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Robust Concentric Circular Antenna Array with Variable Loading Technique in the Presence of Look Direction Disparity

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Abstract—The performance of a Concentric Circular Antenna Array (CCAA) is presented in this paper with variable loading technique. A CCAA geometry is chosen because of its symmetrical configuration which enables the phased array antenna to scan azimuthally with minimal changes in its beam width and side-lobe levels. The performance of CCAA system is degraded, if any disparity occurs between the original signal direction and the steering direction of the beamformer. This performance degradation problem due to look direction disparity can be improved by using robust techniques. This paper proposes a technique, named variable diagonal loading (VDL) technique for CCAA system and compares the performance of the proposed robust CCAA processor with existing CCAA processors. The proposed robust CCAA beamformer enhances the output power 28.9 dB, 9.34 dB and 1.63 dB at 1° disparity angle in comparison to the CCAA standard capon beamformer (SCB), robust SCB and existing novel loading technique. Numerical examples are presented to analyze the performance of the proposed robust beamformer in different scenarios.

1. INTRODUCTION

Smart antenna systems have been used extensively in the communication industries due to their adaptive characteristics since the last decennary. Beamforming techniques are used to make the array antenna system smart. Beamforming is a technique which combines signals from array elements of an array antenna system after multiplying signal from each antenna element with a specified weight [1, 2]. The two main techniques of smart antennas are switched beam array and phased array antennas. The direction of the beam is chosen from a set of predetermined beams in a switched beam array, while the main beam is steered towards a particular direction in a phased array. Using beamforming technique, the beam can be steered at any desired direction electronically, rather than using mechanical rotation of the antenna structure. This electronic manipulation involves changes in both the amplitude and phase excitation of the antenna elements [2, 3].

A CCAA consists of more than one circular antenna array with different radii, and all the circular antenna arrays share a common center. In contrast to linear antenna arrays, the radiation patterns of concentric circular antenna arrays inherently cover the entire space, and the main lobe can be oriented in any desired direction. Large number of antenna elements can be used in a CCAA system compared to an UCA system using same space, whereas it is difficult to install UCA system with large number of antenna elements because of its size limitation [3]. Moreover, the performance of CCAA processor is better than the existing UCA processor [4].

The CCAA with isotropic elements using optimization algorithm called cat swarm optimization (CSO) is presented for the reduction of side-lobe level and improvement in the directivity [5]. Adaptive techniques are used to optimize the radius of the ring and the inter-ring spacing of a CCAA system

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to achieve circularly symmetric pattern with both the reduced SLL and the number of elements [6–8]. A hybrid method based on convex optimization and a deterministic approach is addressed for sparse concentric ring arrays used to optimize both SSL and FNBW [9]. The DOA estimation technique for both circular and concentric circular antenna arrays in the presence of high and low noisy environments is discussed in [10, 11].

The CCAA with delay-and-sum beamforming technique cannot detect and remove directional interference signal. However, the SCB can detect and attenuate the interference signal. If any disparity occurs between the direction of actual signal and the direction at which the array is steered, SCB considers the actual signal as interference signal and highly attenuates the signal [12–16]. The performance degradation due to mismatch between original signal direction and steering angle direction is discussed in [17–21]. The performance degradation problem of a uniform linear array (ULA) system can be minimized by using robust techniques, called robust capon beamforming (RCB) technique [22] and a diagonal loading technique in [23], but with the increase in disparity angle its performance again degrades. Different types of robust algorithms for different array geometries are discussed in [24–28]. The design phenomena about smart antenna system and control strategy are discussed in [29–33]. The techniques discussed in [29–32] are able to optimize the system performance without look direction disparity. The beamformer addressed in [23] is not able to scan beam for entire space, and it is applicable only for 180. The UCA processor discussed in [24] is tough to install with large number of antenna elements because of its size limitation [3].

To overcome the aforementioned difficulties and improve the performance under mismatch robust CCAA processor with variable diagonal loading(VDL) technique is addressed in this paper. The proposed processor has the following desirable properties.

