

Design of Adaptive Array with E-Shape Slot Radiator for Smart Antenna System

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Abstract—This paper presents the design of an 8-element linear array for Adaptive Antenna applications using the Least Mean Square (LMS) algorithm towards improving the directive gain, beam steering capabilities, half-power beam-width, side-lobe level, and bandwidth of array. A conventional patch antenna is optimized to operate at 3.6 GHz (5G applications) with two symmetrical slots and Quarter Wave Transformer for feeding, and this design is extended up to 8 elements using CST Microwave Studio parameterization. The Return Loss (S_{11}), Directivity, HPBW, and VSWR of the antenna array are observed for the 2, 4, and 8 elements adaptive arrays. The inter-element spacing for resulting eight-element antenna array geometry is optimized to obtain maximum directive gain. This geometry appears promising in improving the directive gain from 7.6 dBi to 15.1 dBi for a single element to eight elements, respectively. Further, the LMS algorithm is used to compute the optimal complex weights, considering different angles for the desired User ($+45^\circ$ and -45°) and Interferer ($+20^\circ$ and -20°) during MATLAB simulation, and then these optimal weights are fed to antenna elements using CST for beam steering in a different direction. Maxima in the direction of user and nulls in the direction of interferer are obtained using CST software and found closely matching with MATLAB results.

1. INTRODUCTION

Wireless communication has been found as an integral part of human life where people can communicate anywhere in the globe at a very high speed. An array of antennas may be used in a variety of ways to improve the performance of a communication system [3]. Perhaps the most important is its capability to cancel co-channel interference. An adaptive array works on the assumption that the desired signal and unwanted co-channel interference arrive from different directions. The beam pattern of the array is adjusted to suit the requirements by combining signals from different antennas with appropriate weighting [1]. It also reduces multipath fading, system complexity, cost, BER, and outage probability. It has been argued that adaptive antennas and the algorithms to control them are vital to a high-capacity communication system development [3]. Smart antenna, as one kind of space-domain technique, has attracted much attention since it can exploit additional system capacity in a mature noise-constrained CDMA system, which has been widely applied in all 3G and 4G standards [3].

In a smart antenna system, complex weights are updated automatically in order to generate the maxima in the desired direction and nulls in the direction of interferer as shown in Figure 1. These arrays improve system capacity and find wide usability in many applications like commercial wireless networks such as LTE, IEEE 802.16, Military Radar applications for scanning and beam-forming, mobile communication, satellite communication, and MIMO systems [9]. The benefits of using smart antenna array beam-forming include the improvement of the Mean Square Error (MSE), signal-to-interference-plus-noise ratio (SINR), signal jamming, multipath fading, and directive gain [1]. The term smart

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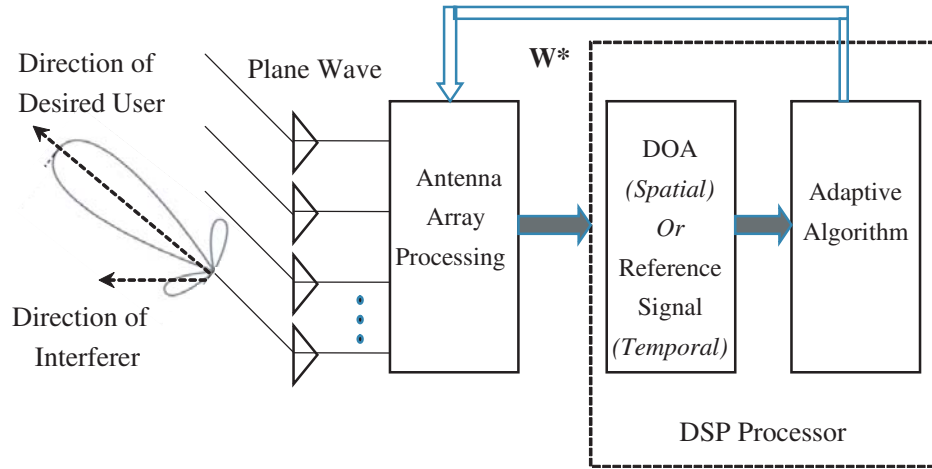


Figure 1. Functional block diagram of adaptive antenna array.

antenna is used for a phased array when the weighting on each element is applied in a dynamic fashion [3]. The weights for each channel are not fixed at the time of the array design, rather those weights are computed by the system dynamically while processing the signal to meet the required objectives [3].

