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ORIGINAL RESEARCH ARTICLE

GPS ANTI-JAMMING TECHNIQUE USING SMART ANTENNA SYSTEMS

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ABSTRACT

This paper presents a global positioning system (GPS) anti-jamming technique using a smart antenna system. In anti-jamming systems, adaptive array antennas are used to estimate the direction of signals arriving at the antenna and spatially filter the desired signal from the unwanted signals by adaptively controlling the direction of the maximum radiated beam. In this study, the uniform linear array was used for the smart antenna configuration. The work compared the performance of non-blind adaptive algorithms with blind algorithms for adaptive beamforming. Non-blind adaptive algorithm using least mean square (LMS) algorithm and blind algorithm using constant modulus algorithm (CMA) was studied and implemented for adaptive beamforming while estimation of signal parameters via rotational invariance technique (ESPRIT) and multiple signal classification (MUSIC) algorithms were implemented for the direction of arrival (DOA) estimation. The effect of varying the number of elements in the antenna array and the required spacing between them was also investigated. Results of comparison carried out using numerical analysis showed that both algorithms performed well for the DOA estimation, with MUSIC algorithm producing a better direction of arrival spectrum with little or no minor peaks. For the beamforming, both LMS and CMA produced maximum radiation in the direction of the desired signal. LMS placed deeper nulls in the directions of interference with faster convergence and fewer errors as compared with CMA that presented errors and was able to suppress the interference to a minimal extent. It was also shown that as the number of elements in the array increases, a more directive beam and DOA spectrum is produced.

1.0 Introduction

The Global Positioning System (GPS) offers satellite navigation services that are widely used in aviation and military applications. The accuracy of received GPS signal and jamming prevention issues are of utmost importance in designing GPS systems due to its areas of critical applications. It is important to design GPS systems with efficient anti-jamming capabilities so as to protect the accuracy of received data. GPS is particularly vulnerable to jamming because the receivers are extremely sensitive in order to receive the extremely weak signals from orbiting satellites (Esmaeilkhah and Lavasani, 2018; Lang *et al.,* 2017; Mukhopadhyay *et al.,* 2007).

When the jamming signals and the desired signal share the same frequency, the conventional filtering techniques become inefficient in eliminating jammers. This has led to the study of various anti-jamming techniques using adaptive antenna system with direction-of-arrival (DOA) estimation and adaptive beamforming algorithms. These smart antenna systems are made up of an array of antenna elements with digital signal processors (DSP) to implement the adaptive signal processing. The objective is to estimate the direction of arrival of all impinging signals and adjust the antenna weights to ideally steer the maximum radiation of the antenna pattern toward the desired signal and to place nulls toward the interfering signals. Therefore, adaptive antenna systems combine multiple antenna elements with a signal processing capability to optimize its radiation and reception pattern automatically in response to the signal environment (Joshi and Dhande, 2014). In a smart antenna system, the optimum weights of each antenna elements are iteratively determined using algorithms based upon different criteria to give a maximum gain in the direction of the source signal and placing the null in the direction of the interference signal (Shivapanchakshari and Aravinda, 2017; Shahab *et al.,* 2017).

These algorithms can be categorized into two classes depending on whether a training signal is used or not. One class of these algorithms is the non-blind adaptive algorithm in which a training signal is used to adjust the array weight vector (Joshi and Dhande, 2014; Ali *et al.,* 2011). Another technique is to use blind adaptive algorithms that do not require a training signal (Rao and Sarma, 2014; Elkassimi *et al.,* 2017; Udawat *et al.,* 2011).

A lot of work has been done on the implementation of anti-jamming systems using non-blind adaptive beamforming algorithms. Joshi and Dhande (2014) used least mean square (LMS) algorithm for adaptive beamforming. They evaluated the effect of the LMS algorithm on its beamforming capability using normalized array factor and the convergence of its mean square error (MSE). The effect of varying the number of antenna elements and the distance between array elements on the array factor and MSE was also evaluated. Ali *et al.* (2011) authors worked on adaptive beamforming algorithms for anti-jamming. They studied and compared the performance of three beamforming algorithms; LMS, optimized-LMS and recursive least square (RLS) algorithms and concluded that RLS algorithm had the best performance as it provided deeper nulls in the direction of the signal not of interest (SNOI) and faster convergence.

A few others considered blind adaptive algorithms. Rao and Sarma (2014) analyzed and compared the beamforming capabilities of LMS, Normalized LMS, Constant Modulus Algorithm (CMA), and RLS for smart antenna application using three different antenna array geometries; linear, circular and planar geometries. Extensive comparison was done using these algorithms and geometries. They also compared the beamforming of LMS and NLMS algorithms using different inter-element spacing and number of elements in the array and concluded that as the number of elements increased, the algorithms converged faster. Though an extensive analysis was done for various beamforming algorithms, implementation of complete beamforming system involving direction of arrival estimation was not considered.

Elkassimi *et al.* (2017) proposed the use of algorithm based on zero-forcing (ZF) and minimum mean square error (MMSE) methods for blind channel equalization. They compared performance of this algorithm with other adaptive filter algorithms like CMA, fractional space CMA (FSCMA) and sign kurtosis maximization adaptive algorithm (SKMAA). Udawat *et al.* (2011), the convergence characteristics of blind beam-forming algorithm known as least square constant modulus algorithm (LSCMA) were analyzed. The algorithm was used with Smart antenna systems (SAS) for improving the performance of a wireless communication system by optimizing the radiation pattern according to the signal environment. Kundu and Ghosh (2008) demonstrated an implementation of real-time adaptive beamforming for code division multiple access 2000 (CDMA2000) reverse link using digital signal processing technique. Simulation was performed for uniform linear array (ULA) of several elements and they found that algorithm computation time and accuracy of beam pattern direction were proportional to the number of antenna elements.

DOA estimation is also a key research area in adaptive array antenna systems. Beulah and Vigneshwani (2014), focused on the design of a smart antenna system based on multiple signal classification (MUSIC) DOA estimation algorithm, and adaptive beamforming using LMS. Array pattern synthesis was achieved using the Dolph-Chebyshev method which is popularly used for obtaining the weights and current excitation for uniformly spaced linear arrays steered to broadside. This method produced array pattern with side lobes of equal magnitude and made use of a class of polynomials called Chebyshev polynomials.