- The main beam can be steered at any arbitrary direction by using CCAA beamformer.
- It is capable to maximize SINR.
- CCAA is able to scan the entire space, i.e., 0° to 360°.
- The proposed CCAA processor is robust against look direction disparity.
- The proposed robust CCAA beamformer enhances the output power 28.9 dB, 9.34 dB and 1.63 dB at 1° disparity angle compared to the CCAA SCB, and beamformers in [22, 26] and [23].
- It provides better capability to cancel directional interference in comparison to the existing beamformers.

This paper is divided into four sections. Section 2 introduces the array geometries and signal model used in this work. Section 3 discusses the proposed beamforming technique. Section 4 analyses and discusses the simulated results, and finally Section 4 concludes the paper.

2. SYSTEM MODEL

The linear antenna array is able to scan the object between 0°–180°, but in many applications, it is essential to scan the object between 0° and 360°. This can be done by using CCAA beamformer because of its circular structure. A block diagram of a communication system using concentric circular antenna array is shown in Fig. 1. After receiving the signal, signal of each antenna element is multiplied by adjustable weight, and weights are estimated according to the desired direction at which one wants to receive the signal.

The general geometry of a concentric circular antenna array is shown in Fig. 2. This CCAA system consists of several ring antenna arrays, which share a common center. The radius of each ring of the antenna array is different, and antenna elements are uniformly distributed, either equal or unequal in number. Referring to Fig. 2, the CCAA system comprises M circular antenna arrays having a radius r_m, where r_m is the radius of the mth ring. The geometry consists of L isotropic elements equally spaced with the center at the origin. The position of each element of the geometry is described by two indices, $m = 1, 2, \ldots, M$ and $l = 1, 2, \ldots, L$. The CCAA geometry is reduced to the regular UCA in the case of $M = 1$. In Fig. 2, the dotted line denotes a plane wave-front incident on the array at an angle α. Let us consider that the two elements of the geometry are positioned at P_1 and P_2. The required

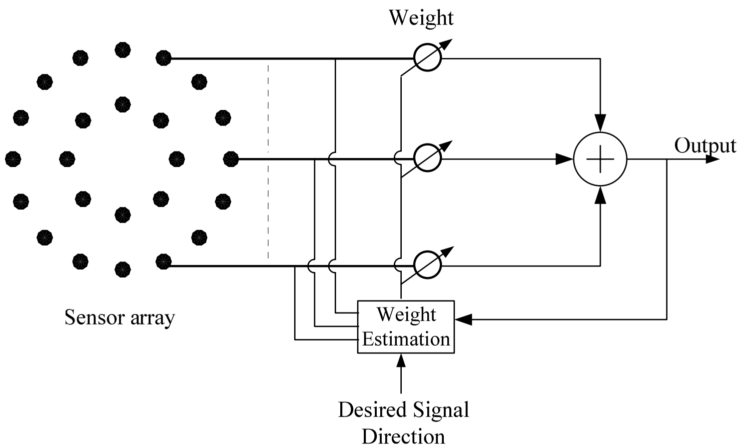

Figure 1. Block diagram of a communication system using concentric circular antenna array.

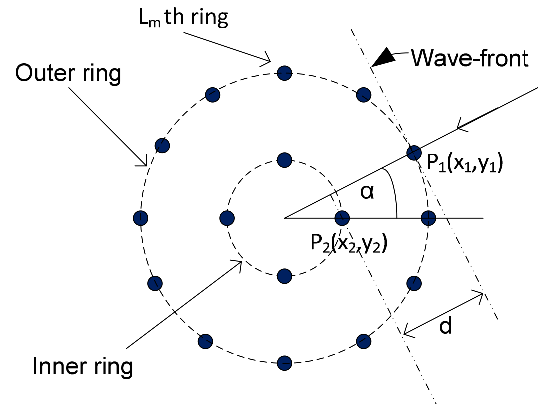

Figure 2. Geometry of concentric circular antenna array system.

distance to travel the wave-front between the two elements is d, then the required time to arrive the wave-front from point P_1 to P_2 is given by,

$$\tau = ((x_1 - x_2)\cos\alpha + (y_1 - y_2)\sin\alpha)/d \tag{1}$$

Both the UCA and CCAA systems have the ability to scan the beam 0°–360°. Fig. 3(b) shows a CCAA structure with 24 antenna elements. If this CCAA structure is compared with the UCA structure of 8 antenna elements shown in Fig. 3(a), one can observe that using the same space, larger number of antenna elements can be used in a CCAA structure. If one wants to use the 24 elements of CCAA system in a UCA system, the required space is increased to 2.25 times of CCAA system, which is shown in Fig. 3(c). Because of this larger size, it is difficult to implement an UCA system in real time compared to a CCAA system.

