A NOVEL ALGORITHM DESIGN FOR ADAPTIVE BEAMFORMING IN UNIFORM LINEAR ARRAY ANTENNA

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Abstract

Adaptive antenna systems use advanced adaptive signal processing algorithms to generate main beams in the direction of interest and steer the nulls in the desired direction to reduce interferences from incoming signals. These algorithms are implemented in various applications such as channel equalization, object tracking, system identification and also in Radar systems which uses phased array antenna setup. In phased array radar systems, the noise and interference mitigation is a challenging task. The optimization of these algorithms to generate signals at a faster rate, steering nulls in the unwanted directions thereby improving the signal qualityis very crucial. Few major factors which effect the Adaptive beam forming are complexity, rate of convergence, placing deeper nulls. A novel algorithm is proposed namely Normalized Leaky Variable Step Size-LMS algorithm. The proposed algorithm is applied to a uniform linear array of 8, 12, 16 and 32 elements configurations for different test cases. To demonstrate the efficiency of the proposed algorithm comparison is made with the traditional Least Mean Square, Variable Step Size LMS, and Leaky LMS algorithms. The results show the rate of convergence performance is substantially improved by more than 50% for the proposed algorithm than the existing ones along with providing deeper nulls for interference suppression.

Keywords: Least Mean Square (LMS) algorithm, Variable Step Size LMS algorithm, Leaky LMS algorithm, Null depth, Rate of Convergence

I.   Introduction

The need to maintain the signal characteristics as per the requirement of the end users is of very crucial task for any communication system. Signals need to be operated successfully even when there are interferences from various external sources which make the signals lose their integrity with external factors such as noise

[XVIII],[II],[I],[VIII],[XV]. The performance of the signals tends to degrade as the external sources influence. Wireless communication systems used fixed antenna setup in the earlier days but recently due to the advancement of the adaptive signal processing capabilities the antenna systems are being replaced to Adaptive antenna systems [V], [IX].

Advanced signal processing algorithms are being developed by researchers to target only specific directions while sending the signals and stop the interferences from corrupting the signals using various techniques such that the signal strength doesn't degrade[I], [XIX], [XX]. These algorithms adapt to the signal environment. In modern integrated communication systems there are sub systems where, an adaptive antenna array along with signal processing block is used to generate signals on interest in user specified directions without getting affected by the external sources[XIII],[X].

The process in which the incoming signals are multiplied with complex weight vectors which adjust the magnitude and phase of the signal at each antenna element and summing them to obtain the desired radiation pattern[XIII],[XIV]. The beams are transmitted from the antenna arrays in the desired directions and nulls are placed in the interferences directions to minimize the signal.

The paper organization is as follows. Section 2 briefs about the existing adaptive beamforming algorithms followed by the proposed algorithm in Section 3. In section 4, the simulation results and performance analysis of these algorithms are elaborated. Section 5 gives the conclusion.

II. Adaptive Beamforming Algorithms

In phased array antennas, the process in beamforming is the basic concept of adaptive filtering technique[VI]. The adaptive algorithm is the important component in the adaptive filtering because it can track a signal which is varying and works in an unknown environment. The choice of algorithm selection depends on the application.

The element spacing is maintained at half the wavelength to remove mutual coupling. The beam patterns are changed by controlling the amplitudes and phases at each antenna element, these adaptive arrays are also known as Phased arrays[XXI]. To obtain the desired beam patterns proper selection of amplitudes and phases is needed. The weight coefficient vectors are combination of amplitudes and phases. These are very essential in generating the array output. Hence these adaptive algorithms play a major role in generating optimum weight coefficient vectors which are then supplied to each antenna element in the array. This section discusses the various adaptive algorithms.

Least Mean Square (LMS)Algorithm

Least Mean Square is the simplest and most popular algorithm with less complexity. It follows a gradient based steepest decent approach to calculate the Mean Square Error (MSE). It is an iterative process[XV],[XX],[XVI],[VII].