The flexibility of array weighting to be adjusted which specifies the array pattern plays an important role in the system. A blind area exists between adjacent beams where gain drops dramatically from the peak region, thus, the users may suffer from signal fading or even call drops when moving across this region [5]. Also, the variation in these blind areas increases the complexity in link budget estimation, which is undesirable in system design [5].

In this paper, we propose a smart array with 8 elements using CST Microwave Studio. The performance parameters, viz, Return Loss, VSWR (Voltage Standing Wave Ratio), and Directive Gain are observed for single, two, four, and eight elements. Further complex weights computed by the LMS algorithm in MATLAB are fed back into CST to check beam steering capabilities of the adaptive array. This array is tested by assuming the direction of the user and interferer for a few cases. Results obtained from MATLAB are found closely matching with CST simulation results.

This paper is outlined as follows. The design of a single element microstrip slot antenna with improved parameters is presented in Section 2. Section 3 presents the design of the eight-element smart array using CST. Section 4 explains analysis of the LMS algorithm and how to use it for the estimation of complex weights. Section 5 presents how these complex weights, assuming different angles for desired user and interferer can be fed back to antenna elements using CST for testing the beam steering capabilities of the array. Finally, all results are concluded in the last section.

2. DESIGN OF E-SHAPE SLOT ANTENNA

For a beam-steering array, initially, a microstrip patch antenna with two symmetrical slots and a quarter wave transformer for feeding is designed around 3.6 GHz to observe the reflection parameters and radiation pattern. Desired reflection parameters and radiation patterns are obtained from this design, and results satisfy all the objectives and aims of this project. CST Microwave Studio parameterization gives enhanced dimensions as given in Table 1. These dimensions are calculated and optimized using standard equations as given in Eqs. (1)–(5) and can be used for the array design with optimum inter-element spacing to improve the overall directive gain of the array. All simulation results of this device are presented in Figures 2–4, and result analysis is presented in Table 2.

Various performance parameters of the antenna, like Return Loss (S_{11}), VSWR, Directive Gain, Bandwidth, HPBW, and Side Lobe Level (SLL) are evaluated around 3.6 GHz. The substrate material used is FR4 with dielectric constant of 4.3 and thickness (height) 1.6 mm. The first step towards this antenna design is to calculate the length and width of the patch using the following equations [2, 6–8].

Table 1. Desired design specifications.

Sr. No.	Parameter	Value (mm)
1.	L (Length of a patch)	19.4 mm
2.	W (Width of a patch)	25.4 mm
3.	t (Thickness of patch)	0.05 mm
4.	Patch Impedance	243Ω
5.	h (Height of substrate)	1.6 mm
6.	W_f (Width of QWT feed line)	0.534
7.	L_f (Length of QWT feed line)	12.06
8.	QWT Impedance	110.22Ω
9.	Length of Slot	8 mm
10.	Width of Slot	3 mm
11.	L_s (Length of substrate)	60
12.	W_s (Width of substrate)	51

Table 2. Result analysis of compact E-shape antenna element.

Sr. No.	Parameter	Value
1.	Resonant Frequency	3.6 GHz
2.	Return Loss (S_{11})	-26.32 dB
3.	VSWR	1.08
4.	Main Lobe Magnitude	7.6 dBi
5.	Half Power Beam Width (HPBW), E -Plane	78.8°
6.	Side Lobe Level (SLL)	-14.8 dB
7.	Main Lobe Direction	0°
8.	Bandwidth	220 MHz

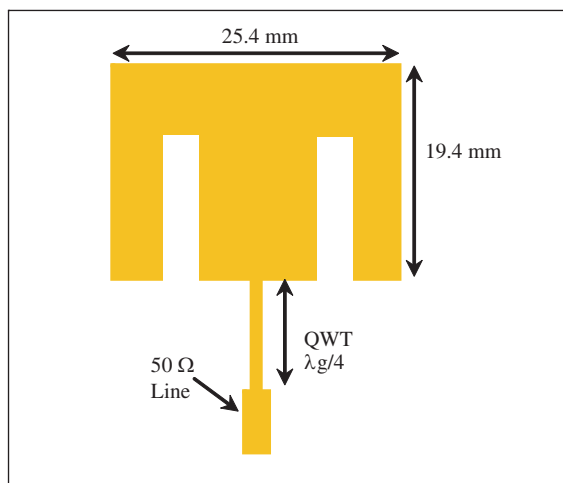


Figure 2. Structure of compact E-Shape single element.

