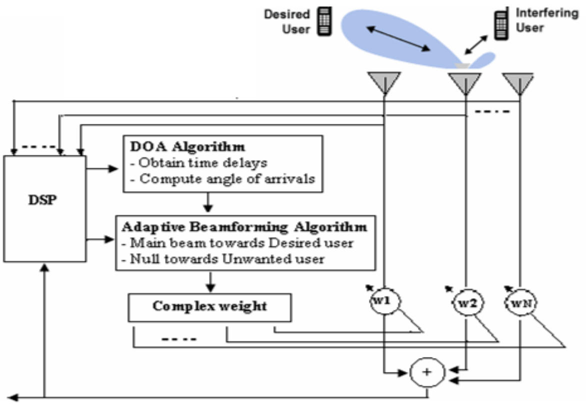

Figure 1. General block diagram of adaptive array antenna

2. ADAPTIVE ARRAY DESIGN

The process of array design commences with the development of a single-element antenna, which is meticulously crafted based on established equations as delineated in [19]–[21]. This initial element takes the form of a microstrip patch antenna, employing the coaxial feed technique. A comprehensive assessment of the antenna's performance parameters, encompassing vital metrics such as s-parameters, reflection coefficient, VSWR, and directivity, is conducted within the vicinity of 2.35 GHz.

Subsequently, this meticulously engineered single-element design serves as the foundational building block for the progression towards more complex array configurations. The expansion unfolds progressively, extending to two-element and four-element arrays before culminating in the development of an eight-element array, each achieved through the versatile capabilities of CST. The substrate material employed in this array's construction is rogers RT/Duroid 5870, characterized with εr=2.33 and thickness of 1.575 mm. The optimized dimensions for the single-element antenna are elaborated in Table 1, serving as the foundational blueprint for the array's geometry. Within the array structure, the spatial arrangement of antenna elements adheres to an inter-element spacing of λ/2, a configuration thoughtfully depicted in Figure 2.

Table 1. Design parameters of antenna

Sr. No	Description	Optimised value
1.	Resonant frequency	2.3 GHz
2.	Patch width	40 mm
3.	Patch length	30 mm
4.	Patch thickness	0.07 mm
5.	Height of substrate	1.57 mm

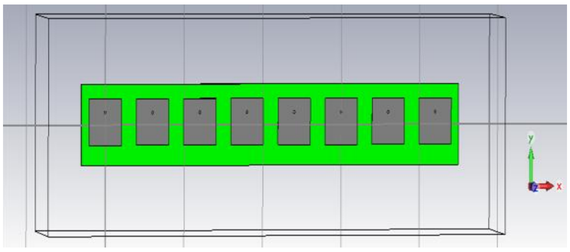

Figure 2. Structure of eight element array antenna

Within a beam-scanning array, the constituent antenna elements spacing is equal, and the maximum electromagnetic energy radiated is intricately intertwined with both the input signal phase and amplitude imparted to these antenna elements. It is noteworthy that the input phase adjustments applied to individual elements profoundly influence the output maxima direction and null direction, while the amplitude controls bestow a distinctive character upon the radiation pattern [25]. If we envisage the array elements arranged along the x-axis, the formation of a radiation characteristics within the xz-plane unfolds as a process in which an adjustable vector of weighting factors, denoted as "W," is multiplication of a spatial vector, symbolized as "A(x)." This relationship is elegantly articulated in (1).

$$P(\theta) = Pe(\theta)Pa(\theta) = \begin{bmatrix} A1e^{j\varphi 1} \\ A2e^{j\varphi 2} \\ . \\ \vdots \\ . \\ Ane^{j\varphi n} \end{bmatrix} \begin{bmatrix} e^{j2\pi\left(\frac{d1}{\lambda}\right)\sin(\theta)} \\ e^{j2\pi\left(\frac{d2}{\lambda}\right)\sin(\theta)} \\ . \\ \vdots \\ . \\ e^{j2\pi\left(\frac{dn}{\lambda}\right)\sin(\theta)} \end{bmatrix} \quad (1)$$

