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Algorithm for Suppression of Wideband Probing in Adaptive Array with Multiple Desired Signals

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ABSTRACT

The integrity of signal environment for a navigation system among other factors depends critically on the capability of the adaptive antenna array in controlling (reconfiguring) its radiation pattern for various signal scenarios. For a signal environment consisting of simultaneous multiple desired signals and probing sources, the output signal-to-noise ratio of the adaptive antenna array depends on the efficiency of the adaptive algorithm employed for weight estimation. Sufficient antenna gain is required to be maintained towards each of the desired signals, while simultaneously suppressing returns towards the sources probing from distinctly different directions. The weight estimation for the multiple desired signal environments is carried out using a novel modified version of the improved least mean square (LMS) algorithm. This modified scheme effectively suppresses the narrowband/wideband probing towards the antenna array (linear/planar). The weight estimation and the steering vector are adapted according to the multiple desired signal environments. Each spectral line of the wideband source is considered as an independent narrowband source. This is incorporated in the correlation matrix of the received signal. The simulation results demonstrate the efficacy of this novel algorithm in active cancellation of narrowband/wideband probing sources, even while the simultaneous multiple signals in desired directions are maintained. The performance of the proposed algorithm is reported to be better than that of standard LMS and recursive LMS algorithm.

Keywords: Adaptive antenna array, desired signals, improved LMS algorithm, probing source, suppression

1. INTRODUCTION

The need to maintain the integrity of the signal environment for any navigation system is of utmost importance. One of its aspects is the requirement to operate successfully even when interference from external sources tends to make the reception difficult. These interferences contribute to the noise floor of the receiver and degrade its performance. An adaptive antenna array is one of the sub-systems of an integrated modern avionic system. It consists of a multi-sector antenna array with an integral signal processing capability to optimise the radiation pattern automatically. Such antenna arrays, if used in satellite navigation systems, offer advanced capabilities to overcome interference at the expense of size, cost and manufacturing complexity. These are mostly used in military applications to combat intentional interference by shaping the antenna radiation pattern and placing nulls in the direction of interference. Such antennas are commonly known as controlled radiation pattern arrays (CRPAs), due to their ability to control their radiation patterns as a function of the interference threats.

The antenna array technology in general, is computationally intensive and the currently available devices are costly, besides being power-intensive. The potential of adaptive array processing has been established, yet it is not clear whether the adaptive array approach is compatible with cost factor for commercial avionics applications. This cost factor includes not only the cost of the equipment, but also installation, maintenance, as well as volume, weight and power consumption constraints. However, it is expected that the continual improvements in device technology have the potential of low power consumption and cost modules in the near future.

In a steered-beam adaptive array, for a single desired signal, steering weights are chosen such that the main beam of the quiescent pattern (pattern without any probing source) points in the direction of the desired signal[1]. However when there are simultaneous multiple desired signals, the quiescent pattern has independent multiple beams towards each of the desired directions[2]. To maximise output signal-to-noise ratio of the received signals, many weight adaptation algorithms like least mean square (LMS), recursive least square (RLS), etc. are, in general, employed to generate the reference pattern. Its generation is one of the difficult tasks to accomplish especially when there are multiple desired signals from different directions[3].

Another important fact is that in an optimum beam former, the output from each array sensor is combined as a weight vector to pass a desired signal without any distortion, thereby maximising the attenuation of the probing sources[4]. However, performance of such optimum beam formers degrades drastically in the presence of wideband sources.

Present study explores the suppression capabilities of adaptive antenna arrays for wideband probing sources even

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in the presence of multiple desired signals. When the antenna array receives multiple sources simultaneously, its pattern should have main lobes towards each of the sources. The point constraints are imposed to the weight updating equation so that both the number and directions of the main lobes should correspond to the desired signals. Using the concept of improved LMS algorithm[5], the expressions for steering vectors, projection vectors, and weight estimation are derived for the present requirement. This improved LMS algorithm provides the optimal weight coefficients from which the desired adapted pattern is obtained. Further, the correlation matrix is calculated considering the spectral distribution of the incident sources. It is based on the concept of considering each spectral line as a single narrowband source. This modifies the weight coefficients accordingly, leading to the suppression of a wideband probing source in the adapted pattern.

The simulations were carried out for the active cancellation of (narrowband/wideband) hostile sources probing a uniform linear/planar antenna array. Results for both linear and planar antenna arrays demonstrate the efficacy of the improved LMS algorithm in active cancellation of the probing effect even when simultaneous multiple desired signals are required.

