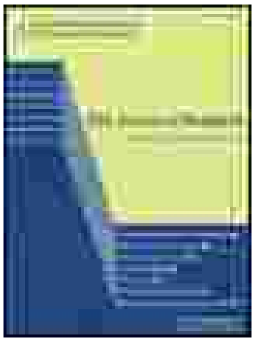

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Kaiser Window Based Blind Beamformers for Radar Application

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ABSTRACT
Blind beamforming algorithms are the first choice for radar applications as they won't use any training signal. But the major downside of constant modulus algorithm (CMA) is very low convergence rate. To overcome this problem and to make this algorithm more suitable for real-time applications, we firstly improved the convergence rate of CMA by making its step size adaptive. Then, we applied Kaiser window to improved CMA and conventional least-square CMA (LS-CMA) to suppress the sidelobe levels. These proposed algorithms are named Kaiser window-constant modulus algorithm and Kaiser window least square-constant modulus algorithm, respectively. Computer simulations validate the effectiveness of the proposed beamformers.

KEYWORDS
Blind beamforming; CMA; Hanning; Kaiser; LS-CMA; Smart antenna

1. INTRODUCTION

In the radar technology, sidelobe level (SLL) is one of the important issues. Most of the power is wasted due to sidelobes. Hence an algorithm with reduced SLL is always an advantageous aspect in the beamforming technology. The constant modulus algorithm (CMA) is the well-known blind beamforming algorithm which does not require a reference radio signal. This feature provides stable performance and easy implementation. The use of this beamformer in smart antenna system reduces multipath fading, co-channel interference and background noise. Because of these reasons, blind beamformers has got great attention in mobile radio communications. CMA was proposed by Godard [1] and Treichler *et al.* [2] use the steepest descent method in its cost function equation. The slow convergence rate of CMA limits its application in rapidly changing channel conditions. Faster CMA beamformer was proposed by Agree in [3–4] which uses non-linear least squares for the rapid correction of CM signals. This beamformer is known as least-square CMA (LS-CMA). It is also called as a Gauss method and autoregressive estimator [4]. The main advantage of LS-CMA is its convergence rate which is much faster than CMA. Bakhar and Vani [5], Khalaf *et al.* [6], and van der Veen in [7] presented algebraic CMA (ACMA) which uses deterministic properties like constant modulus to separate the superposition of impinging source signals on adaptive arrays. He devised zero-forcing ACMA (ZF-ACMA) in [7–9] which converges to zero-forcing beamformer. This yields enhanced performance in applications [10]. Furthermore, he proposed adaptive-ACMA in [11] the computational complexity of which is reasonable for recovering all weight vectors. A CMA-based peak-to-average power ratio (PAPR) reduction in MIMO OFDM/A is presented in [12]. In Ref. [13], a Hanning window is applied to CMA to suppress peak SLL (PSLL) up to −44 dB using 20 antennas. The paper does not discuss about convergence improvement and has less suppression in PSLL. To overcome these drawbacks and to make beamformers more suitable for real-time applications, we firstly improved the convergence rate by making its step size adaptive and then applied Kaiser window to both CMA and LS-CMA to suppress the PSLL. Simulation results obtained in section VII proves that the proposed methods have an improvement of 48 dB over the methods discussed in [13].

2. PROBLEM FORMULATION

Figure 1 shows the geometry of uniform linear array (ULA) for signal detection and estimation. Consider a geometry of ULA with "N" antenna elements, $N = (0, 1, 2, \ldots, N-1)$, with "$m$" number of source signals. Let the spacing between each antenna element be $d = \lambda/2$.

$$\mathbf{x}_k = \mathbf{A}\mathbf{d}_k + \mathbf{n}_k \tag{1}$$

Here

$\mathbf{A} = [\mathbf{a}(\theta_1), \mathbf{a}(\theta_2), \ldots, \mathbf{a}(\theta_m)]$ denotes the steering matrix.

$a(\theta) = [1, \exp[j2\pi \sin(\theta)d/\lambda], \ldots, \exp[j2\pi(N-1)\sin(\theta)d/\lambda]]$ $\mathbf{d}_k = [\mathbf{d}_{1k}, \mathbf{d}_{2k}, \ldots, \mathbf{d}_{mk}]^{\mathrm{T}}$ denotes the source vector.