Mukhopadhyay *et al.,* (2007) proposed a new simple DOA estimation method based on the mechanical rotation of an array plane by small angles. In this method, the frequencies of the signals impinging on the array must be known. By taking the ratio of these frequencies before and after rotation of the array plane and comparing with ratio of the cosine function of the angle of arrival (AOA) before and after rotation, a simple trigonometric equation was obtained for DOA estimation. Simulations showed that the estimated DOAs and frequencies matched with actual values. The authors also showed that adaptive beamforming using LMS algorithm can be used to constructively receive signal with multipath interference.

Very few papers addressed anti-jamming techniques for GPS receivers. In Zhang and Amin (2012), authors proposed a novel array-based anti-jamming GPS receiver that enables effective jammer suppression with negligible phase distortion. They pointed out that one of the major problems with existing blind anti-jamming array signal processing technique is that they introduce errors in the carrier phase, and developed a technique that achieves GPS signal phase continuity by using accurate estimation of phase rotated steering vector of the GPS signal. In Chi (2016), the authors proposed an anti-jamming measurement method based on antenna array. This method uses array antenna to estimate the direction of arrival of jamming signal through MUSIC algorithm. The adaptive nulling algorithm based on the linear constrained minimum variance algorithm is used to eliminate the jamming signals and hold the navigation signal.

According to the above papers, non-blind adaptive algorithms require prior information like the reference signal and direction of arrival (DOA) of the signal and may not be suitable for GPS systems. In this paper, the performance of non-blind adaptive algorithm using LMS algorithm and blind algorithm using CMA algorithm is studied and implemented for adaptive beamforming while the estimation of signal parameters via rotational invariance technique (ESPRIT) and MUSIC algorithms have been implemented for DOA estimation purposes. The purpose is to compare these known techniques and determine the most suitable for an anti-jamming system in GPS receivers.

2. Materials and Methods

2.1. GPS Signal Generation

GPS signal generation is achieved by modulating a carrier frequency with pseudorandom noise (PRN) codes. The precision code (P-code) and coarse acquisition (C/A) code are used for GPS and two carrier frequencies which are the L1 that contains both codes and the L2 carrier that is modulated with only the P-code exist. This paper focused on the L1 signal generation.

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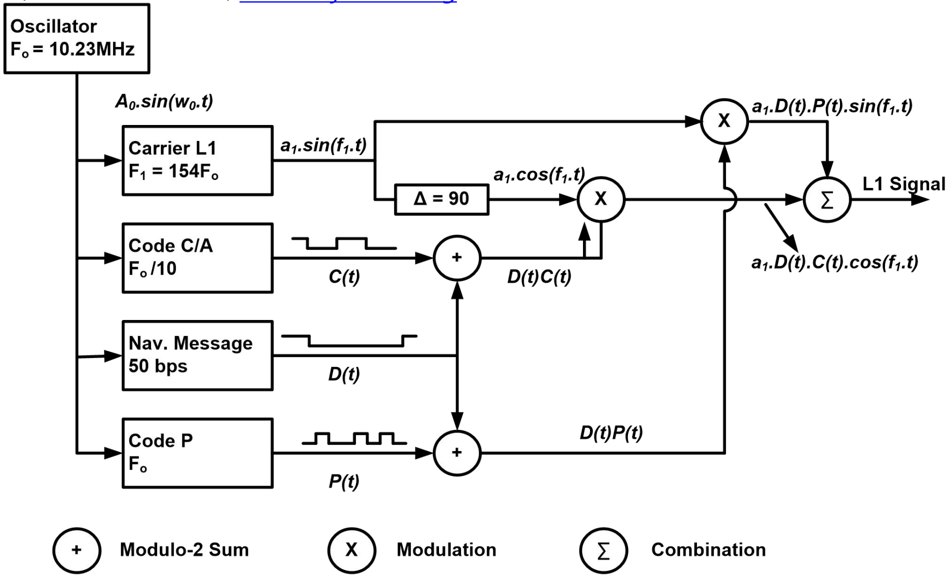

Figure 1: Block diagram of GPS L1 Signal Generation (Saab, 2012)

Figure 1 shows the functional block diagram describing the GPS signal generation. The system is driven by a 10.23MHz clock signal producing a pure sine wave. Multiplying this clock frequency by 154 gives the L1 carrier frequency (1.57542 GHz). The clock frequency is stabilized to 1.023MHz, which is the chipping rate of the C/A code and applied as the clock signal for C/A code generation. The P-code is generated at the clock frequency. After code generation, the codes are combined with the navigation data with a data rate of 50bps through modulo-2 adders. This is accomplished through an XOR operation.

The results of the modulo-2 addition of the C/A code and the navigation data with the modulo-2 addition of the P-code and the navigational data are supplied to the BPSK modulators (Borre *et al.,* 2012). The system uses two modulators to achieve an in-phase and quadrature modulation of the codes, therefore the output of the modulators is two components of the L1 signal with a 90° phase shift between them. The outputs from the two modulators are then summed together to form the resulting L1 signal.

2.2 Interference Signals Generation

The interference signals used in the simulation was generated using a random process. An excerpt is given below showing the process and the MATLAB code used. From the extract, random numbers were generated for the number of interfering signals, iSize. These random numbers were used to form a matrix of the same size as the GPS signal, data. This is for easy addition and other matrix operation. The generated signal is assigned a steering vector and combined with the GPS signal using an AWGN channel to form the received signal.

```
%% Generate interferer signal
idata = [];
for i=1:iSize
id = randn(1, length(data));
idata = [idata; id];
end
```

2.3 GPS Receiver System Implementation

The functional block diagram of the system implementation is shown in Figure 2. It shows that the system locates the desired signal using the direction-of-arrival (DOA) algorithm, and continuously tracks it by adaptively adjusting the weights of the elements.