Where, "Pe(θ)" corresponds to the element pattern at a given angular position denoted by "θ" within the xz-plane. This element pattern characterizes the individual antenna element's radiation properties. "Pa(θ)" designates the array factor, which essentially captures the radiation pattern formed by the entire array when considering its response at that specific angular position, θ, within the xz-plane. Each "Ane jΨn" signifies the complex weighting factor assigned to the nth element in the array. These factors, determined by both phase (ψn) and amplitude, play a pivotal role in shaping the radiation characteristics. Lastly, "dn" denotes the distance of the nth element from the central position, influencing the array's overall geometry. Collectively, these elements contribute to the complex interplay of factors that define the array's radiation pattern in the xz-plane.

3. ARRAY SIMULATION

As discussed in the above, we embarked on a comprehensive simulation process encompassing the optimized geometries for both single and eight elements utilizing CST. Our primary focus during this simulation was on vital performance parameters, which encompassed VSWR, reflection coefficient, radiation characteristics, and s-parameters. A detailed breakdown of these simulation outcomes, ranging from a solitary antenna element to an 8-element array, can be perused in the Table 2. The geometric configuration for the eight-element array can be visually comprehended in Figure 1, offering an essential visual reference.

In Figures 3 to 5, we encapsulate the graphical representations of the VSWR, reflection coefficient, and radiation characteristics, respectively, specifically for the 8-element array. It is crucial to highlight that the initial design of the single element antenna adhered to established equations documented in. This foundational design was subsequently honed and expanded to encompass eight elements in the quest for optimal performance parameters. The synthesized results have been meticulously compared and tabulated in Table 2.