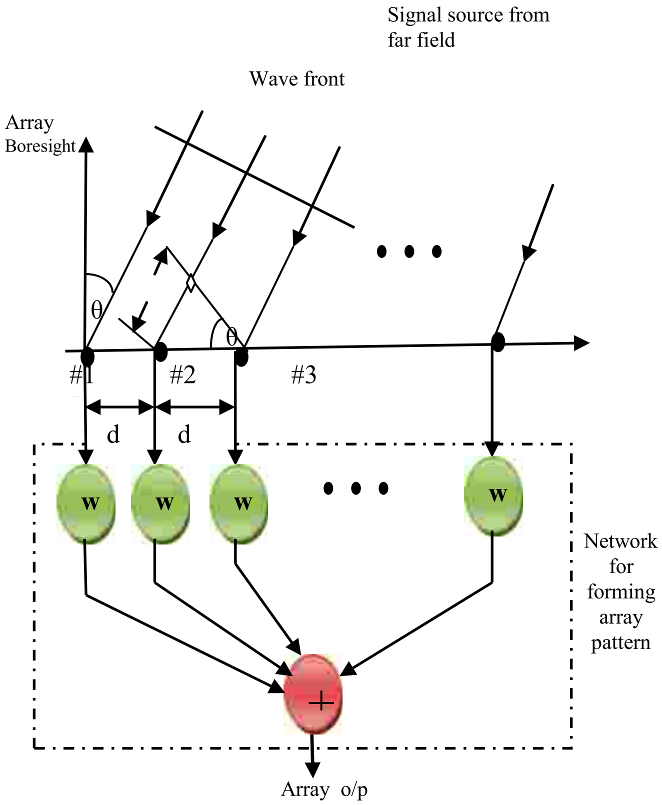

Figure 1: Geometry of considered ULA

$\mathbf{n}_k = [\mathbf{n}_{1k}, \mathbf{n}_{2k}, \ldots, \mathbf{n}_{mk}]^{\mathrm{T}}$ represents the noise vector.

The output expression of CMA and LS-CMA array is given by

$$y(k) = x_k^{\mathrm{T}}(k)w = w^{\mathrm{H}}x_k \tag{2}$$

Here $w = [w_1, w_2 \ldots . w_N]^{\mathrm{T}}$ denotes the array weight and $(\cdot)^{\mathrm{T}}$ is the transpose; $(\cdot)^{\mathrm{H}}$ is the Hermitian transpose of a vector.

3. BLIND BEAMFORMING ALGORITHM

3.1 Constant Modulus Algorithm (CMA)

CMA uses a gradient-based method. Most of the beamforming algorithm in array signal processing tries to minimize the error between antenna array output and a reference signal. The reference signal used in the algorithm is usually a training sequence signal which trains the desired signal or the adaptive antenna array using a priori knowledge of arriving signals [2].

CMA scheme computes the array weights without using any training signal. The weight updating expression for this scheme is given as

$$w_{k+1} = w_k + \mu\, \xi\, \bar{x}_k \tag{3}$$

Here, μ is the step size and ε is the mean square error (MSE) and whose value is expressed as

$$\mathrm{MSE} = \xi = \left(\Im_k - \frac{\Im_k}{|\Im_k|}\right) \tag{4}$$

$$\Im_k = \bar{x}(k)^{\mathrm{T}} w(k) = w(k)^{\mathrm{H}} \bar{x}(k) \tag{5}$$

3.2 Least-Square Constant Modulus Algorithm (LS-CMA)

The major downside of CMA beamformer is its slow convergence rate. The slow convergence rate makes the algorithm to deteriorate from its performance. The use of non-linear least squares can actually enhance the convergence time significantly. Hence this method, when used for CMA, is referred to as LS-CMA. Practically this scheme is about 100 times faster than the standard CMA [2].

$$\mathfrak{R} = -[\bar{J}_w \bar{J}_w^{\mathrm{H}}]^{-1} \bar{J}_w \varsigma \tag{6}$$

$\varsigma = [\varsigma_1, \ldots \varsigma_K]^{\mathrm{T}}$ is the data sample error

$\bar{J}_w =$ complex Jacobin of ς and this can be expressed as

$$\bar{J}_w = [\nabla \varsigma_1, \ldots \nabla \varsigma_K] \tag{7}$$

The weight update expression for LS-CMA can be given as

$$\begin{aligned} w_{k+1} &= w_k - \mathfrak{R} \\ &= w_k - [([\bar{J}_w \bar{J}_w^{\mathrm{H}}]^{-1} \bar{J}_w \varsigma)] \end{aligned} \tag{8}$$

Hence the LS-CMA array output can be obtained as

$$\Im_k = \bar{x}_k^{\mathrm{T}} w_k = w_k^{\mathrm{H}} \bar{x}_k \tag{9}$$

4. PROPOSED BLIND BEAMFORMERS

4.1 Improved CMA

In this approach, the rate of convergence of normal CMA is accelerated by making the step size adaptive. It is expressed as

$$w_{k+1} = w_k - \frac{2\mu_k}{||x_k||^2} x_k \left(\Im_k - \frac{\Im_k}{|\Im_k|}\right) \tag{10}$$

where μ_k is the adaptive step size and this adapts to the input source signal. This avoids the weights from diverging. The adaptive step size in normal CMA enhances the convergence rate.