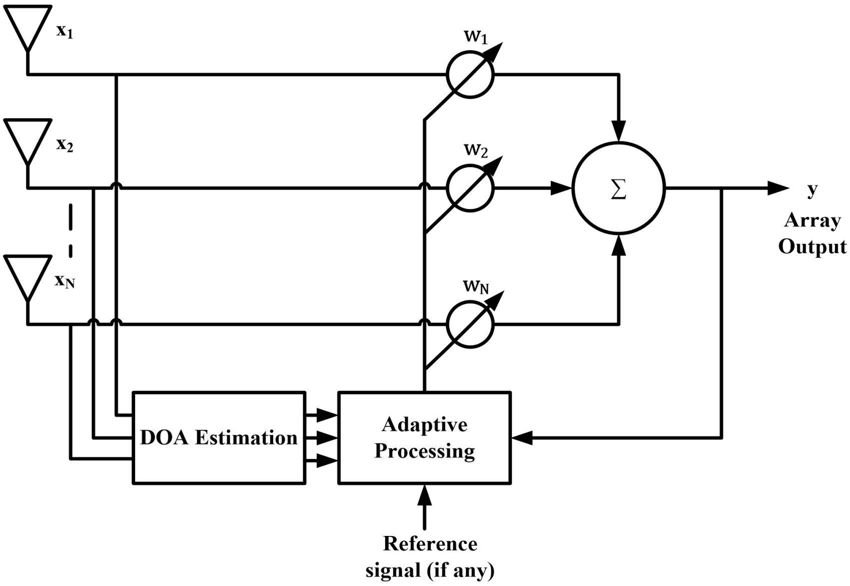

Figure 2: The functional block diagram of the system implementation (Moghaddam *et al.,* 2011)

By using a cost function, the adaptive algorithm computes the appropriate weights that result in an optimum radiation pattern. The next subsections will consider in details the steps needed to implement the algorithms used in the functional blocks.

2.3.1 DOA Estimation Using MUSIC

MUSIC algorithm is one of the angles of arrival (AOA) estimation method used in this paper. It is a subspace-based method and relies on the following properties;

The space spanned by the correlation matrix eigenvectors may be partitioned into two subspaces; the signal subspace and the noise subspace.

The noise subspace is spanned by the eigenvectors associated with smaller eigenvalues of the correlation matrix, and the signal subspace is spanned by the eigenvectors associated with the large eigenvalues of the matrix

The steering vectors corresponding to the directional sources are orthogonal to the noise subspace. Therefore the product of the array steering vector and the noise subspace is null (zero) for a particular angle of arrival (AOA).

The process has been extensively studied in previous literature (Kintz and Gupta, 2016; Sit et al., 2012; Huang et al., 2005) and is summarized in the algorithm described in Algorithm 1.

Algorithm 1: MUSIC Algorithm

Input: Received GPS signal and interference signals.

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Output: Direction of Arrival (DOA) of the signals.

Procedure:

1. Collect input samples $\mathrm{x}(\mathrm{t}_\mathrm{k})$, $\mathrm{k} = 1,2,\cdots,\mathrm{K}$ and estimate the input covariance matrix;

$$\mathrm{R}_{\mathrm{xx}} \approx \frac{1}{\mathrm{K}}\sum_{\mathrm{k}=1}^{\mathrm{K}} \mathrm{x}(\mathrm{t}_\mathrm{k})\mathrm{x}^\mathrm{H}(\mathrm{t}_\mathrm{k}) = \frac{1}{\mathrm{K}}\mathrm{XX}^\mathrm{H},$$

where K is the number of snapshots.

2. Perform Eigen decomposition on R_{xx}.

$$\mathrm{R}_{\mathrm{xx}}\mathrm{V} = \mathrm{V}\Lambda,$$

where $\Lambda = \mathrm{diag}\{\lambda_1, \lambda_2, \cdots, \lambda_\mathrm{N}\}$, and $\lambda_1 \geq \lambda_2 \geq \ldots \geq \lambda_\mathrm{N}$ are the eigenvalues and V contains all the corresponding eigenvectors of R_{xx}.

3. Sort the eigenvalues of R_{xx}. For N number of antenna elements and M number of signals, the $\mathrm{N} - \mathrm{M}$ eigenvalues of R_{xx} correspond to the smallest eigenvalues.

$$\lambda_1 \geq \lambda_2 \geq \ldots \geq \lambda_\mathrm{M} \geq \lambda_{\mathrm{M}+1} \geq \cdots \geq \lambda_\mathrm{N}.$$

4. Form a matrix V_n containing the eigenvectors corresponding to the smallest eigenvalues of R_{xx} to obtain the noise subspace.

$$\mathrm{V}_\mathrm{n} = [\mathrm{q}_{\mathrm{M}+1}, \cdots, \mathrm{q}_\mathrm{N}],$$

where q_i, for all $\mathrm{i} = \mathrm{M} + 1, \mathrm{M} + 2, \cdots, \mathrm{N}$, are the eigenvectors corresponding to the smallest eigenvalue λ_{min}.

5. Compute the MUSIC spectrum as;

$$\mathrm{P}_{\mathrm{MUSIC}}(\theta) = \frac{1}{\mathrm{a}^\mathrm{H}(\theta)\mathrm{V}_\mathrm{n}\mathrm{V}_\mathrm{n}^\mathrm{H}\mathrm{a}(\theta)}$$

where $\mathrm{a}(\theta)$ is the steering vector corresponding to the DOA.

6. Find the M largest peaks of the music spectrum, $P_{MUSIC}(\theta)$, to obtain DOA estimates.

2.3.2 DOA Estimation Using ESPRIT

The steps to implement ESPRIT algorithm which has been extensively studied in previous literature (Pradhan and Bera, 2015; Qian et al., 2014; Gao and Gershman, 2005) is summarized in Algorithm 2.

Algorithm 2: ESPRIT Algorithm

Input: Correlation matrix of the received signal at the array.

Output: Direction of arrival (DOA) of the signals.

Procedure:

1. Estimate the array correlation matrices R_{yy} and R_{zz} from the data samples from two identical sub arrays. Perform Eigen decomposition and find their eigenvalues and eigenvectors. For example, the Eigen decomposition of R_{yy} gives;

$$\mathrm{R}_{\mathrm{yy}} = \mathrm{V}\Lambda\mathrm{V},$$

where $\Lambda = \mathrm{diag}\{\lambda_1, \lambda_2, \cdots, \lambda_\mathrm{N}\}$ and $\mathrm{V} = \{\mathrm{q}_1, \mathrm{q}_2, \cdots, \mathrm{q}_\mathrm{N}\}$ are the eigenvalues and eigenvectors of R_{yy}.