2. WEIGHT ESTIMATION USING IMPROVED LMS ALGORITHM

In adaptive array processing, selective gains and nulls are placed towards the directions of the signals and probing sources, respectively. To adjust the weights fed to the antenna elements, so as to get the desired response towards the signals impinging the antenna array, various adaptive algorithms are being used. The LMS algorithm is one of the common examples. This algorithm works on the principle of iterative calculation of weights. The optimum values of weights are determined to minimise the mean output noise power. The auto-correlation matrix (ACM) is constrained to have Toeplitz structure.

The improved LMS algorithm is the algorithm in which the gradient is not only estimated from ACM, but it also uses all the previously available samples for updating the weights of array[5]. The recursive LMS is another example of such an algorithm. On the other hand, in the standard LMS algorithm, only one latest sample is used for updating the weights. The recursive algorithm can be used for array of arbitrary geometry. The improved LMS algorithm exploits the structure of ACM for an array, and hence, it can be used only for uniform arrays. Recursive least squares (RLS) algorithm uses a least-square method to estimate the covariance and cross-correlation matrix while the various other forms of LMS algorithms use the statistical mean squared approach. On comparing the performance of various algorithms[5], it can be demonstrated that the improved LMS algorithm has lower output noise power than the RLS algorithm for strong input signals.

Figure 1 shows the output noise power for a 10-element uniform linear array with λ/2 spacing between the elements. The simulation results are presented for the case of two probing sources from two distinct directions (72°, 100; 98°, 1) and one desired signal having power ratio of 100. The power levels of the probing sources are different (100 and 1). It is apparent that the improved LMS has better performance as compared to RLS, and the standard LMS algorithm, both in terms of output noise power level and the convergence rate. Moreover, the improved LMS algorithm has better weight covariance properties than the standard LMS. The performance of improved LMS is found to be better as the signal power is increased. In the presence of a very strong signal, such as 30 dB more than the uncorrelated noise, it performs far better than the RLS algorithm, both in terms of convergence and output noise power.

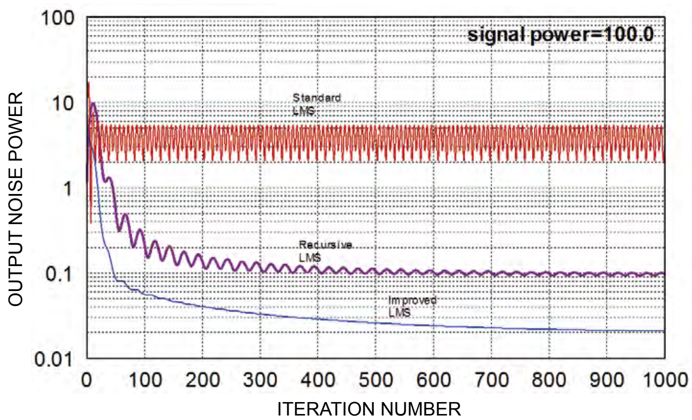

Figure 1. Mean output noise power for a 10-element uniform linear array, λ/2 spacing, 2 probing sources: 72°, 100; 98°, 1.

These simulation results were for a signal scenario consisting of only one desired signal and multiple probing sources impinging the antenna array from distinctly different directions. However, there can be a situation, when more than one desired signal along with the interfering signals impinge the antenna array. For such a signal environment consisting of multiple desired signals, it is required that steering vectors are defined in such a way that the antenna pattern has main lobes towards each of the desired direction. The projection vector, and hence, the weight updating equation is derived for the case of multiple simultaneous desired signals. The resultant weight updating equation is given by

$$W(n+1) = P[W(n) - \mu g(W(n))] + \frac{S_1}{S_1^H S_1} + \frac{S_2}{S_2^H S_2} + \ldots + \frac{S_m}{S_m^H S_m} \quad (1)$$

where μ is the step size, n is the snapshot considered. The projection operator, P is given by

$$P = I - \frac{S_1 S_1^H}{S_1^H S_1} - \frac{S_2 S_2^H}{S_2^H S_2} - \ldots - \frac{S_m S_m^H}{S_m^H S_m} \quad (2)$$

where $g(W(n))$ is an unbiased estimate of the gradient of $W^H(n) RW(n)$ wrt $W(n)$, R being the auto-correlation matrix. I is the identity matrix and $S_1, S_2, \ldots, S_m$ represent the steering vectors corresponding to m desired signals impinging the array at different angles. This is the modified version of improved LMS algorithm.