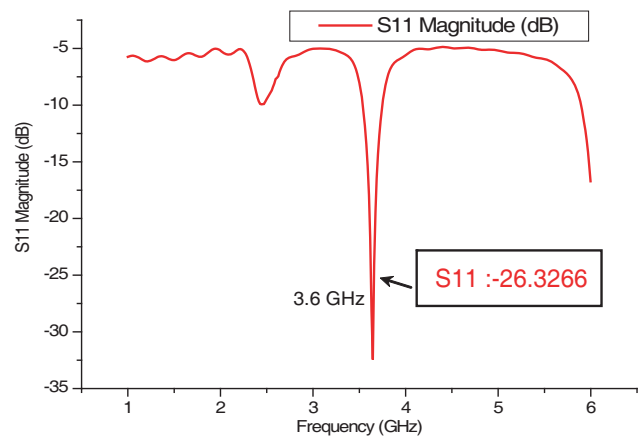


Figure 3. Return loss (S_{11}) measurement, -26.32 dB, at 3.6 GHz.

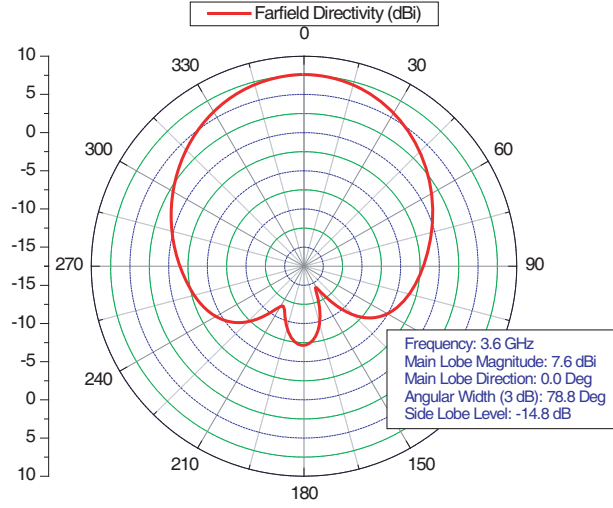


Figure 4. Radiation pattern, E -plane magnitude 7.6 dBi at 3.6 GHz.

2.1. Antenna Patch Width Calculations

The width of microstrip patch can be calculated using

$$w = \frac{c}{2fr} \sqrt{\frac{2}{\epsilon_r + 1}} \quad (1)$$

where c — Speed of light (3×10^8 m/sec); fr — Resonant frequency (3.6 GHz); ϵ_r — Dielectric constant of FR4 (4.3).

2.2. Antenna Patch Length Calculations

For estimation of length, the first step is to calculate effective dielectric constant [2, 6–8], extended incremental and effective length. These calculations are carried out by using Equations (2), (3), and (4) respectively.

$$L_{eff} = L + 2\Delta L = c/(2fr\sqrt{\epsilon_{eff}}) \quad (2)$$

where length L and effective dielectric constant ϵ_{eff} are given by

$$L = \frac{c}{2fr\sqrt{\epsilon_r}} - 2\Delta L \quad (3)$$

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} * \frac{1}{\sqrt{1 + \frac{12h}{w}}} \quad (4)$$

Extended incremental length ΔL due to fringing effect can be found [2, 6–8] using the following equation

$$\Delta L = 0.412 * h \frac{(\epsilon_r f f + 0.3) \left(\frac{w}{h} + 0.264\right)}{(\epsilon_r f f + 0.258) \left(\frac{w}{h} + 0.8\right)} \quad (5)$$

where h = height of substrate (1.6 mm).

Return Loss (S_{11}) obtained for this design is -26.32 dB at 3.6 GHz. The obtained value of VSWR is 1.08 at 3.6 GHz. Radiation Pattern in E -plane is observed, and the Directive Gain is 7.6 dBi at 3.6 GHz. Half Power Beam Width (HPBW) is 78.8° in E -plane. Side Lobe Level (SLL) is -14.8 dB. Main Lobe direction is at 0° which is required for beam steering array and is adjusted with optimization of ground plane dimensions. For proper impedance matching, the feed line is designed using a Quarter Wave Transformer (QWT). The numerical values of all performance parameters are presented in Table 2.