2. Form two matrices U_y and U_z with their columns being the M eigenvectors associated with the largest eigenvalues of each correlation matrix.

For a ULA, this is achieved by first forming a $N \times M$ matrix U which its columns are the M eigenvectors associated with the largest eigenvalues of the estimated array correlation matrix R_{xx} of the full array of N elements. Then select the first $L < N$ rows of U to form U_y and the last of its L rows to form U_z.

3. Form a $2M \times 2M$ matrix C and perform its Eigen decomposition;

$$C = \begin{bmatrix} U_y^H \\ U_z^H \end{bmatrix} [U_y \quad U_z],$$

$$C = V_c \Lambda V_c^H \quad ,$$

where $\Lambda = \mathrm{diag}\{\lambda_1, \lambda_2, \cdots, \lambda_{2M}\}$ with $\lambda_1 \geq \lambda_2 \geq \ldots \geq \lambda_{2M}$ are the eigenvalues of C while V_c contains the eigenvectors corresponding to the eigenvalues.

4. Partition V_c into four matrices of dimension $M \times M$ as follows;

$$V_c = \begin{bmatrix} V_{11} & V_{12} \\ V_{21} & V_{22} \end{bmatrix}$$

5. Calculate the eigenvalues λ_m, $m = 1, \cdots\cdots, M$, of the matrix $-V_{11}V_{22}^{-1}$.
6. Estimate the angle of arrival θ_m using;

$$\theta_m = \sin^{-1}\left\{\frac{\mathrm{Arg}(\lambda_m)}{2\pi\Delta_0}\right\}, m = 1,2, \ldots\ldots, M$$

---

3. Beamforming Methods

3.1 Beamforming Using LMS

One of the adaptive algorithms that will be used to optimize the weights of the array elements for adaptive beamforming is the LMS algorithm. Figure 2 shows the output of the system $y(n)$and it is given by;

$$y(n) = w^H(n)x(n). \tag{1}$$

The error between the desired signal $d(n)$ and system output $y(n)$ is given as;

$$e(n) = d(n) - y(n)\,. \tag{2}$$

The LMS weight update equation is given by;

$$w(n+1) = w(n) + \mu\left[-\hat{\nabla}J(n)\right] , \tag{3}$$

where μ is the step size parameter which controls the speed of convergence and lies between 0 and 1.$\hat{\nabla}J(n)$ denotes the instantaneous estimate of the gradient which is given as;

$$\hat{\nabla}J(n) = \frac{\partial J}{\partial w_i} = \begin{bmatrix} \frac{\partial J}{\partial w_0} \\ \frac{\partial J}{\partial w_1} \\ \vdots \\ \frac{\partial J}{\partial w_N} \end{bmatrix} . \tag{4}$$

The gradient estimate can simply be obtained by taking the error value for a single input pattern, squaring it and differentiating with respect to weight w.

$$\hat{\nabla}J(n) = \frac{\partial e^2(n)}{\partial w(n)} = \frac{\partial e^2(n)}{\partial e(n)} \cdot \frac{\partial e(n)}{\partial w(n)} , \tag{5}$$

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$$= 2e(n) \cdot \frac{\partial\left[d(n) - w^H(n)x(n)\right]}{\partial w(n)} \tag{6}$$

Since $e(n) = d(n) - W^H(n)x(n)$,

$$\therefore \hat{\nabla} J(n) = -2e(n)x(n). \tag{7}$$

Putting equation (7) into equation (3), the weight update equation is given by;

$$w(n+1) = w(n) + 2\mu x(n)e^*(n)\,. \tag{8}$$

Therefore, the LMS algorithm can be described by the three equations as given below;

$$\left.\begin{array}{c} y(n) = w^H(n)x(n) \\ e(n) = d(n) - y(n) \\ w(n+1) = w(n) + 2\mu x(n)e^*(n) \end{array}\right\} \tag{9}$$

The logical flowchart for its implementation is shown in Figure 3.

3.2 Beamforming Using CMA

Constant Modulus algorithm is another method used in this study to adjust the weights of the array elements to an optimal value for adaptive beamforming. CM algorithm implementation is similar to LMS but differs in its error signal computation since it is a blind method and does not require any reference signal for its operation. The flowchart for its implementation is shown in Figure 4.

The cost function to be minimized is given as;

$$J(w) = E\left[\left(\left|w(n)^H x(n)\right| - 1\right)^2\right] = E\left[(|y(n)| - 1)^2\right]. \tag{10}$$

Taking the gradient of the above cost function yields;

$$\nabla J(w) = \frac{\partial J(w)}{\partial w} = E\left[\frac{\partial}{\partial w}(|y(n)| - 1)^2\right], \tag{11}$$

and if $u = (|y(n)| - 1)$, then

$$\nabla J(w) = E\left[\frac{\partial u^2}{\partial w}\right] = E\left[\frac{\partial u^2}{\partial u} \cdot \frac{\partial u}{\partial w}\right] \tag{12}$$

$$= E\left[2u \cdot \frac{\partial (y(n)y^*(n))^{1/2}}{\partial w}\right] = E\left[2u \cdot \frac{\partial (w(n)^H x(n)x(n)^H w(n))^{1/2}}{\partial w}\right] \tag{13}$$

If $w(n)^H x(n)x(n)^H w(n) = v$, then

$$\nabla J(w) = E\left[2u \cdot \frac{\partial v^{1/2}}{\partial w}\right] = E\left[2u \cdot \frac{\partial v^{1/2}}{\partial v} \cdot \frac{\partial v}{\partial w}\right] \tag{14}$$

$$= E\left[2u \cdot \frac{v^{-1/2}}{2} \cdot x(n)x(n)^H w(n)\right] = E\left[2(|y(n)| - 1) \cdot \frac{y(n)x(n)}{2|y(n)|}\right] \tag{15}$$