The array weights are computed as

$$W(n + 1) = W(n) + \mu e^*(n)x(n) \tag{1}$$

where, the step size is given by μ and it should lie between $0 < \mu < \frac{1}{\lambda}$. The largest Eigenvalue of the array correlation matrix is given by λ. For better convergence the step size μ can be taken as shown in below Eq. (2)

$$0 \leq \mu \leq \frac{1}{2\,Tr[R_{xx}]} \tag{2}$$

R_{xx} is the array correlation matrix, it can be formulated as shown in Eq. (3)

$$R_{xx} = x(n)x^H(n) \tag{3}$$

The step size is a constant value. It controls the rate of convergence and stability. Since the convergence rate is directly proportional to the step size parameter μ, smaller the step size slower the convergence rate and larger the step size faster the convergence rate. This is at the cost of instability[XV],[IV]. The main drawback of least mean square algorithm is its convergence speed[III].

Variable Step Size LMS Algorithm

The problem of choosing step size in the standard least mean square algorithm is overcome by varying the step size. The LMS algorithm has a fixed step size, whereas in this the step size is varied as the weight updating takes place[XIX], [XXII].

There is no change in the weight updating equation seen earlier in the standard LMS.

$$W(n + 1) = W(n) + \mu e^*(n)x(n) \tag{4}$$

For updating the step size, two constants are considered α and γ.

where,

$$\mu(n + 1) = \alpha.\mu + \gamma.e(n)^2 \tag{5}$$

In the above equation α (0 <α>1) and γ (γ > 1) are constants. The step size $\mu(n + 1)$ is limited by μ_{max} and μ_{min}. The maximum possible rate of convergence is selected by the value of μ_{max}. The value of μ_{min} is selected depending on the desired level of steady-state misadjustment.

Leaky LMS Algorithm

Leaky LMS algorithm is a variant of least mean square algorithm. The higher Eigen values poses a drawback in the LMS algorithm as it takes longer time to converge which in turn slows down the complete system. A leakage factor ψ is introduced to solve the drifting problem caused by the non-ideal conditions and improve the rate of convergence[XVII], [XI], [XII]. The weights are updated at each iteration with the following equation.

$$W(n + 1) = (1 - \mu\psi) * W(n) + \mu e^*(n)x(n) \tag{6}$$

where, μ is the step size and leakage factor is ψ, which is considered to be very less (ψ =0.001). Since the Eigen spread of Leaky LMS is less than LMS it converges

quickly. The leakage factor is considered to be minimal because the higher the value higher the error and the algorithm doesn't converge.

III. Proposed Algorithm

This section introduces a novel algorithm namely Normalized Leaky Variable Step Size-LMS algorithm designed for adaptive beamforming in adaptive antenna systems which are a part of communication systems. The optimized weightsvector are assigned to each antenna element in the uniformly linear array antenna such that they generate main beam towards the direction of interest and nulls are steered in the direction of interferences. In Fig. 1 the block diagram of the adaptive antenna system where the proposed algorithm is implemented for a uniform linear antenna array configuration as shown. The output is represented by $y(n)$.

The resultant array output $y(n)$ is the summation of the product between the weight coefficients (phase and amplitude coefficients) at the each antenna element and the incoming input signal $x(n)$[XXIII].

$$y(n) = w_N^H . x(n) \qquad (7)$$

The weights are given by $w = \{w_1, w_2, w_3 \dots \dots \dots w_N\}$, the optimum weights vectors w are selected such that suppression of the noise signals or interference like clutter or jammer will take place[XVIII]. H denotes the Hermitian transpose (complex conjugate). The input signal is given as $x(n) = \{x_1, x_2, x_3 \dots \dots \dots x_N\}$.