The ULA employs these weights for processing the received data $x(t)$ to obtain the array output,

$$y(t)=w^H x(t) \tag{3}$$

The received signal is given by

$$x(t) = As(t) + n(t) \tag{4}$$

where, $A = [a(\theta_1)\ \ a(\theta_2)\ \ ...\ a(\theta_k)]$ is the response matrix, $a(\theta_k) = e^{-jkd(i-1)\sin\theta_k}$ is the complex response of the sensor to k^{th} signal, d is the spacing between the sensors, c is the propagation speed of the signal. $s(t) = [s_1(t)\ s_2(t)\ ...\ s_k(t)]^T$ is the signal source vector, and $n(t) = [n_1(t)\ n_2(t)\ ...\ n_k(t)]^T$ is the noise vector. The superscript T denotes the transpose operation.

If the signal impinging on the antenna array is wideband, i.e. distributed over finite frequency range, the correlation matrix must be modified. For such a signal environment, it is assumed that each spectral line of the wideband source is an individual narrowband signal[6]. Thus, the correlation matrix for a wideband signals is given by

$$R = R_q + \sum_{r=1}^{K} \sum_{l=1}^{L} P_{rl} R_{rl} \tag{5}$$

where, P_{rl} is the power ratio and R_{rl} is the covariance matrix of l^{th} spectral line of r^{th} interfering source. For the receiver noise power equal to unity, R_q, the quiescent covariance matrix will be an identity matrix. The mn^{th} component of R_{rl} is given as

$$(R_{rl})_{mn} = e^{j2u_{rl}(n-m)} \tag{6}$$

where, $u_{rl} = (1 + \frac{\Delta f_l}{f_0}) \frac{\pi}{2} \sin\theta_r$

The extent of the frequency spread, i.e. $\Delta f / f_o$ for a particular hostile source of l^{th} spectral line is computed using the expression,

$$\frac{\Delta f}{f_o} = \left(\frac{B_r}{100}\right)\left[\frac{-1}{2} + \left(\frac{l-1}{L_r - 1}\right)\right]$$

where, B_r is the bandwidth and L_r is the number of spectral lines[7]. The correlation matrix given by Eqn (5) is incorporated in the weight updation, i.e., Eqn (1). These weights of the adaptive array antenna are such that when their optimal value is multiplied with the received signals using Eqn (3), selective gain/null arrangements for different signal beams can be achieved.

3. ACTIVE CANCELLATION OF NARROW-BAND/ WIDEBAND PROBING SOURCES

The simulation results of the performance analysis of linear/planar phased arrays using improved LMS algorithm for a signal environment consisting of multiple simultaneous desired signals and probing sources is presented. In all the cases, the power of the desired signal is assumed to be lower than the power of interfering sources.

3.1 Narrowband Probing Sources

A uniform linear array with 10 isotropic antenna elements is considered. The spacing between the elements is fixed to half a wavelength. A simple scenario with two desired signals (60°, 120°; 0 dB each) and two interfering signals (80°, 150°; 30 dB each) has been considered. The resultant adapted beam pattern obtained is shown in Fig. 2. The quiescent pattern, i.e., pattern without probing sources, is also included in the plot. The adapted pattern using standard LMS and recursive LMS algorithms is also shown. It can be observed that the adapted pattern of standard LMS and recursive LMS algorithms do not show suppression of the probing sources, although the main lobes corresponds to each of the desired directions accurately. However this is not the case of the proposed improved LMS algorithm. The antenna array along with the proposed algorithm is found to be efficient enough to maintain sufficient gain towards the desired directions and simultaneously placing deep nulls in the directions of probing sources.

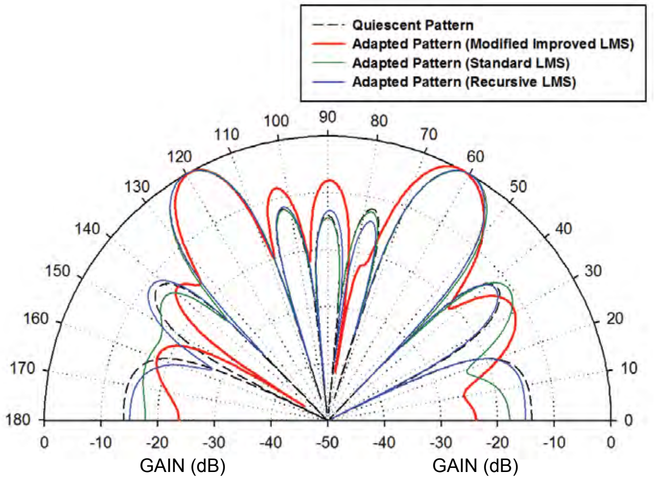

Figure 2. Adapted beam pattern using improved LMS algorithm, standard LMS, and recursive LMS algorithm. Two desired signals (60°, 120°, 0 dB each) with two narrowband probing sources (80°, 150°, 30 dB each) were considered.