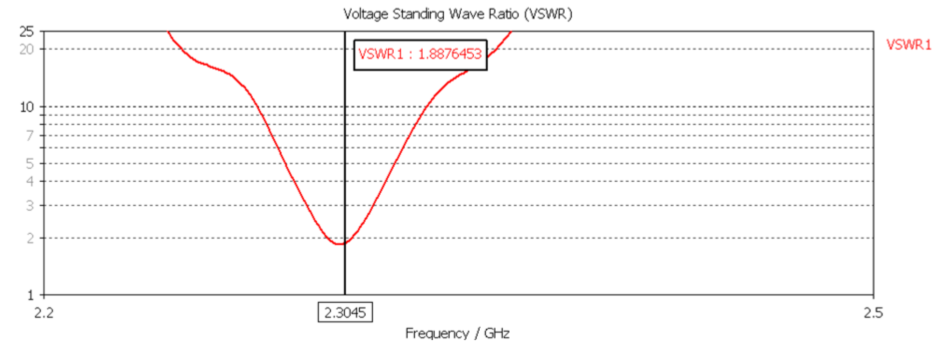

Figure 3. VSWR measurement for 8-element array

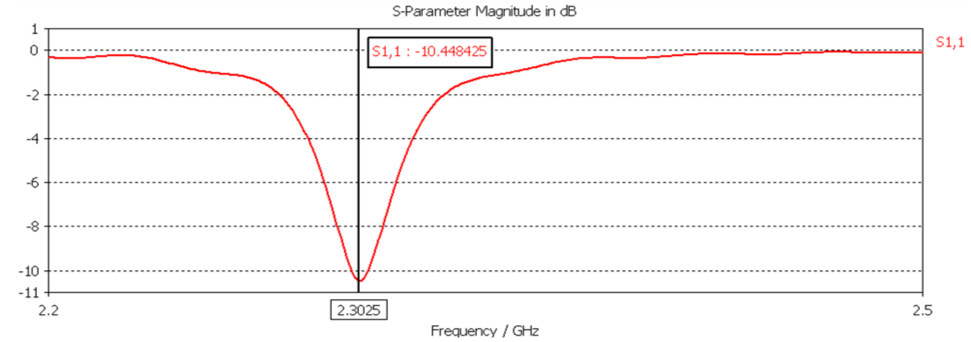

Figure 4. Reflection coefficient measurement for 8-element array

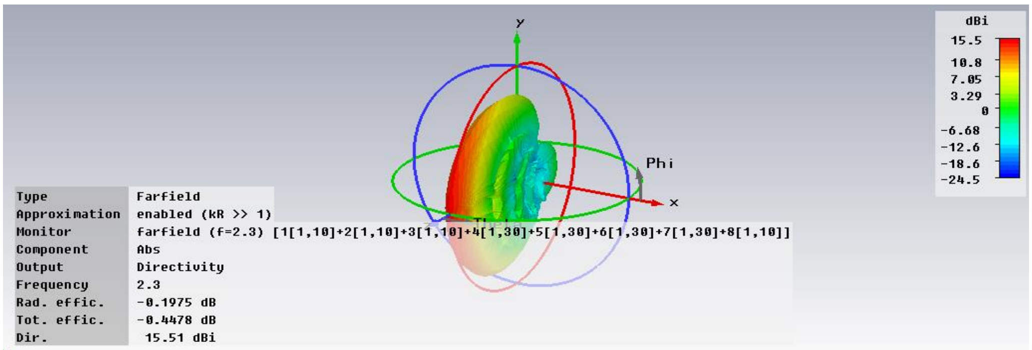

Figure 5. Radiation pattern (3D) with directivity 15.5 dBi

Table 2. The performance of array with different elements

Sr. No	Parameter	Value for single element	Value for two elements	Value for four elements	Value for eight elements
1.	Return loss	-15.47 dB	-20.48 dB	-15.091 dB	-10.44 dB
2.	Reflection coefficient	0.194	0.173	0.243	0.299
3.	VSWR	1.49	1.56	1.88	1.85
4.	Directive gain	6.2 dBi	9.1 dBi	12.7 dBi	15.5 dBi

The discerning observation from these results is that, as the number of elements within the array escalates, there is a noteworthy augmentation in the directive gain of the array. The directive gain exhibits a substantial improvement, advancing from an initial 6.2 dBi for the single element to a remarkable 23.5 dBi for the 8-element array. This gain in directive gain underscores the effectiveness of extending the array. However, it’s worth noting that both return loss and VSWR exhibit an increase commensurate with the element’s number, which is an undesired trend. Nonetheless, these values remain within acceptable ranges, ensuring that the overall performance of the eight-element array remains suitable for the intended application.

4. HARDWARE TESTING AND RESULT DISCUSSION

Antenna arrays serve as a fundamental means to achieve intricate radiation patterns while minimally impacting the antenna impedance characteristics. In the typical scenario, a single antenna element exhibits a relatively broad radiation pattern, which translates to a lower level of directive gain. However, in various array applications, a substantial boost in directive gain becomes imperative [24].

To cater to these practical requirements, enhancing the directive gain entails augmenting the electrical dimensions of the antenna. This enlargement primarily involves increasing the element number within the array structure. By doing so, we effectively steer the antenna system towards the desired high directive gain, aligning it with the specific performance goals sought in various applications.

In line with the designs outlined in the preceding sections, physical implementations of the eight-element array were realized and subjected to rigorous measurements employing a vector analyzer. The front side view of array’s physical manifestation is illustrated in Figure 6, offering a tangible perspective. The measurement results, as highlighted in Figures 7 and 8, have yielded values for reflection coefficient and VSWR. Remarkably, these empirical measurements closely mirror the simulated results, thereby reinforcing the consistency and accuracy of the design and simulation processes.

Figure 6. Hardware for eight element adaptive array antenna using coaxial feeding