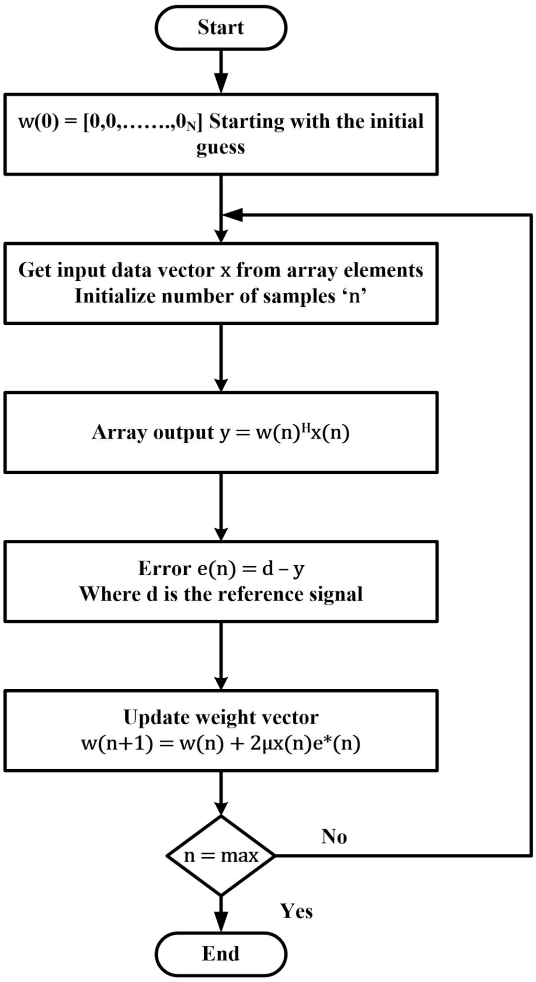

Figure 3: Flowchart of LMS algorithm implementation.

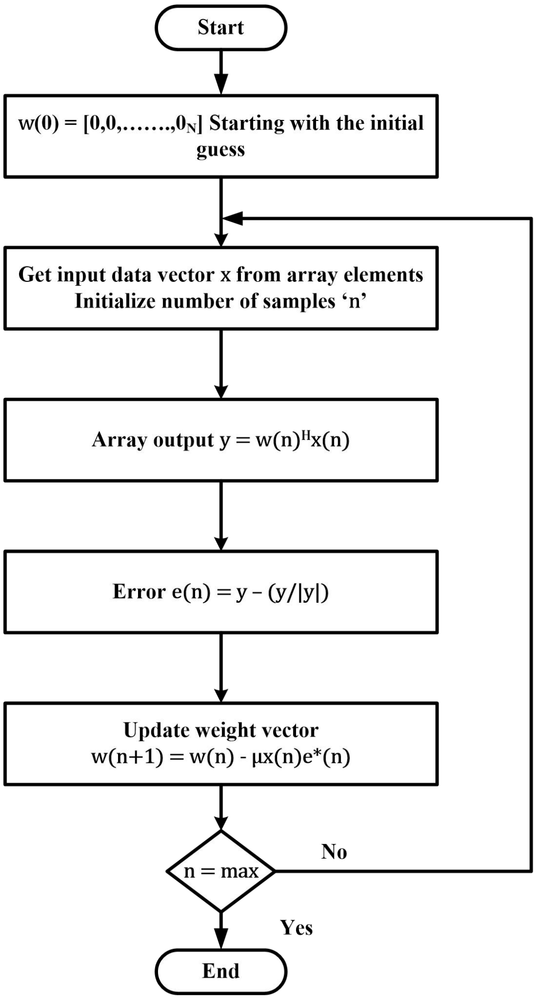

Figure 4: Flowchart of CM algorithm implementation.

Removing the expectation parameter gives the instantaneous gradient value as;

$$\nabla J(w) = \left(y(n) - \frac{y(n)}{|y(n)|}\right) x(n) \tag{16}$$

Equation (16) can then be used to replace the gradient term in the traditional LMS weight update algorithm of equation(3) to yield;

$$w(n+1) = w(n) - \mu x(n)\left(y(n) - \frac{y(n)}{|y(n)|}\right) \tag{17}$$

This is similar to LMS but with update error, e, expressed as;

$$e(n) = y(n) - \frac{y(n)}{|y(n)|} \tag{18}$$

Therefore the CMA can be described by the three equations set given below;

$$\left.\begin{aligned} y(n) &= w^{H}(n)x(n \\ e(n) &= y(n) - \frac{y(n)}{|y(n)|} \\ w(n+1) &= w(n) - \mu x(n)e^{*}(n) \end{aligned}\right\} \tag{19}$$

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4. Results and Discussions

In this paper, for the simulation, it is assumed that the desired GPS signal impinging on a uniform linear array of eight elements arrives at an angle of 0° and will be estimated using the DOA algorithms. In addition, there are two interference signals arriving at angles of 50° and -60°. Both LMS and CMA are used for beamforming. Table1 gives a complete list of parameters used for the simulation and their respective values.

Table 1: Simulation Parameters

Parameter	Value
Desired Signal Angle	0°
Interference Signal Angles	50° and -60°
Signal to Noise Ratio (SNR)	25dB
LMS Step-size Parameter	0.005
CMA Step-size parameter	0.00005
Number of Array Elements	8
Inter-element Spacing	0.5λ

Figure 5 shows the MUSIC and ESPRIT spectrum of the estimated angles of arrival of both the desired and interference signals. From the figures, it can be seen that both DOA algorithms gave an accurate estimate of the directions of arrival. Since both DOA algorithms were able to estimate the correct angles of arrival, only one of the algorithms was used for other results as they produced a similar response.

The plots of Figure 6 show the radiation pattern and amplitude response of the array output in the simulations. From the plots, it can be seen that both beamforming algorithms used were able to give maximum radiation in the direction of the desired GPS signal (0°). In terms of placing nulls in the directions of interference, LMS algorithm had the best response by placing deeper nulls in these directions (50° and -60°) whereas CM algorithm had a shallow null at 50° and couldn't place a null at -60° though a minor side lobe was formed. This is because CMA is less stable and presented some errors during implementation and as shown in subsequent results. The figure shows that the algorithms achieved the goal of the system by placing maximum radiation in the direction of the desired signal.