The variation of noise power level with number of snapshots is shown in Fig. 3. The results are compared for the algorithms, viz., standard LMS, recursive LMS, and the proposed improved LMS algorithm. It can be seen that the

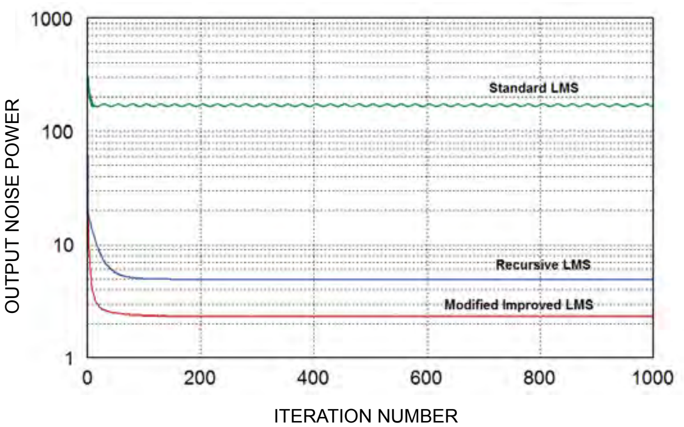

Figure 3. Output noise power of 10-element uniform linear array in the presence of two desired signals (60°, 120°, 0 dB each) and two probing sources (80°, 150°, 30 dB each).

output noise power of the array decreases drastically with time. This signifies that the complex weights adapt to their optimum values within a few iterations. The lowest output noise power is achieved by the improved LMS algorithm for a given signal scenario. Moreover, the convergence rate of the proposed algorithm is also excellent.

Next, the array radiation pattern in the presence of two desired signals and three probing sources is presented in Fig. 4. The desired signals were assumed to arrive at the same directions with the same input powers as in the previous case. Three sources were considered to be probing from the directions of 90°, 140° and 145°, each with 30 dB power levels. Good suppression capability of the array employing improved LMS algorithm is demonstrated by the nulls obtained in the directions of the probing sources.

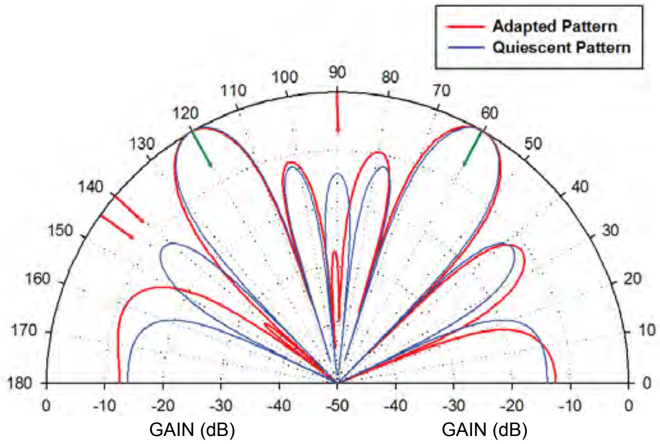

Figure 4. Adapted beam pattern for signal environment consisting of two desired signals (60°, 120°, power ratio of 1 each) and three probing sources (90°, 140°, 145°, power ratio of 1000 each).

3.2 Wideband Probing Sources

The performance of adaptive antenna array employing improved LMS algorithm was evaluated in the presence of wideband probing sources. A wideband source is assumed to be equivalent to many narrowband sources depending upon the number of spectral lines[6]. The phase factor and the covariance matrix corresponding to the wideband probing source were calculated considering equal frequency spread around a centre frequency. Simulations were carried out considering all the desired signals to be narrowband.