3. SMART ARRAY DESIGN

An antenna array is a mechanism in which we can realize radiation patterns without significantly altering the antenna impedance. Usually, the radiation pattern of a single element is relatively wide and provides the low value of directive gain compared to the array. For many applications, high directive gain is necessary [1].

For practical needs, this is accomplished by increasing the electrical size of the antenna that is by increasing the number of array elements. In a linear beam-steering array, elements are equally spaced, and maximum radiation is a function of phase and amplitude distribution of excitation signal applied to elements. The phase shift applied to each element decides the direction of maxima, and amplitude decides the shape of the radiation pattern. If array elements are placed in the x -axis, a radiation pattern formed in xz -plane can be realized as a fully adjustable weighting factor vector multiplied by a space distribution vector as given in Eq. (6).

$$P(\theta) = Pe(\theta)Pa(\theta) = Pe(\theta) \begin{bmatrix} A_1 e^{j\psi_1} \\ A_2 e^{j\psi_2} \\ \vdots \\ A_n e^{j\psi_n} \end{bmatrix} \begin{bmatrix} e^{j2\pi(\frac{d_1}{\lambda}) \sin(\theta)} \\ e^{j2\pi(\frac{d_2}{\lambda}) \sin(\theta)} \\ \vdots \\ e^{j2\pi(\frac{d_n}{\lambda}) \sin(\theta)} \end{bmatrix} \quad (6)$$

In Equation (1), $Pe(\theta)$ and $Pa(\theta)$ are the element pattern and array factor, respectively, in angular position θ at the xz -plane, and $A_n e^{j\psi_n}$ and d_n represent the n th element complex weighting factor and distance from central position respectively. The geometry of the eight-element smart array is presented in Figure 5 in which all elements are identical with separate excitation ports. Return loss, radiation patterns 3D and 2D are given in Figures 6–8. All performance parameters are obtained around 3.6 GHz. The optimal value for return loss is -23.95 dB, and maximum directive gain obtained is 15.1 dBi as given in Figures 6 and 7, respectively. When the progressive phase shift applied to array elements is zero, the direction of maxima will be in 0° as shown in Figure 8. All optimized performance parameters of the array are presented in Table 3.

Table 3. Result analysis of 8 element adaptive array.

Sr. No.	Parameter	Value
1.	Resonant Frequency	3.6 GHz
2.	Return Loss (S_{11})	-23.95 dB
3.	VSWR	1.39
4.	Main Lobe Magnitude	15.1 dBi
5.	Half Power Beam Width (HPBW), E -Plane	77.3°
6.	Side Lobe Level (SLL)	-13.2 dB
7.	Main Lobe Direction	0°
8.	Bandwidth	160 MHz

4. WEIGHT ESTIMATION FOR BEAM STEERING USING LMS ALGORITHM AND RESULT

The optimal directive gain of adaptive array is determined by the optimality of the weights applied to the individual elements excitation signals. Least Mean Square (LMS) algorithm is one of the most popular algorithms to determine these optimal weights [10–13]. The LMS algorithm is a gradient-based approach, and it incorporates an iterative procedure that makes successive corrections to the weight vector in the direction of the negative of the gradient vector which eventually leads to the minimum mean square error at the current time [10–13].

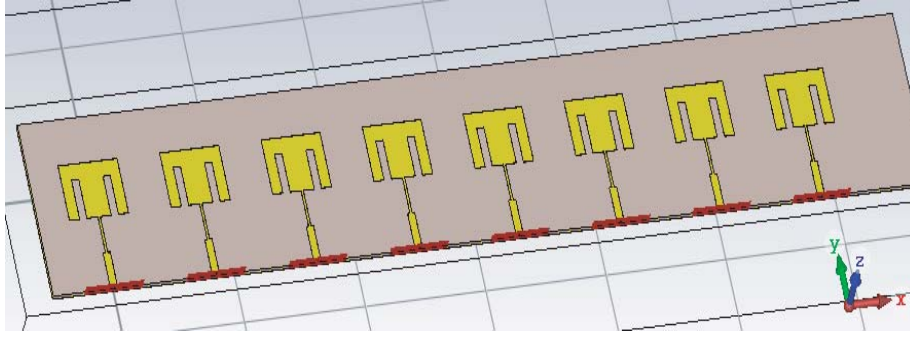


Figure 5. Structure of 8 element adaptive array with separate excitation ports.