4.2 Proposed KW-CMA Algorithm

Similar to H-CMA and HW-CMA, Kaiser window is applied to the improved CMA. Now let us apply Kaiser window to Equation (6) to reduce the SLL as

$$w_{k+1} = w_k - \left[\frac{2\mu}{||x(n)||^2}(N, \chi_o)\bar{x}_k\xi\right] \tag{11}$$

$$w_k = \frac{I\left[\chi_k\sqrt{1-\left(\frac{n-\alpha}{\alpha}\right)^2}\right]}{I[\chi_k]}, \text{ here, } \alpha = \frac{N}{2} \tag{12}$$

χ_k is the parameter used to control the shape of radiation pattern and it is given by empirical relations as

$$\chi_o = \begin{cases} 0.1102(\aleph_k - 8.7), & \aleph_k > 50 \\ 0.5842(\aleph_k - 21)^{0.4} + 0.07886(\aleph_k - 21), & 50 \geq \aleph_k \leq 21 \\ 0 & \aleph_k < 21 \end{cases} \tag{13}$$

Here, $\aleph_k$ = attenuation parameter of SLL expressed in decibels.

The modified Bessel function of the first kind is given as

$$I(x) = 1 + \frac{0.25x^2}{(1!)^2} + \frac{(0.25x^2)^2}{(2!)^2} + \cdots \tag{14}$$

The array observation vector of (1) can be written as

$$\overset{*}{x}(k) = d_r(k) + a_r(\theta_r) + \sum_{i=1}^{m} d_i(k)a(\theta_i) + n(k) \tag{15}$$

where d_r and d_i are the required and interference signals, respectively. θ_r and θ_i are the required and interference azimuth angles, respectively. a_r and a_i are the required and interference steering vectors, respectively. "m" is the number of interference signals.

Finally, the antenna array output for Kaiser window-constant modulus algorithm (KW-CMA) is given as

$$\Im_k = \bar{x}_k^{\mathrm{T}} w_k = w_k^{\mathrm{H}} \bar{x}_k \tag{16}$$

4.3 Proposed KWLS-CMA Algorithm

Let us use Kaiser window technique to LS-CMA beamformer as

$$w(k+1) = w(k) - \mathrm{kaiser}(N, \chi_o)\vec{v} \tag{17}$$

The array output of Kaiser window least square-constant modulus algorithm (KWLS-CMA) is expressed as

$$\Im(k)_{(\mathrm{KWLS-CMA})} = \overset{*}{x}(k)^{\mathrm{T}} w = w^{\mathrm{H}} \overset{*}{x}(k) \tag{18}$$

5. SIMULATION RESULTS

Let us consider the CM signal arrives at the receiver through a direct path and there are two additional multipaths and consider that the channel is frequency selective. Let the direct path be defined as a binary sequence of 32 chips and the chip values be ±1. Let these values are sampled minimum four times per chip. Let us assume that the angle of direct path is 20° and the angles of multipath are 30° and 45°. Due to these multi paths, time delays are introduced in the binary sequence. Let us choose $L = 8$, $d = \lambda/2$ and $\mu = 0.5$. Figure 2 shows the induced and output signal of CMA antenna array. The output signal has slight time delay due to multipaths. Figure 3 shows the pattern of CMA with look direction at 0°.

Let us use the same conditions and assumptions used to simulate the classical CMA with Number of antenna elements, $N = 8$, Inter-element spacing, $d = \lambda/2$ and block length $K = 20$ data points. Let us consider the initial weight $w(1) = 1$. Figure 4 shows the induced and output signal of LS-CMA antenna array. The output signal has slight time delay due to multipaths. Figure 5 shows the pattern of LS-CMA.