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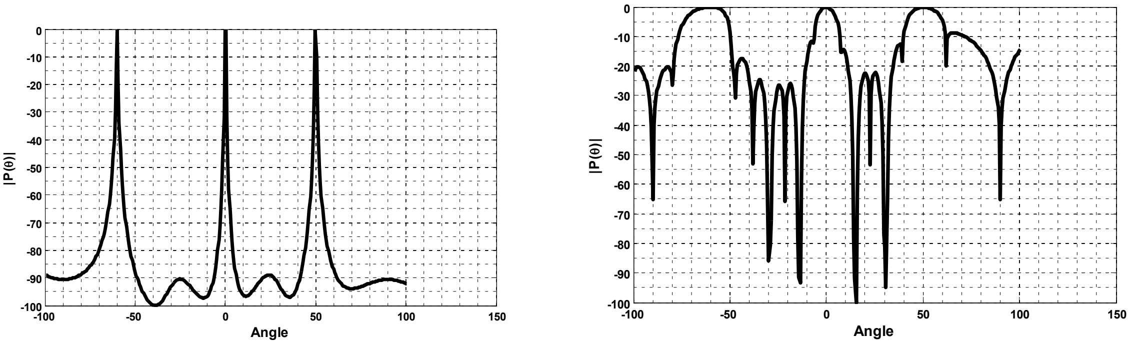
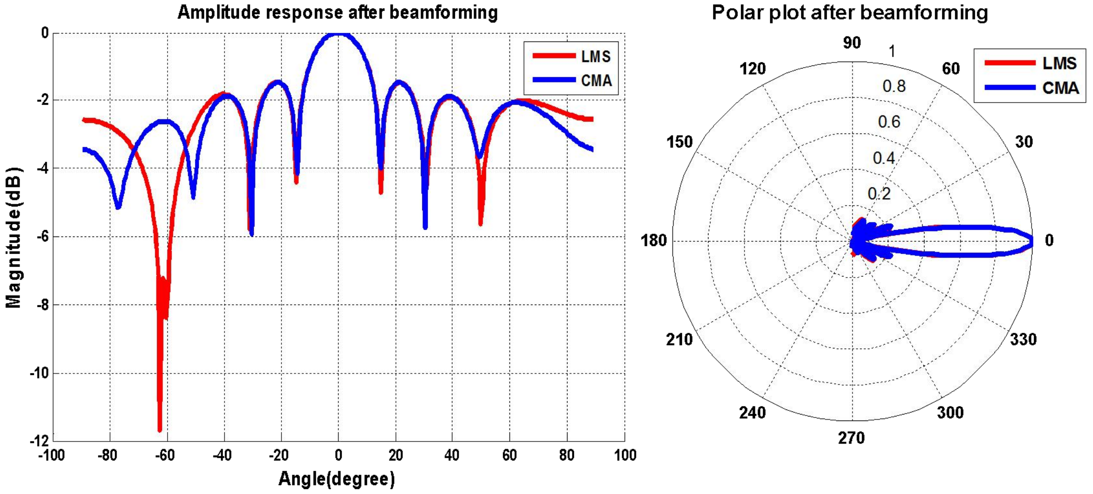


(a) (b)

Figure 5: (a) MUSIC spectrum of estimated angles of arrival of the signals (b) Equivalent ESPRIT spectrum.



(a) (b)

Figure 6: (a) Radiation pattern of the system after beamforming (b) Polar representation

Figure 7 depicts the Mean Square Error (MSE) plot or convergence plot for the CMA and LMS algorithm respectively. It was observed that the LMS algorithm converged to a near-zero value before 100 iterations whereas implementing the system with CMA presented lots of errors. It was also observed that the CMA attempted to converge at some point, but due to the discrete nature of the desired signal as shown later, erroneous results were obtained while tracking of the amplitude levels is done.

Figure 8 shows the acquisition and tracking curve of the system. It can be seen that the system is excellent in tracking the reference signal when the LMS algorithm is implemented and there is no delay in the output of the system to align perfectly with the reference signal. On the other hand, it was difficult for the output of the system to track and align to the reference signal when the CM algorithm is implemented. Finally, a phase comparison of the system output and the reference signal as shown in figure 9 indicates that there is no much difference between the two when either of the algorithms is used.

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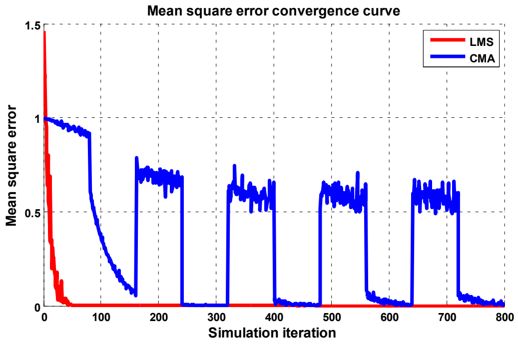