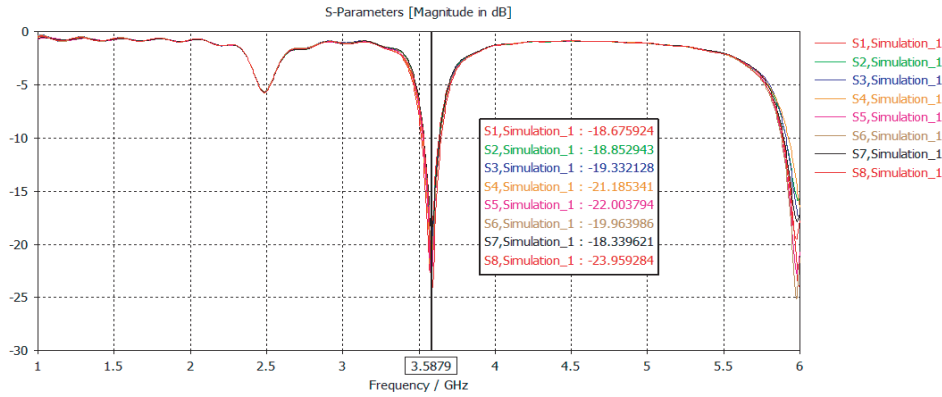


Figure 6. Return loss measurement (−23.95 dB).

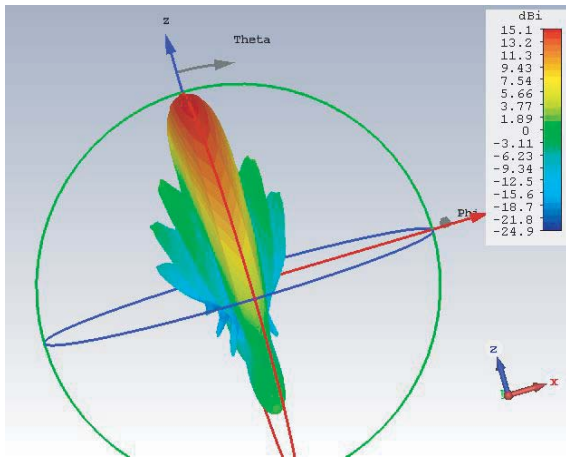


Figure 7. Radiation pattern 3D, directivity 15.1 dBi.

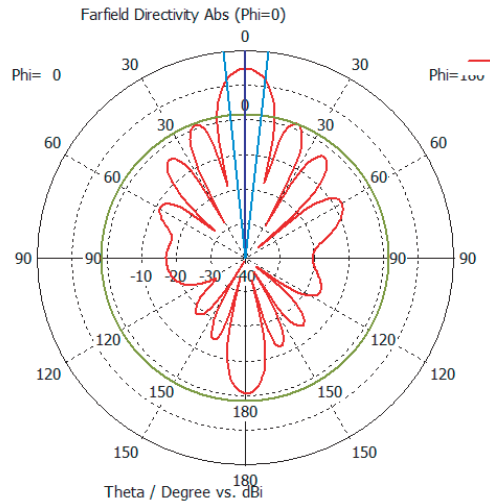


Figure 8. Direction of maxima is at 0°.

In LMS algorithm optimal weight after each iteration is computed using Eq. (7)

$$W(n + 1) = W(n) - \mu_g(W(n)) \tag{7}$$

where $W(n + 1)$ denotes the new weights computed at the $(n + 1)$ th iteration; μ is a positive scalar (gradient step size) that controls the convergence characteristics of the algorithm; and $g(w(n))$ is an

unbiased estimate of the MSE gradient. For a given $w(n)$, the MSE is given by,

$$\xi(W(n)) = E[|r(n+1)|^2] + W^H(n)RW(n) - W^H(n)Z - Z^H W(n) \quad (8)$$

where $r(n+1)$ is a reference signal sample, and R is an array correlation matrix. The MSE gradient at the n th iteration is obtained by differentiating above Equation (8) with respect to w , yielding Equation (9).

$$\nabla_W \xi(W)|_{W=W(n)} = 2RW(n) - 2Z \quad (9)$$

At the $(n+1)$ th iteration, the array operates with weights $w(n)$ computed at the previous iteration; however, the array signal vector is $x(n+1)$; the reference signal sample is $r(n+1)$; and the array output is as given in Equation (10).