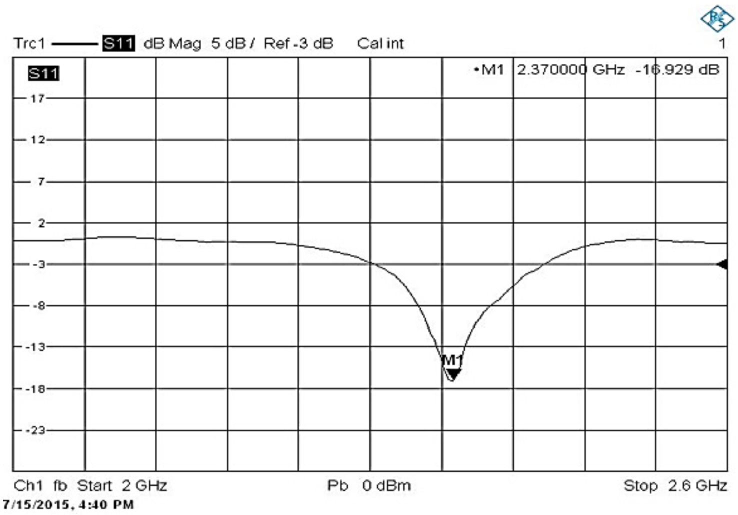

Figure 7. Return loss measurement of array prototype using network analyzer (-16.9 dB)

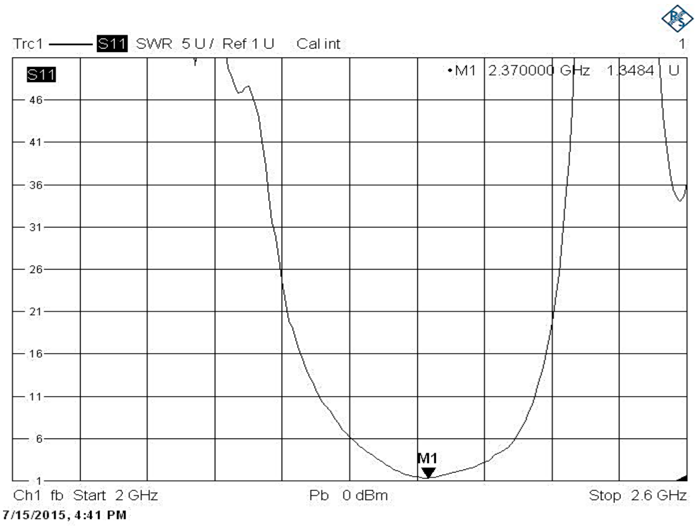

Figure 8. VSWR measurement of array prototype using network analyzer (1.84)

5. LMS ALGORITHM WEIGHT CALCULATION

The pursuit of directivity in an adaptive antenna array hinges on the refinement of the weights applied to each element's excitation signals. The LMS algorithm stands as one of the most popular methods for reducing these complex weights. LMS is rooted in a gradient of error, characterized by a repetitive process which successively adjusts the weights in the opposite direction to the gradient vector, ultimately converging with MSE error at the present real time [25].

The optimal weights after each iteration in the LMS algorithm are determined by the (2),

$$W(n+1) = W(n) - \mu_g(w(n)) \tag{2}$$

here, W(n+1) signifies the recalculated weights at the (n+1) th iteration, with µ being a positive scalar, known as the gradient step size, that governs the convergence properties of the algorithm. The term g(W(n)) represents an unbiased weight estimate for the mean square error gradient. For a given weight w(n), the mean square error is mathematically expressed as in (3),

$$\xi\big(W(n)\big) = E[|r(n+1)|^2] + W^H(n)RW(n) - W^H(n) - Z^H W(n) \tag{3}$$

in (3), r(n+1) is a sample of the required reference signal, and R is the array's matrix for correlation. The gradient of the MSE at the nth iteration can be calculated by taking the derivative of the (3) with respect to w, leading to,

$$\nabla_w\, \xi\ (W)|_{w=w(n)} = 2RW(n) - 2Z \tag{4}$$

during the (n+1) th iteration, the working of the array with the weights w(n) calculated in the previous iteration. However, the array input vector is x(n+1), the sample of reference signal is r (n+1), and therefore the array's output is given as,

$$Y\big(W(n)\big) = W^H(n) * X(n+1) \tag{5}$$

the LMS algorithm uses an estimate of the error gradient by substituting R and Z with their noisy estimates which is available at the (n+1) th iteration, resulting in,

$$g\big(W(n)\big) = 2X(n+1)X^H(n+1)W(n) - 2X(n+1)r^*(n+1) \tag{6}$$

the error, denoted as Ɛ (w (n)), between output of the array and the input reference signal can be defined as;