The adapted pattern of the array along with the quiescent pattern is shown in Fig. 5, when two desired signals (60°, 1; 120°, 1) and two wideband probing sources (80°, 1000, 2 per cent BW, 3 lines; 150°, 100, 2 per cent BW, 3 lines) were considered to impinge on the array. It is apparent that both the probing sources having finite spectral distribution are suppressed efficiently. Accurate nulls were placed towards each probing direction signifying almost no energy transmitted towards these. This makes the array invisible to the radar source trying to probe the antenna array. Earlier studies for one desired signal have shown that when the antenna array nulls an interfering signal, the null depth depends on power level of the interfering signal[7]. The result obtained for the present scenario with simultaneous multiple desired signals is also on the expected lines. It can be readily observed from the pattern that the source with higher power is suppressed more.

In Fig. 6, adapted beam pattern for a signal scenario, having three closely spaced wideband probing sources is shown. These probing sources are assumed to arrive arbitrarily from 88°, 90° and 92° having 2 per cent BW, 3 lines; 5 per cent BW, 6 lines; 2 per cent BW, 3 lines, respectively. The power ratio of the sources are unequal, i.e., 600, 1200, 400, respectively. It is seen that the sidelobe within the probing directions is suppressed extensively while the main lobes in the pattern remain undistorted.

Then a 16×10 planar antenna array was considered. Figure 7 represents the case of three desired signals (-50°, -10°, 30°) and two probing sources (5°, -30°). One of the probing sources (5°) is narrowband while the one probing at -30° is wideband with 5 per cent bandwidth and 6 spectral lines. The resultant

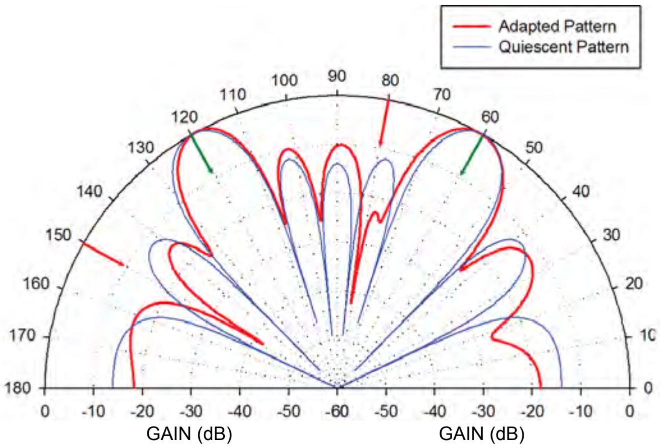

Figure 5. Adapted beam pattern when two desired signals (60°, 120°, 0 dB each) with two wideband probing sources (80°, 30 dB, 2 per cent BW, 3 lines; 150°, 30 dB, 2 per cent BW, 3 lines).

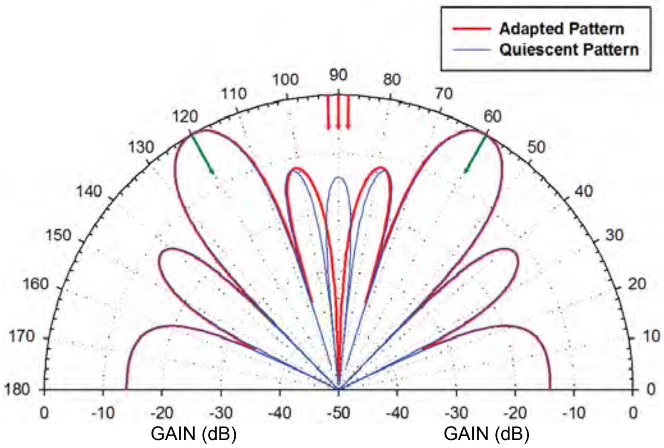

Figure 6. Adapted beam pattern for two desired signals (60°, 120°, 0 dB each) and three closely spaced wideband probing sources (88°, 600, 2 per cent BW, 3 lines; 90°, 1200, 5 per cent BW, 6 lines; 92°, 400, 2 per cent BW, 3 lines).