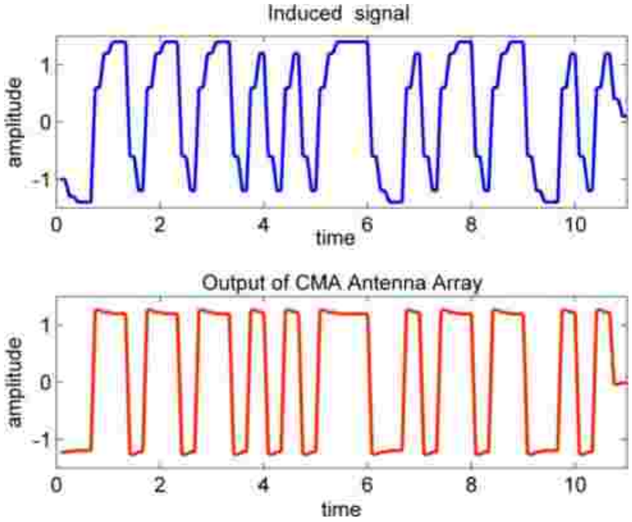

Figure 2: Induced and output signal of CMA

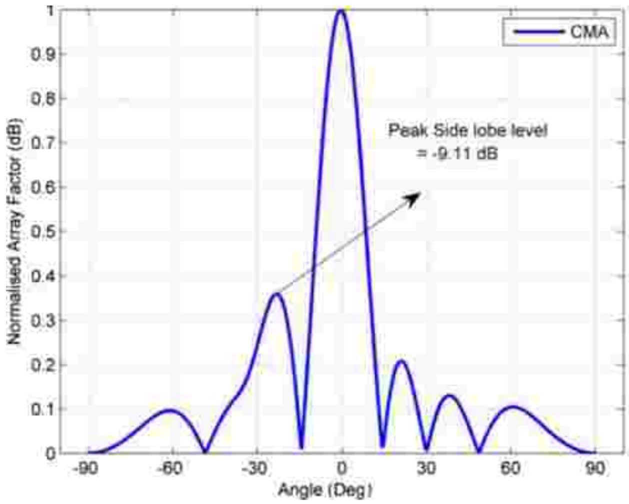

Figure 3: Radiation pattern of classical CMA

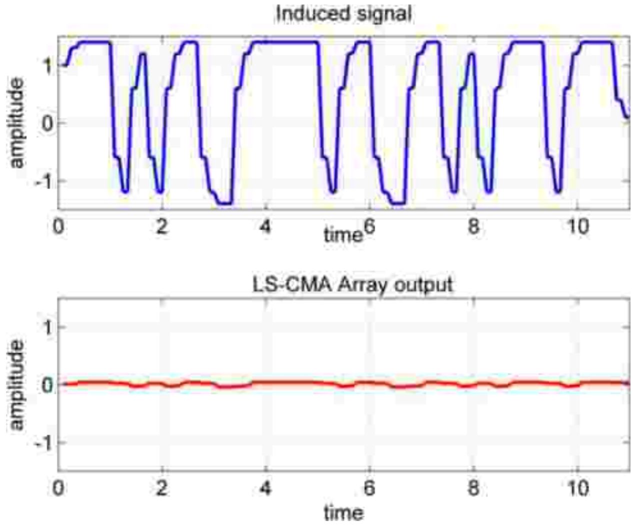

Figure 4: Induced and output signal of LS-CMA

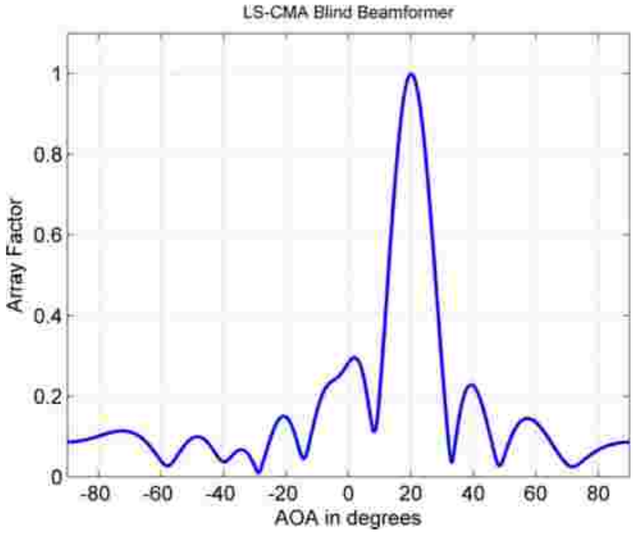

Figure 5: Radiation pattern of LS-CMA

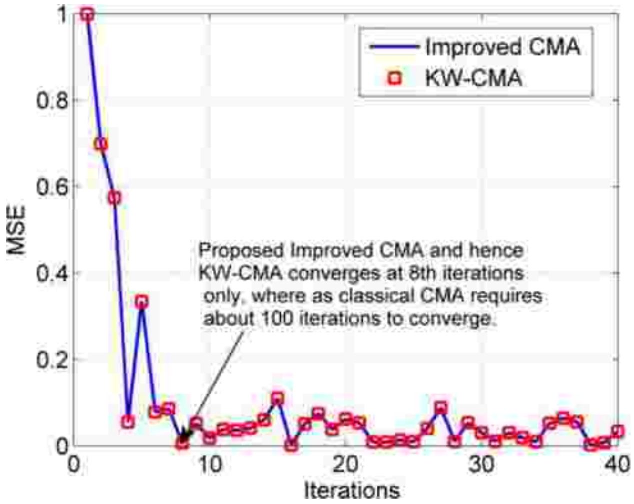

Figure 6: MSE versus iterations of KW-CMA

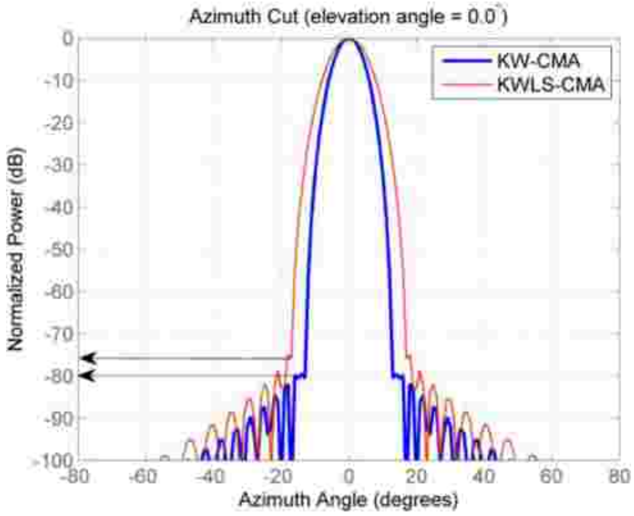

Figure 7: Radiation pattern of KW-CMA and KWLS-CMA for $N = 5$

We considered an ULA with the number of snapshots = 100, array element spacing $d = \lambda/2$ and angle of arrival (AOA) of signal is assumed at 0° with interferences at 50° and $-30°$. The plot of normalized array factor of KW-CMA and KWLS-CMA is shown in Figure 6.

Figures 7–10 shows the array output power gain versus AOA for $N = 5$, 10, 15 and 20, respectively. Table 1 summarizes the performance analysis of KWLS-CMA and KW-CMA.

5.1 Analysis of Convergence Rate

Classic CMA requires over 100 computer simulation iterations to make MSE minimum which is undesirable in most of the practical applications. Figure 6 demonstrates