The problem definition is to find the optimum weight vectors to suppress the interferences by placing deeper nulls and converge at a faster rate to produce the desired radiation pattern. This is possible by modifying the weight equation as given in Eq. (8)

$$w(n + 1) = (1 - \mu \, \psi) * w(n) + \left[\frac{\mu}{\lfloor \|x(n)\|^2} \right] . sgn\{e^*(n)\}. sgn\{x(n)\} \qquad (8)$$

where, $sgn\{x(n)\}$ the signum function of input is given as

$$sgn\{x(n)\} = \begin{cases} +1 & x(n) > 0; \\ 0 & x(n) = 0; \\ -1 & x(n) < 0; \end{cases} \qquad (9)$$

The step size is μ and leakage factor is ψ, which is considered to be very less ($\psi = 0.001$).

The desired signal is denoted by $s(n)$. $e(n)$ denotes the error signal. The difference between the output signal $y(n)$ and $s(n)$ gives the error signal $e(n)$.

$$e(n) = s(n) - y(n) \qquad (10)$$

These are necessary to calculate the weight coefficients in Eq.(8). The error signal is quantized with the Signum function in Eq. (8). This helps to accelerate the rate of convergence.
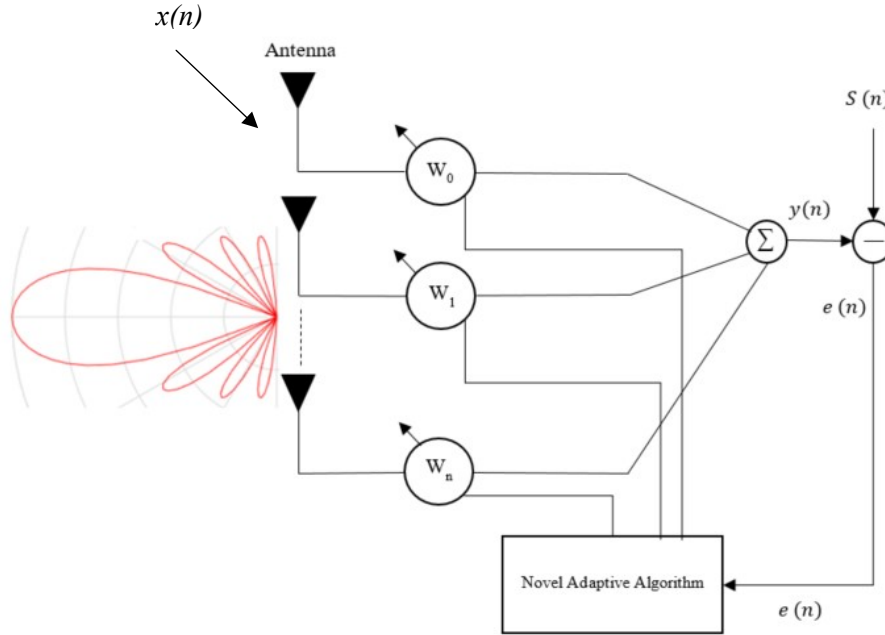
Fig. 1: Proposed Adaptive antenna system

A uniform linear antenna array configuration is considered for the proposed adaptive antenna system. The array factor for the linear antenna array with uniform spacingis given by [II]

$$AF\ (\theta) = \sum_{n=1}^{N} W_n e^{j(n-1)kdco} \tag{11}$$

In the Eq. (11), N denotes the number of antenna array elements. Angle of incidence of interference signal is given by θ. The *w*eight coefficient is given by W. λ is the wavelength and wave number $(2\pi/\lambda)$ is k.

IV. Simulation Results

In this paper, the focus is on the performance analysis of proposed algorithm along with LMS, Variable step size LMS and Leaky LMS. Emphasis is made on two criteria rate of convergence and producing deeper nulls. All the simulation results are implemented in MATLAB 2019b under windows 10 environment on the same PC equipped with 2.5 GHz Intel core (TM) i7-6500U and 8 GB RAM. The simulation parameters considered are given in Table1.