$$Y(W(n)) = W^H(n) * X(n+1) \quad (10)$$

LMS algorithm uses an estimate of the gradient by replacing R and z by their noisy estimates available at the $(n+1)$ th iteration, leading to Equation (11).

$$g(W(n)) = 2X(n+1)X^H(n+1)W(n) - 2X(n+1)r^*(n+1) \quad (11)$$

Since the error $\varepsilon(W(n))$ between the array output and reference signal is given by Equation (12)

$$\varepsilon(W(n)) = r(n+1) - W^H(n)X(n+1) \quad (12)$$

It follows from Equation (11) that,

$$g(W(n)) = -2X(n+1)\varepsilon^*(W(n)) \quad (13)$$

Thus, the estimated gradient is a product of the error between the array output and the reference signal and the array signals after the n th iteration as given in Eq. (13). Taking the conditional expectation on both sides of Eq. (11), it can be easily established that the mean of the gradient estimate for a given $w(n)$ becomes as given in Equation (14).

$$\bar{g}(W(n)) = 2RW(n) - 2Z \quad (14)$$

where $\bar{g}(W(n))$ denotes the mean of the gradient estimate for a given $W(n)$. From Eqs. (9) and (14) it follows that the gradient estimate is unbiased. Compared to other LMS algorithm is relatively simple. It does not require correlation function calculation nor does it require matrix inversions [5].

LMS algorithm is simulated using MATLAB for eight elements with 3.6 GHz frequency, and the complex weights created have been used for excitation of the array in the CST Microwave Studio. It has been observed that simulation results for beam steering in CST are almost the same as per the directions assumed in MATLAB. While simulating the LMS algorithm in MATLAB, initially it has been assumed that the user is at $+45^\circ$ and that interferer is at $+20^\circ$. Figure 9 indicates a polar plot using CST, in which the beam is generated in the direction of the user ($+45^\circ$), and null is introduced in the direction of interferer ($+20^\circ$). Then weights are computed by considering user at -45° ($+315^\circ$) and interferer at -20° ($+340^\circ$). Figure 10 indicates the polar plot using CST after feeding complex weights computed by the LMS algorithm for desired user at -45° and interferer at -20° .

In [13], frequency-tuning mechanism is implemented using varactor diodes for a two-element array for single band, and bandwidth obtained is 180 MHz only. This design is optimized for a relative frequency tuning range of 10% extending from 2.15 to 2.38 GHz, and return loss S_{11} is -34 dB. Radiation pattern covers scanning angles from -23° to $+23^\circ$ across broadside with only 9 maxima directions.

Two groups of novel zero-index meta-materials and three metallic strips are introduced, and therefore, a 0.7_1.2 dBi gain enhancement is shown in [14] using two element array. S_{11} and S_{22} are below -10 dB from 45.5 to 49.5 GHz, and the measured gain is all greater than 5 dBi within this single band. Maximum directive gain of the array is 7.2 dBi with 4 maxima only.

The two-element array with complex feed N/W is shown in [15]. In this paper, the core building block is a dual-mode coupler, which operates in two bands around 1.5 GHz and 2.5 GHz. Compared to the proposed array, only six maxima are generated at $+10^\circ$, $+20^\circ$, $+30^\circ$, -10° , -20° , and -30° . Scanning range of this array is only -30° to $+30^\circ$ with return loss -26 dB. Bandwidth is 130 MHz which is also less than the proposed antenna and array. In [16], a 64-element array is designed using Butler Matrix (8×8) based complex feed N/W. Gain for single element is only 3.6 dBi, and Return Loss is -18 dB which is also less than the proposed array. Bandwidth obtained is 2.4 to 2.5 GHz, that

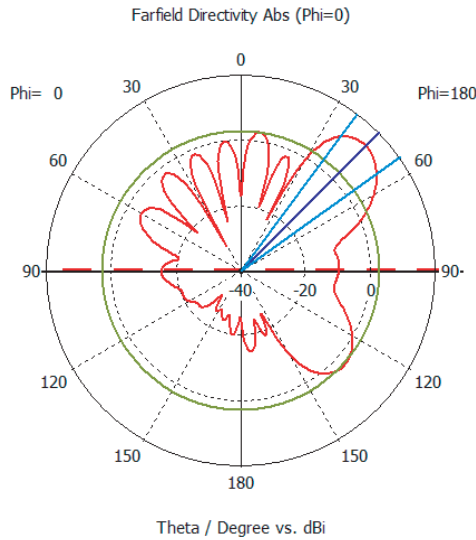


Figure 9. Direction of user at $+45^\circ$ and interferer at $+20^\circ$.