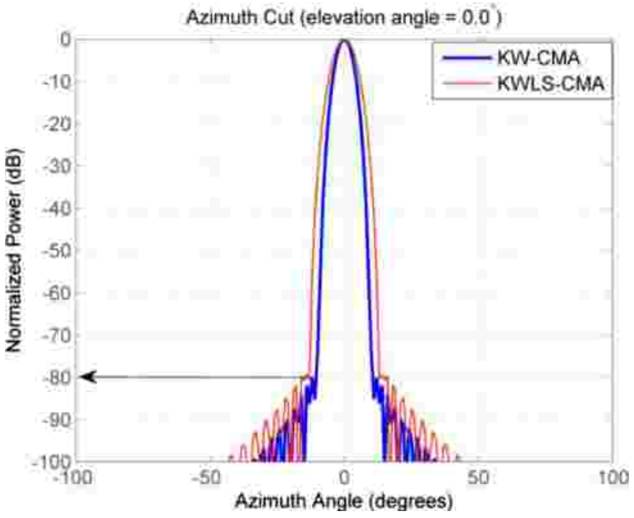

Figure 8: Radiation pattern of KW-CMA and KWLS-CMA for $N = 10$

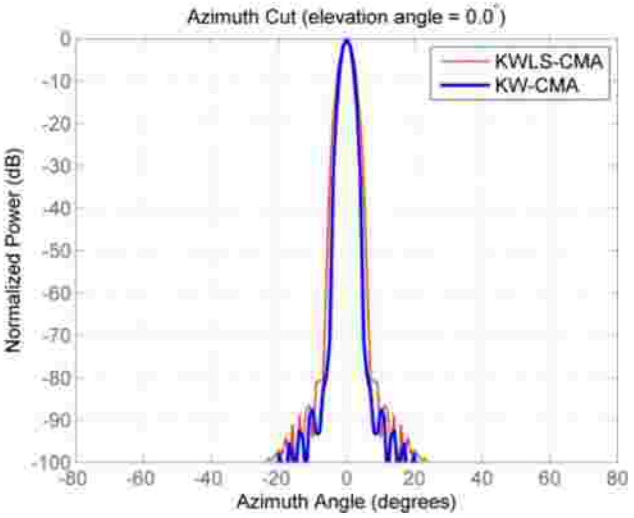

Figure 9: Radiation pattern of KW-CMA and KWLS-CMA for $N = 15$

that the improved CMA proposed KW-CMA algorithms require just 8 iterations for beamforming with main lobe in the user directions and nulls in the interference directions.

5.2 Analysis of PSLL of KW-CMA and KWLS-CMA

From the simulated results, it can be noticed that SLL of both KW-CMA and KWLS-CMA is significantly reduced as the array elements are increased. From Tables 1 and 2, we can notice that, for large arrays ($N = 20$) SLL of -90dB and -92 dB with the beamwidth of 8.1 degrees are achieved for KW-CMA and KW-LSCMA, respectively. Table 3 summarizes the performances of various beamformers.

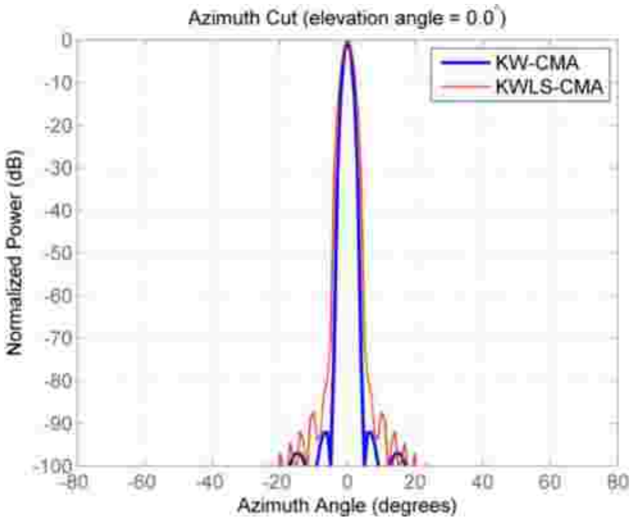

Figure 10: Radiation pattern of KW-CMA and KWLS-CMA for $N = 20$

Table 1: Performance analysis of the proposed KW-CMA algorithms

S. no.	N	SLL (dB)	Beamwidth (deg)
1	5	−58	26.2
2	10	−71	19.1
3	15	−81	15
4	20	−92	8.1

Table 2: Performance analysis of the proposed KWLS-CMA algorithms

S. no.	N	SLL (dB)	Beamwidth (deg)
1	5	−58	26.2
2	10	−72	19.4
3	15	−80	15.2
4	20	−90	8.1

Table 3: Performance analysis of various algorithms

Algorithm	Iterations	PSLL (dB)
LMS [7]	80	7.12
RLS [7]	15	7.5
CGM [14]	8	6.5
CMA [1]	90	6.98
LS-CMA [3]	12	6.97
VSSLMS [7]	50	7.98
VSSNLMS [15]	50	6.43
HW-CMA [13]	8	−44
HW-SCMA [13]	6	−44
KW-CMA [This work]	8	−90
KW-LSCMA [This work]	6	−92

6. CONCLUSION

A new KW-CMA and KWLS-CMA algorithms are proposed in this study. These blind beamformers are implemented using MATLAB software. Classical CMA has slow convergence rate as compared to LS-CMA, which is its major drawback. This limits its use in practical applications where multipath fading is one of the major considerations. Proposed beamformers, particularly KW-CMA, not only reduce SLL effectively but also improve the convergence. Significant reduction in sidelobes is observed by the introduction of Kaiser Window to classical blind algorithms. As result of it, proposed algorithms reduce SLL below -90 dB without much affecting the beamwidth. Hence the proposed blind beamforming algorithms increase convergence rate, directivity and stability with the significant reduction of SLL below -70 dB for small array elements ($N = 10$) and below -90 dB for large arrays ($N > 20$). Hence the proposed KW-CMA and KWLS-CMA can be used in the practical radar communications.

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