Table1:Simulation parameters

S. No	Parameters	Values
1.	Antenna array configuration	ULA
2.	Total no. of antenna elements	8, 12, 16, 32
3.	Inter-element spacing (d)	$\lambda/2$
4.	Direction of desired signal	90^0
5.	Direction of interference	40^0
6.	Step size (μ)	$0 < \mu < 1$

A.   Rate of Convergence Analysis

In the following section, the rate of convergence analysis is performed for the earlier mentioned adaptive algorithms with the suitable parameters given in Table 1.The convergence behavior of an adaptive algorithm is described by mean square error. The mean square error is plotted against the total number of iterations to find out the rate of convergence. For each iteration, the weight is estimated by the given weight equation for the specific algorithm and the mean square error is computed. The mean square error are shown in Fig 2- Fig 5 for various ULA configurations.

Rate of convergence for 8-element uniform linear array is shown in Fig 2. It can be seen that for LMS and leaky LMS the algorithm converges after 62 iterations whereas for VSS-LMS it takes more than 150 iterations. The optimal weights are obtained after 27 iterations for the proposed algorithm.
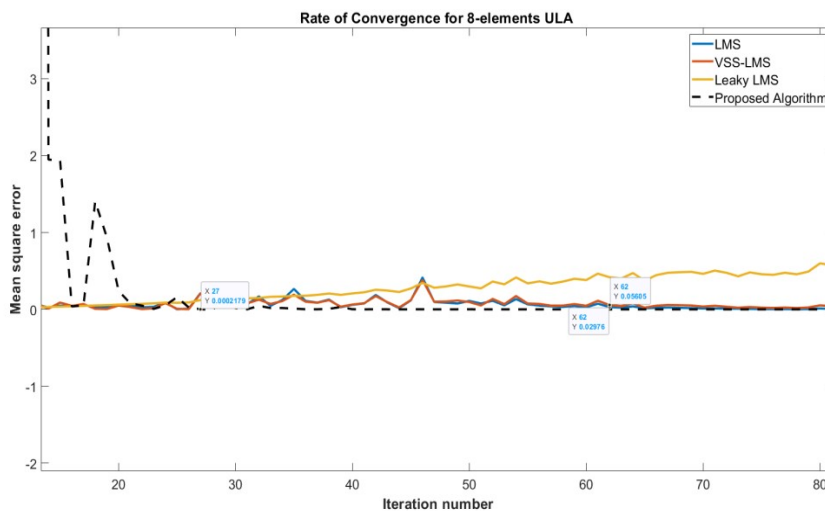

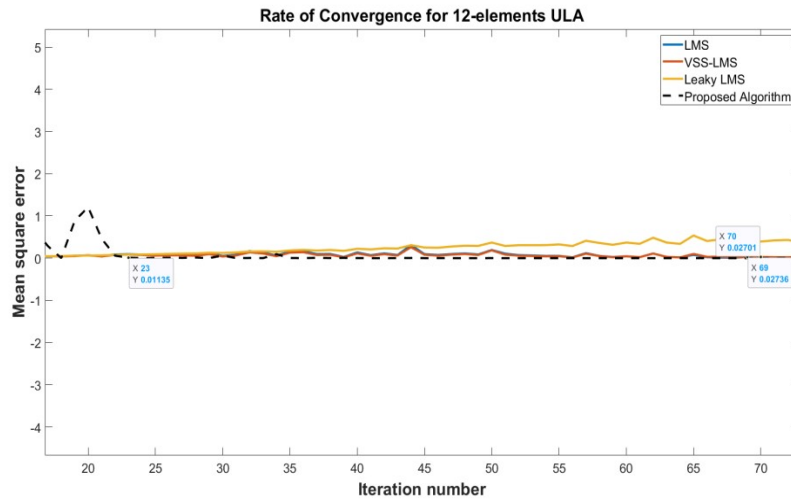**Fig.2:**Mean square error vs Iteration number for 8-element ULA