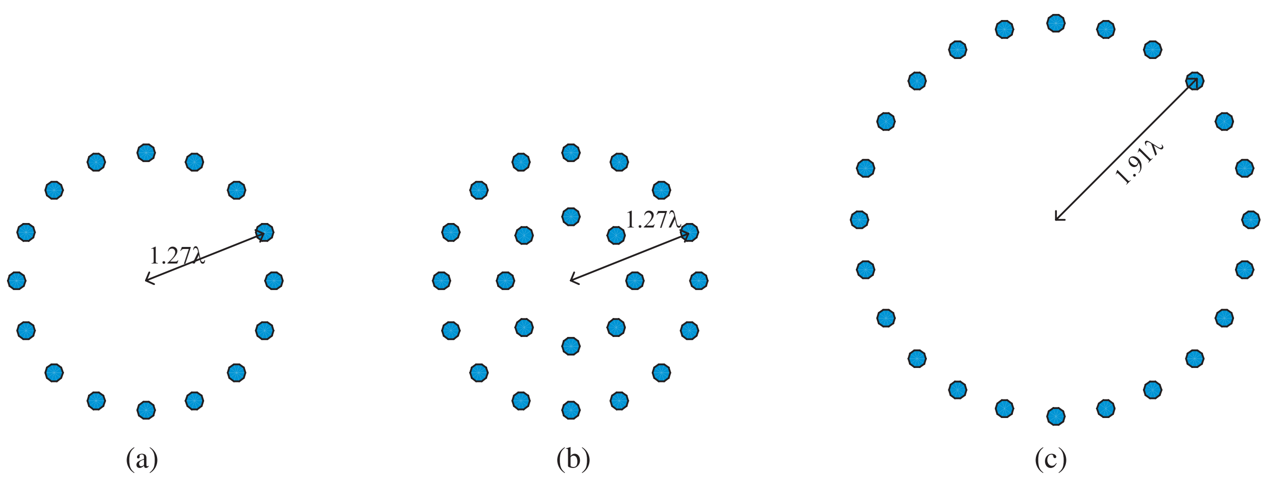

Figure 3. (a) 16 elements UCA structure; (b) 24 elements CCAA structure; (c) 24 elements UCA structure.

The steps for calculating output power are shown in Fig. 4. The induced signal on any array elements due to kth source at any time instant is expressed in complex notation as $m_k(t)e^{j2\pi ft}$. If it is assumed that signal is arrived from the kth source at an angle $(\varphi_k\theta_k)$ and time requires to induce the signal in the lth element is $\tau_l(\varphi_k\theta_k)$, then induced signal on any array elements can be expressed as $m_k(t)e^{j2\pi f(t-\tau_l(\varphi_k,\theta_k))}$. The m_k and f denote complex modulation frequency and carrier frequency respectively. With N directional sources and in the presence of background noise, signal induced in the

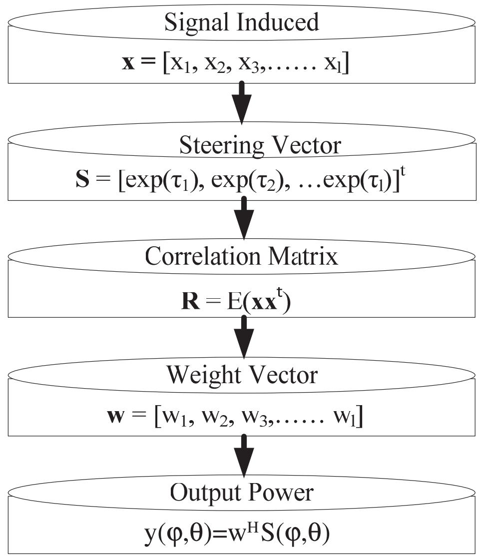

Figure 4. Steps of calculating output power for an antenna array system.

lth element can be written as

$$x_l\,(t) = \sum_{k=1}^{N} m_k(t) e^{j2\pi f(t-\tau_l(\varphi_k,\theta_k))} + n_l(t) \tag{2}$$

where, n_l is the noise component at the lth element. It is assumed that the noise is uncorrelated with directional sources, that is $E[m_k(t)n_l(t)] = 0$. It is also assumed that noises on different elements are uncorrelated, that is $E[n_k(t)n_l(t)] = 0$ for $k \neq l$ and $E[n_k(t)n_l(t)] = \sigma^2$ for $k = l$, where σ^2 is denoted as the noise power.