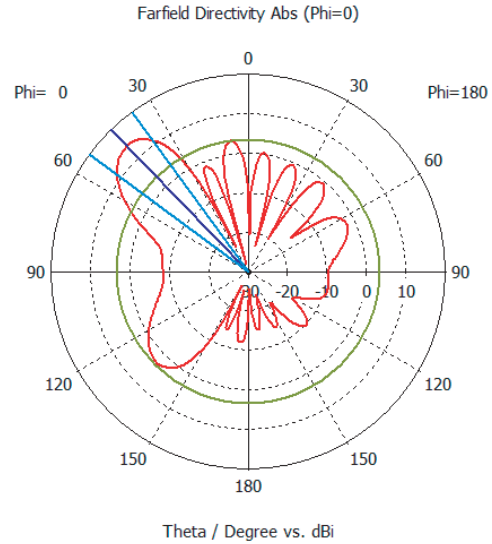


Figure 10. Direction of user at -45° ($+315^\circ$) and interferer at -20° ($+340^\circ$).

is only 100 MHz. Inset feed technique is used. Scanning range is small that is -15° to $+15^\circ$ only. This design is too much complicated compared to the proposed array design. Only six maxima in different directions are possible.

Beam shaping using HDC and delay lines to realize a flat response in its two beams covering regions with less than 0.55 dB fluctuation is presented in [5]. Directive gain obtained is only 11.2 dBi. Length and width for single element is 15.9 mm with feed point at 5.1 mm. Scanning range is limited to -45° to $+45^\circ$. Prototype is built and tested for 5.3 to 5.5 GHz with bandwidth 200 MHz. Side lobe level is also poor compared to the proposed array that is -8.23 dB only. Maxima are possible in only two directions.

In [17], linear array for smart antenna applications at 1.85 GHz with 16 elements is designed using LMS algorithm. Directive gain is only 5.68 dB for single element with bandwidth 120 MHz only. Inter element spacing is 0.9λ , and directivity obtained is 15.2 dBi only. Weights are estimated for $+45^\circ$ and $+30^\circ$ using LMS Algorithm. Side lobe level is also poor that is -9.12 dB. Directions of maxima using CST are at $+40^\circ$ and at $+32^\circ$.

Compared to all above designs of array, the proposed design has improved performance parameters as shown in Tables 2 and 3. Bandwidth of single element is 220 MHz with directive gain 7.6 dBi. Proposed eight-element adaptive array is very efficient, and maxima and nulls are possible at any direction with respective to the direction of user and interferer.

5. CONCLUSION AND FUTURE SCOPE

An adaptive antenna array with eight elements resonating at 3.6 GHz for 5G S-Band Adaptive Antenna applications is proposed in this research work. The proposed antenna array gives a high gain in the desired direction of the user and minima in the direction of the interferer. CST Simulation results are analyzed for VSWR, Return Loss, and Directive Gain with one, two, four, and eight antenna elements. It has been verified that when we increase the array elements, the directive gain also increases from 7.6 dBi to 15.1 dBi.

Optimal beam steering is also achieved by estimating complex weights using the LMS algorithm in MATLAB, and then these weights are applied to array elements using CST. For these MATLAB simulations, two different angles are considered for User ($+45^\circ$ and -45°) and Interferer ($+20^\circ$ and -20°). Maxima are obtained at $+45^\circ$ and -45° whereas Nulls are obtained at $+20^\circ$ and -20° using CST which closely matches MATLAB results.

It has been observed that because of two symmetrical slots added in the original patch, QWT used in feed-line, and proper optimization, Directive Gain of proposed array design is improved compared to [4, 5, 15–17]. The bandwidth of proposed array design is also improved compared to [4, 16, 17].

The obtained results are encouraging and promise their usability for 5G S-Band Adaptive Antenna applications. The future research direction would explore the time-varying user and interferer locations, a number of simultaneous users and interferer, other novel weight estimation algorithms for beam steering applications. In addition to this DSP processor, a complete transceiver chain with standard beam steering algorithms can be used for real-time practical implementation.

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