Fig.3: Mean square error vs Iteration number for 12-element ULA

Fig 3.Shows the rate of convergence for 12-element ULA. It is seen that both LMS and leaky LMS converges after 62 iterations. The proposed algorithm was able to converge after 23 iterations. VSS-LMS algorithm was taking more than 150 iterations.
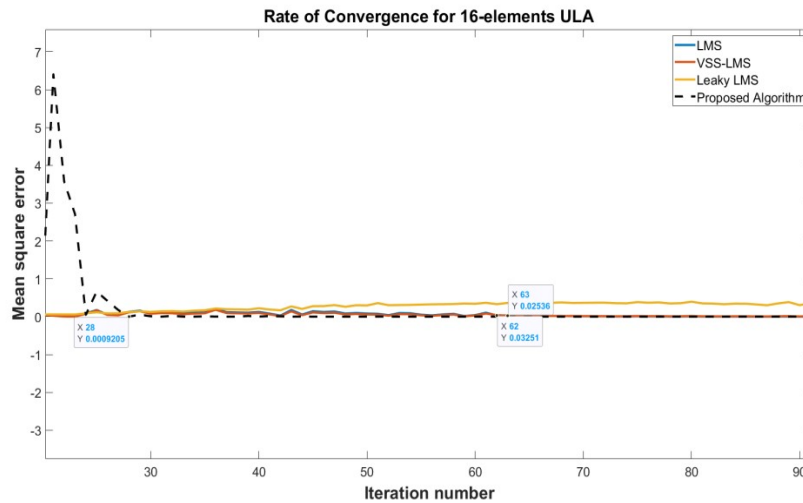

Fig. 4: Mean square error vs Iteration number for 16-element ULA

Fig 4 and Fig 5 are the simulation results of the rate of convergence for 16 and 32 elements ULA respectively. For 16 elements, the LMS and leaky LMS were converging around 62 and 63. The better performing proposed algorithm converged at 28 iterations. In the case of 32 elements the proposed algorithm converged at 15 iterations. LMS and leaky LMS converged at 55 and 42 iterations. In both the cases the VSS-LMS took more than 150 iterations.
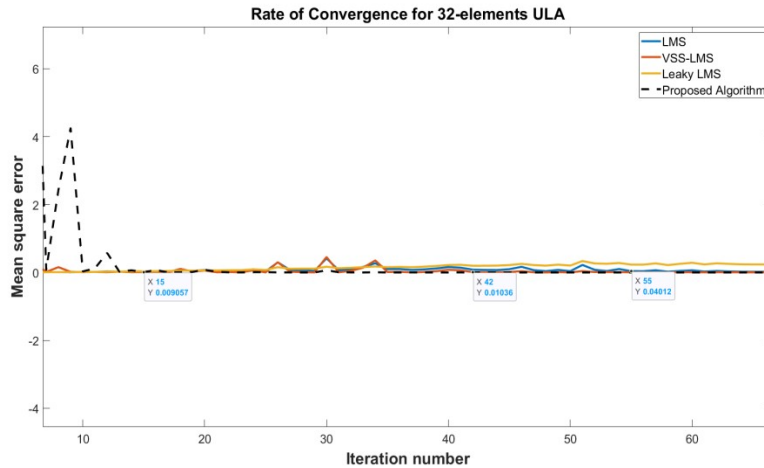
Fig. 5: Mean square error vs. Iteration number for 32-element ULA

Table 2 shows the rate of convergence analysis of the adaptive beamforming algorithms. It is seen that the proposed algorithm out performs the existing algorithms by taking significantly less amount of time to converge.