Figure 7: MSE convergence of both LMS and CM algorithm

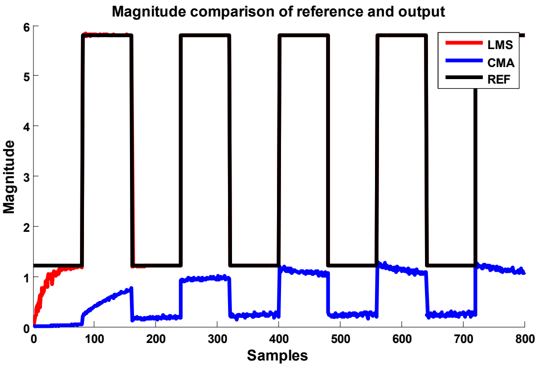


Figure 8: Tracking and acquisition curve of the system

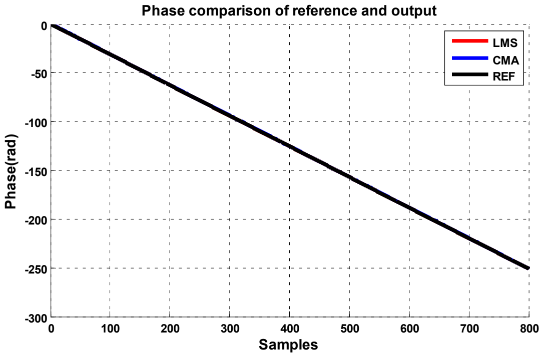


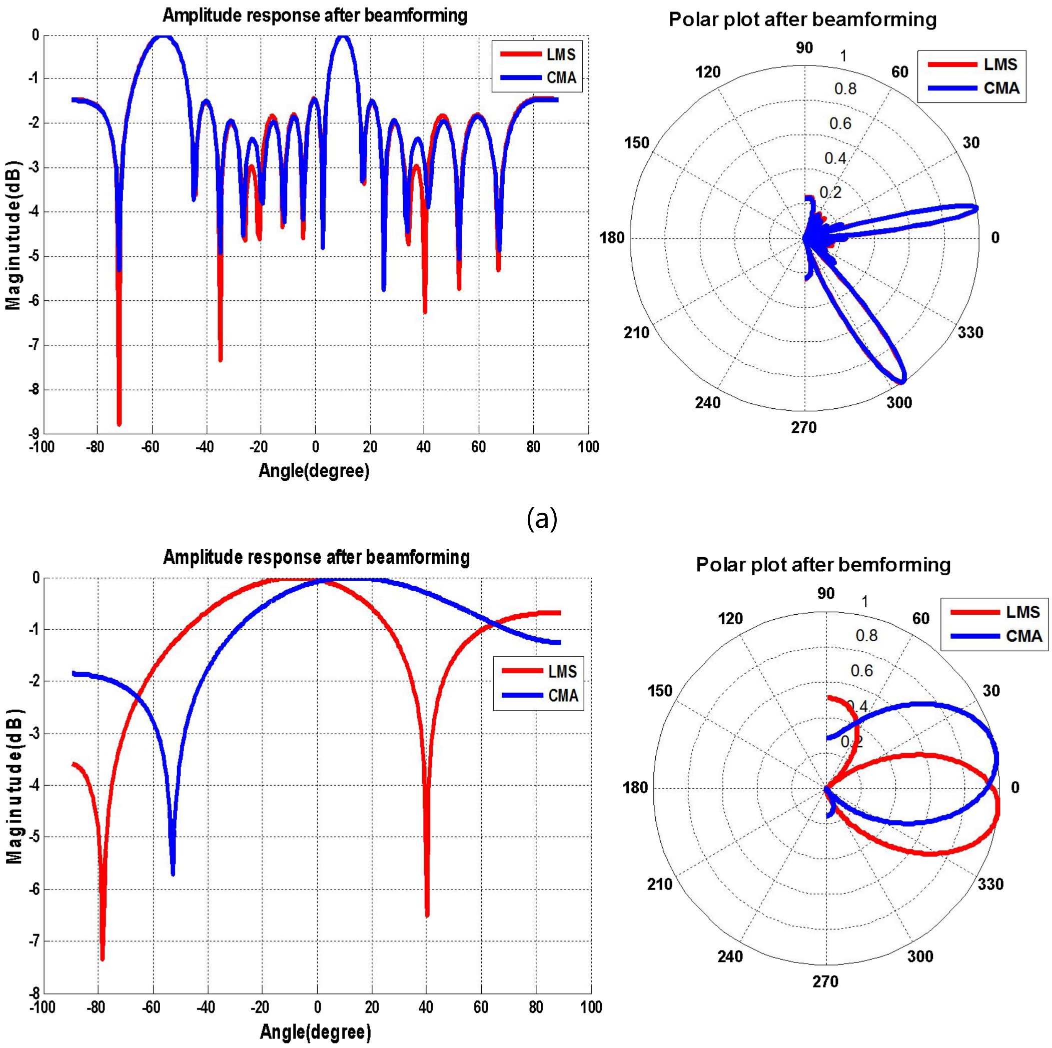
Figure 9: Phase comparison of the system output and the reference signal

4.1 Effect of Array Elements Spacing on Beamforming

For this part of the simulation, it is assumed that the desired signal impinges on the ULA of eight elements at an angle of $10°$, and also a single interference signal arrives at angle $40°$. Figure 10 shows the effect of the antenna array elements separation distance on the radiation pattern. It shows that the inter-element spacing is an important factor to be considered in the design of an antenna array system.

Figure 10 (a) shows that when the inter-element spacing is greater than $\lambda/2$, especially when it is greater than or equal to a wavelength (λ), grating lobes appear (at $-55°$ from the plot) which degrades system performance. Grating lobes are unintended maximum radiation in other directions other than the desired direction and occur when array element separation is too large. Therefore, to avoid this, the element separation should not be equal to multiples of a wavelength ($d \neq n\lambda,\ n = 1, 2, 3, \cdots$).

Furthermore, Figure 10 (b) shows that when elements are spaced closely (typically less than $\lambda/2$), mutual coupling effect occurs. This is a situation whereby the radiation characteristics of an excited array element are influenced by the presence of the others. This usually causes the maximum and nulls of the radiation pattern to shift thereby causing the DOA and beamforming algorithms to produce inaccurate results. Therefore, in other to produce the desired radiation pattern, the elements have to be far enough to avoid mutual coupling, and the spacing should not be too large to avoid grating lobes. For all practical applications, a spacing of $\lambda/2$ is recommended.



(a)

(b)

Figure 10: Effect of inter-element spacing on beamforming (a) $d = \lambda$, (b) $d = \lambda/8$

4.2.2 Effect of the Number of Array Elements on Beamforming

In this performance study, the step size of both the LMS and CM algorithms were adjusted to 0.00005 and 0.000005 respectively to ensure the system produced a good response. The angle of arrival of the desired signal was maintained at 10°, and that of the interference at 40°.

From Figure 11 and also comparing with Figure 6 where the number of elements N is eight, it is observed that as the number of elements in the array increases, the directivity of the array radiated output increases with multiple side lobes of narrow beamwidth and low power levels. This shows that a more directive radiation can be achieved by increasing the number of array elements.