$$\mathcal{E}\big(W(n)\big) = r(n+1) - W^H(n)X(n+1) \tag{7}$$

hence, from (6), it follows that,

$$g\left(W(n)\right) = -2X(n+1)\mathcal{E}^{*}\left(W(n)\right) \tag{8}$$

as a consequence, the estimated error gradient is the product of the error between output of the array and input reference signal and the array gives signals after the nth iteration. Calculating the conditional expectation on both sides of (6) reveals that the mean of the gradient estimate for a given w(n) becomes,

$$\tilde{g}\left(W(n)\right) = 2RW(n) - 2Z \tag{9}$$

where $g^{\leftharpoonup}\left(W(n)\right)$ signifies the mean of the gradient estimate for a given w(n). In (4) and (9) jointly establish that the gradient estimate is unbiased. Comparatively, the LMS algorithm is characterized by its simplicity. It operates without necessitating matrix inversion [6], yet it is particularly suited for static environments.

The LMS algorithm was implemented through MATLAB for an eight-element array operating at 2.35 GHz. The complex weights obtained from this simulation were subsequently employed to excite the array within CST microwave studio. Notably, the results generated from the CST simulation exhibited remarkable consistency with the findings from the MATLAB simulation. In the MATLAB-based LMS simulation, an initial scenario was considered in which the user was positioned at an angle of 60°, while the interferer was located at 10°. As depicted in Figure 9, a polar plot illustrates that the beam was effectively steered in the direction of the user at 60°, concurrently introducing a null in the direction of the unwanted interferer at 10°.

Transitioning to the CST simulation after implementing the weights calculated by the LMS, the desired user's angle was adjusted to 54° with the interferer persisting at 10°, as demonstrated in Figure 10. The polar plot conveys the beam's directionality towards the user at 54° while maintaining the null towards the interferer at 10°. Figures 11 and 12 showcase parallel outcomes for a different scenario, involving a desired user at 30° and an unwanted interferer at 15°. In the MATLAB-based simulation, the user's angle of 30° results in a beam direction at 28° with a null at 15°. Subsequently, the CST simulation consistently demonstrates a beam peak at 28° and a null at 15°, corroborating the successful beam-steering capabilities of the LMS algorithm. These findings highlight the effectiveness of the LMS algorithm in dynamically controlling the array's radiation pattern to optimize signal reception for the user while mitigating interference from undesired sources, as facilitated by both MATLAB and CST simulations.

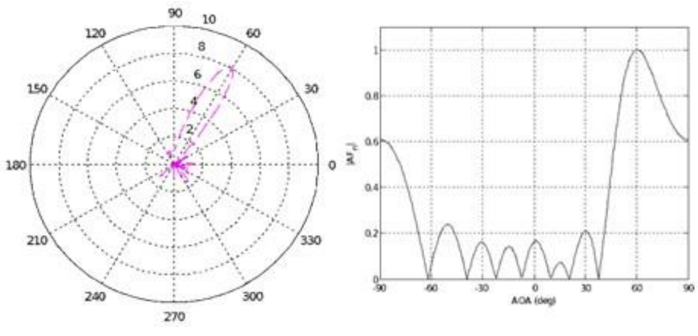

Figure 9. Polar plot (left) and rectangular plot (right) using MATLAB (desired user: 60° and interferer: 10°)

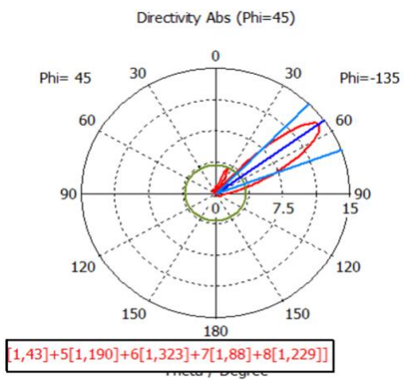

Figure 10. Polar plot obtained using CST (main lobe direction for desired user is 54° and interferer at 10°)