Table 2: Performance comparison of rate of convergence

ALGORITHM	TOTAL NUMBER OF ITERATIONS			
	8-Elements	12-Elements	16-Elements	32-Elements
LMS	62	62	63	55
VSS-LMS	More than 150 iterations observed in all the cases			
Leaky LMS	62	62	62	42
Proposed Algorithm	27	23	28	15
Percentage of improvement**	56.45	62.90	54.83	64.28

*** Proposed algorithm compared to Leaky LMS algorithm*

Table 2 also gives the percentage improvement comparison of the rate of convergence. The proposed algorithm shows a major improvement in the performance of converging at a faster rate when compared to the advanced Leaky least mean square algorithm. For the 8-element configuration the percentage improvement is 56.45%. In 12-element configuration 62.90% percentage improvement is observed. The percentage improvement of 54.88% is observed in 16-elements and 64.28% is seen for 32-element configuration. This is because of the modified weight update equation in the proposed algorithm. Among the algorithms mentioned, VSS-LMS take more than 150 iterations to converge in all the cases.

B.   Radiation Pattern Showing the Deeper Nulls

Radiation pattern is a graphical or mathematical representation of the power radiated from the antenna. The radiation pattern is plotted for normalized array factor against the direction of the signals. The radiation pattern helps in understanding where exactly the main beam is directed, directions where the nulls are formed in order to suppress the interferences.

Fig6 shows the radiation pattern for 8-elements ULA, in this the null depths are being analyzed. The deeper the nulls, better scope of reducing the interferences. The null depth obtained for LMS is -62.31 dB, VSS-LMS is around -47.68 dB, Leaky LMS is -52.73 dB and the best null depth obtained is for the proposed algorithm at -67.73 dB.
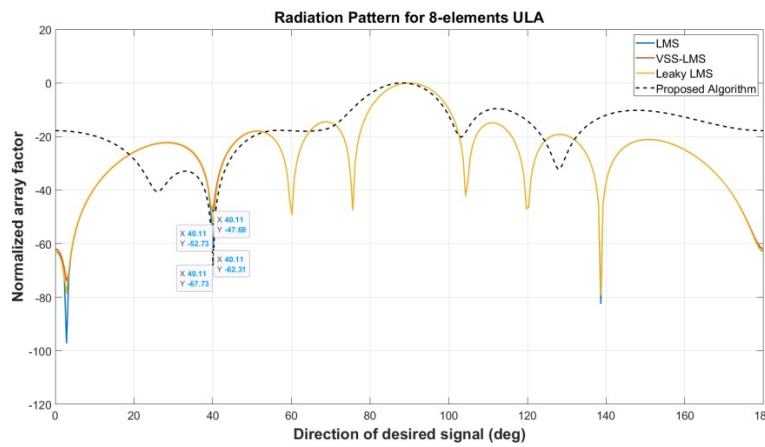

Fig. 6: Radiation pattern with deep nulls at 40^0 with N = 8
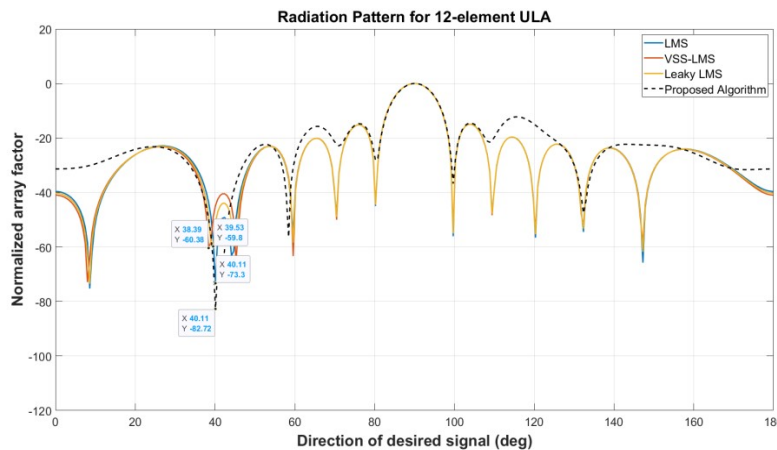