In Figure 12, the number of elements N is varied between 8, 20 and 50, and it was observed that as the number of elements in the array increases, estimated DOA spectral beamwidth becomes narrower, the directivity of the array is enhanced meaning that its ability to distinguish spatial signals is improved. Therefore an accurate DOA estimation can be achieved by increasing the

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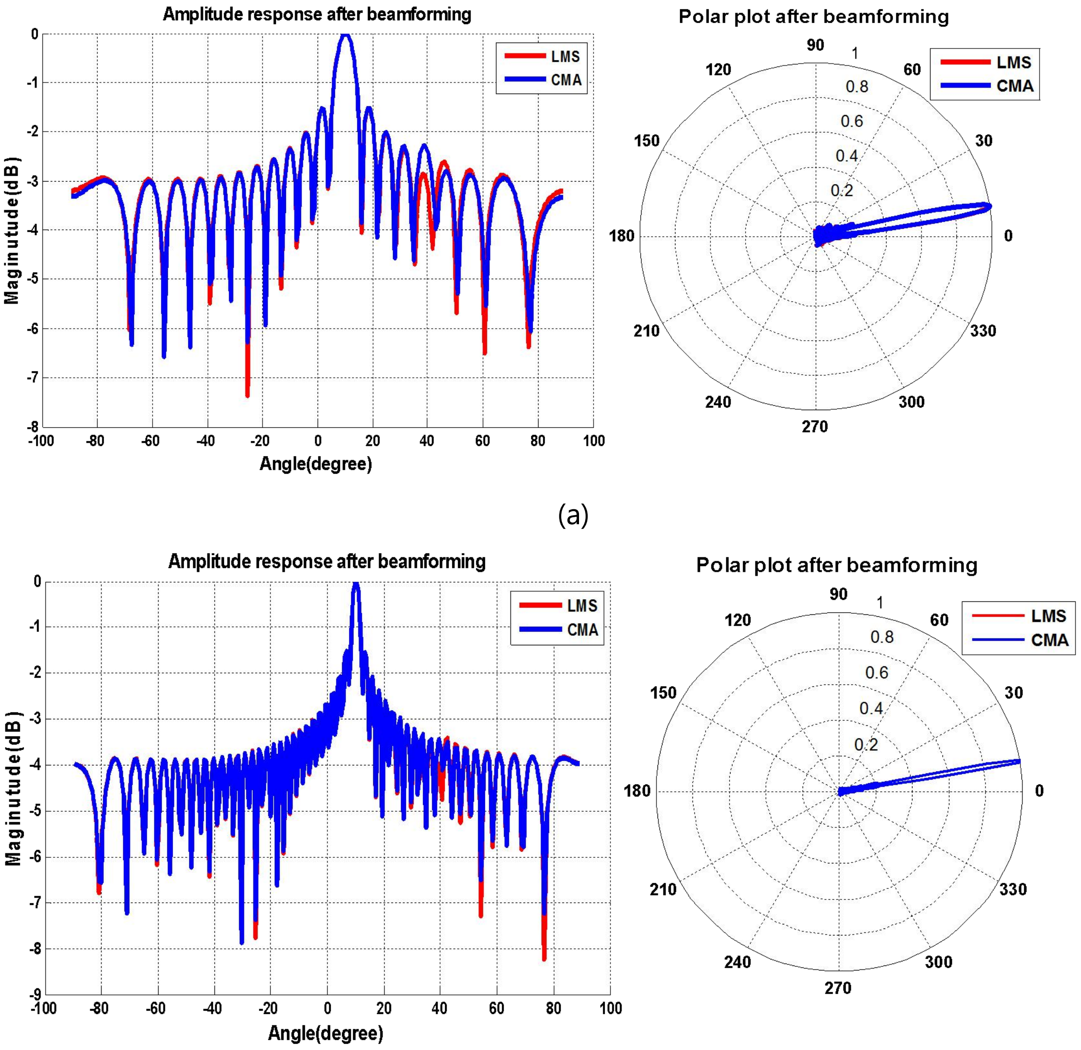
number of array elements, however, this can increase the data processing and computational requirements of the system and thereby negatively affecting the system speed.



(a)

(b)

Figure 11: Effect of number of elements N on beam pattern (a) N = 20, (b) N = 50

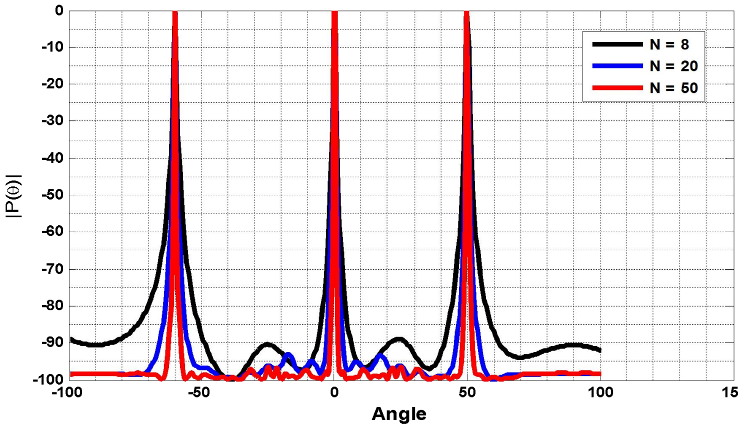


Figure 12: Effect of number of elements N on DOA estimation using MUSIC spectrum

5. Conclusion

This paper focused on the implementation of an anti-jamming system using DOA estimation and adaptive beamforming algorithms for GPS application. MUSIC and ESPRIT DOA estimation algorithms, as well as LMS and CMA adaptive beamforming algorithms, were considered in this study. MATLAB was used to develop these algorithms and to model the desired (GPS) and interference signals. Simulation results presented showed that for the DOA estimation, both algorithms are high-resolution algorithms as seen by the accuracy of the estimated direction of arrival although MUSIC algorithm produced a better direction of arrival spectrum with little or no minor peaks. Also for the beamforming, both LMS and CMA produced maximum radiation in the direction of the desired signal. LMS placed deeper nulls in the directions of interference with faster convergence and fewer errors as compared with CMA, which presented errors and was able to suppress the interference to an extent. It was also shown that as the number of elements in the array increases, a more directive beam and DOA spectrum is produced. In conclusion, the results show that smart antenna system is viable and very instrumental in the development of anti-jamming systems.

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