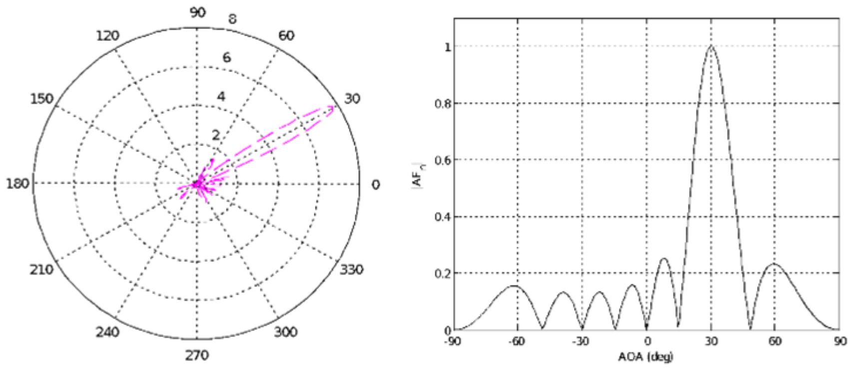

Figure 11. Polar plot (left) and rectangular plot (right) using MATLAB software (desired user is assumed at 30° and unwanted interferer is at 15°)

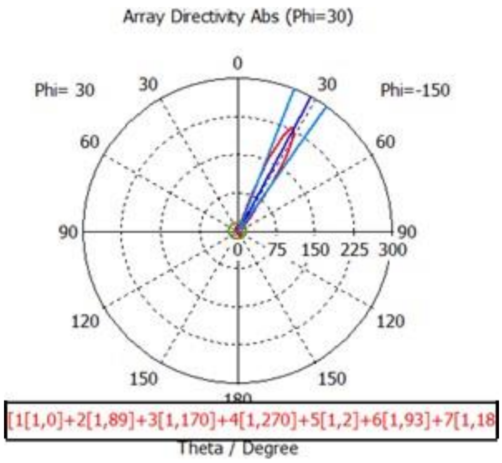

Figure 12. Polar plot obtained using CST (main lobe direction for desired user is 28° and interferer direction is 15°)

6. CONCLUSION AND FUTURE SCOPE

In this paper, we present the design of an antenna array with adaptive capabilities consisting of eight elements operating at 2.35 GHz, tailored for LTE applications. The core objective of this proposed antenna array is to achieve a notably high gain in the direction of the intended user, while concurrently minimizing gain, effectively creating a null in the direction of interfering signals. The performance of this antenna array is rigorously analyzed through CST simulations, with a focus on key metrics like voltage standing wave ratio, reflection coefficient, and directivity. This investigation encompasses scenarios involving one, two, four, and eight antenna elements. It is strikingly evident from the results that as the number of array elements increases, the directive gain exhibits a proportional enhancement, progressing from an initial value of 6.2 dBi to a substantial 15.5 dBi. Moreover, the crucial aspect of beam steering is seamlessly achieved through the estimation of complex weights using the LMS algorithm in MATLAB. These meticulously computed weights are then applied to the individual elements of the array via CST simulations.

The MATLAB-based LMS simulations encompass different scenarios, considering various angles for the user (60° and 30°) and the interferer (10° and 15°). Intriguingly, the CST simulations remarkably mirror the MATLAB results. When simulating the CST beam-steering process, we observed maxima at 54° and 28° for the user angles, while nulls were successfully positioned at 10° and 15°, closely aligning with the findings from MATLAB. This underscores the proficiency of the LMS algorithm in dynamically adapting the array’s radiation pattern to optimize user signal reception and nullify interference from undesired sources. The experimental validation of our design was executed using a VNA, effectively substantiating the credibility of the simulation results. The results obtained from these comprehensive analyses are indeed promising, signifying the suitability of our proposed array design for S-band applications within the 4G and 5G domains. As a glimpse into future research directions, we envision exploring the adaptability of the array to dynamic user and interferer positions, accommodating an increased number of simultaneous users and interferers, and investigating alternative weight estimation algorithms tailored to beam-steering applications. These pursuits hold the potential to further enhance the practical utility and versatility of our adaptive antenna array.

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BIOGRAPHIES OF AUTHORS

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