Fig. 7: Radiation pattern with deep nulls at 40^0 with N = 12

In Fig 7 shows the radiation pattern for 12-elements ULA is considered. The null depth obtained for LMS is -73.30 dB, VSS-LMS is around -60.38 dB, Leaky LMS is -59.80 dB and the best null depth obtained is for the proposed algorithm at -82.72 dB.
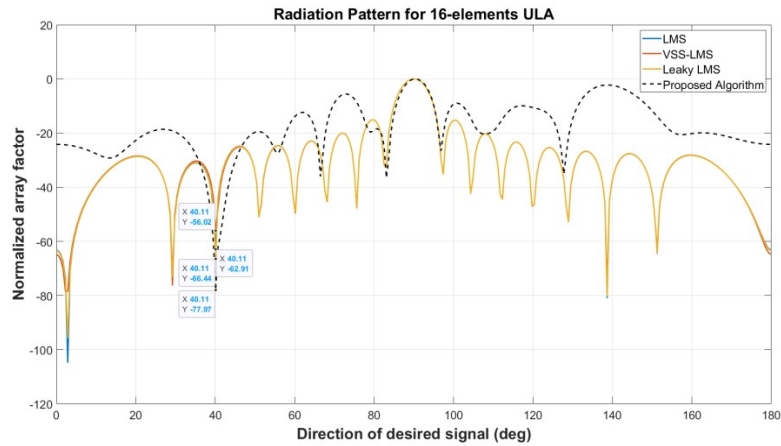
Fig. 8: Radiation pattern with deep nulls at 40^0 with N = 16

Fig 8 shows the radiation pattern for 16-elements ULA. The null depth obtained for LMS is -62.91 dB, VSS-LMS is around -56.02 dB, Leaky LMS is -66.44 dB and the best null depth obtained is for the proposed algorithm at -77.97 dB.
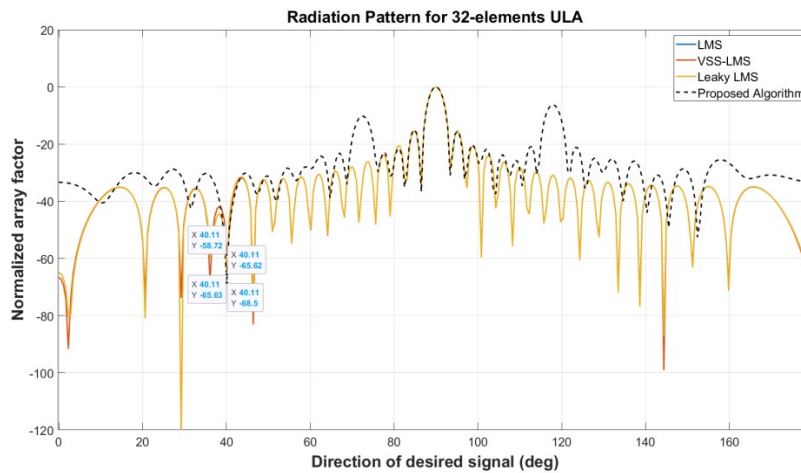

Fig. 9: Radiation pattern with deep nulls at 40^0 with N = 32

Fig 9illustrates the radiation pattern for 32-elements Uniform linear array. The null depth obtained for LMS is -65.63 dB, VSS-LMS is around -58.72 dB, Leaky LMS is -65.62 dB and the best null depth obtained is for the proposed algorithm at -68.50 dB.

V.   Conclusion

A novel adaptive beamforming algorithm is developed in this paper. In the simulation experiments the two major criteria are focused, the rate of convergence and deeper nulls in the directions of interferences. The performance analysis is carried out for four configurations of a uniform linear array antenna. The results obtained clearly show that the proposed algorithm converges at a faster rate with placing deeper nulls to mitigate the interference signals than the existing LMS,

Variable step size LMS and Leaky LMS algorithms. It is observed that there is more than 50% improvement in the convergence rate for the proposed algorithm with the existing algorithms in all uniform linear array configurations considered.

VI. Acknowledgment

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