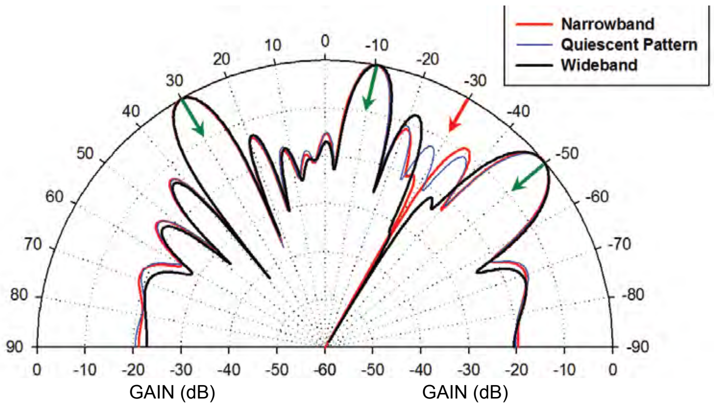

Figure 7. Adapted beam pattern of 16 x 10 planar antenna array. Three desired signals at (- 50°, - 10°, 30°) and one wideband probing source at (- 30°, 2 per cent, 3 lines).

pattern consists of multiple main lobes, each pointing towards desired directions along with accurate and deep nulls towards the probing direction. The difference in pattern for the case of two narrowband and wideband sources probing at 5° and - 30° shows the same trend as in the previous cases. Let one consider a slightly complicated case of three desired signals (- 60°, 10°, 30°) and three closely spaced wideband probing sources with different bandwidths (- 25°, 5 per cent, 6 spectral lines; - 35°, 2 per cent, 3 spectral lines; - 20°, 10 per cent, 5 spectral lines). It is observed from Fig. 8 that each probing source is suppressed efficiently resulting in a deep and wide null in the pattern. This demonstrates the capability of a narrowband antenna array (linear/planar) along with an efficient improved LMS algorithm to cater to the narrowband/wideband signal environment, having either a single or multiple probing sources.

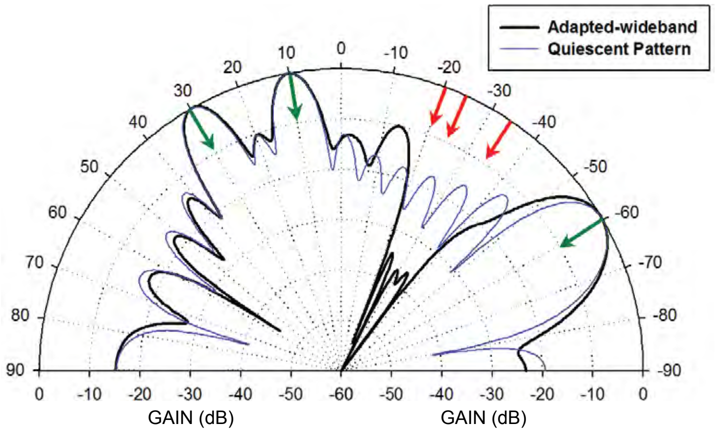

Figure 8. Adapted beam pattern of 16 x 10 planar antenna array. Three desired signals at (- 60°, 10°, 30°) and 3 wideband probing sources at (- 25°, 5 per cent, 6 spectral lines; - 35°, 2 per cent, 3 spectral lines; - 20°, 10 per cent, 5 spectral lines).

4. CONCLUSIONS

To improve the performance of adaptive antenna array, called controlled radiation pattern arrays, in a practical signal scenario consisting of multiple desired and undesired signals is studied. These sources can be narrowband or may be distributed over finite frequency bands. The projection vectors and weight updating equation for improved LMS algorithm and the correlation matrix are derived for such a signal scenario. It is found that unlike the standard LMS, and the RLS algorithms, the performance of the proposed improved LMS algorithm does not depend on signal power level. In the presence of very strong signal, such as 30 dB, more than the uncorrelated noise, improved LMS algorithm performs far better than the standard LMS algorithm and RLS algorithm, both in terms of convergence and output noise power.

The simulation studies demonstrate the capabilities of linear and planar adaptive arrays along with an improved LMS algorithm in nullifying the narrowband, as well as the wideband probing effect of the hostile sources. It has potential, for not only accurate placement of the nulls in the adapted pattern, but also in the maintenance of sufficient gain towards each of the desired directions. The effect of bandwidth as well as the power level of the probing sources on the adapted pattern has been analysed. In case of wideband sources, the adaptive algorithm places broader nulls towards the probing direction. This may be due to the fact that each spectral line of the source is considered as a narrowband source.

The main objective of the study was to analyse the performance of steered beam adaptive array for multiple simultaneous desired signal environments and wideband probing sources. This capability of adaptive antenna array along with an efficient algorithm has widespread applications in aerospace engineering. For example, the effective cancellation of probing in antenna array can be explored for active RCS reduction. Moreover, such adaptive arrays when integrated with an avionics will eliminate the mechanical scanning for beam steering and better reception even in a hostile environment. Thus, these arrays have the potential to enhance the robustness of the entire navigation system.

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