In the presence of noise and interference, the array correlation matrix can be given as [2],

$$\mathbf{R} = p_s \mathbf{S_0} \mathbf{S_0^H} + p_I \mathbf{S_I} \mathbf{S_I^H} + \sigma_n^2 \mathbf{I} \tag{3}$$

where p_s, p_I and σ_n^2 denote the desired signal power, interference signal power and random noise power, respectively. $\mathbf{S_0}$ and $\mathbf{S_I}$ are the steering vectors at the look direction and interference direction, respectively. After calculating steering vector $\mathbf{S}$ and correlation matrix $\mathbf{R}$, the weighting vector can be given as [3],

$$\hat{W} = \frac{R^{-1} S_0}{S_o^H R^{-1} S_0} \tag{4}$$

3. BEAMFORMING TECHNIQUES

The performance of antenna array depends on which beamforming technique is applied. Beamforming techniques are mainly categorized into two types, delay-and-sum beamforming and SCB. As discussed in the introduction section, the delay and sum beamformer cannot detect and cancel interferences. In this section, the SCB with VDL technique is discussed. The performance of the proposed technique is compared with the existing SCB, RCB [22] and novel diagonal loading technique [23].

The performance of a concentric circular antenna array can be optimized by using VDL compared to the RCB technique. The proposed CCAA based VDL technique is automatic, and the loading level is dependent on signal power, noise power, norm of steering vector both with & without look direction error consideration and steering vector distortion bound. Using VDL technique, the new array correlation matrix due to look direction error can be calculated as [12],

$$\mathbf{R_{new}} = \mathbf{R} + \mathbf{R^{-1}} * \lambda * \mathbf{I} \tag{5}$$

where, λ is shown in the following equation,

$$\lambda = \frac{\varepsilon\left(\sigma_n^2 + p_s\|\mathbf{S_0}\|^2\right)}{\|\mathbf{S_{ac}}\| - \varepsilon} \tag{6}$$

where, p_s denotes the signal power, σ_n^2 the noise power, and norms of the steering vector with and without the look direction disparity are denoted by $\|\mathbf{S_0}\|$ and $\|\mathbf{S_{ac}}\|$, respectively. The steering vector distortion bound ε is given by,

$$\varepsilon = \max(\|\mathbf{S_0} - \mathbf{S_{ac}}\|) \tag{7}$$

It should be noted that with the increase of ε, loading factor increases and approaches infinite when ε is exactly equal to the norm of $\mathbf{S_{ac}}$. VDL provides a close form expression for the loading factor with some approximations. This VDL technique offers a loading factor using a scaled inverse of the original correlation matrix which has more weight adaptation capabilities with look direction error than ODL [13].

4. PERFORMANCE EVALUATION

In this section, the performance of CCAA is evaluated. For analyzing the performance, a two-ring CCAA system with 8 elements in the inner ring and 16 elements in the outer ring is considered. The interelement spacing is considered as half wavelength. It is assumed that the desired signal source broadside to the array is present with a unity power and the directional interferences are assumed to be uncorrelated with the look direction signal. The signal frequency is taken as 3 MHz.

Figure 5 shows a power pattern comparison of SCB, RCB, Diagonal Loading method proposed in [23] and the proposed VDL method for CCAA beamformer. For this example, a signal is considered to receive at 20°, but the direction of actual signal is considered at 21°. A directional interference signal is considered at an angle −25°. From the above mentioned figure, one can easily observe that SCB shows a high attenuation at original signal direction 21°, which means that the performance of SCB is highly degraded and the original signal considered as interference because of the disparity between steering direction and original signal direction. This performance degradation problem can be improved by using robust beamforming technique used in RCB and beamformer in [23]. The performance can be further improved by using the VDL technique for CCAA beamformer.

Table 1. Output power comparison of SCB, RCB, diagonal loading method [23] and proposed VDL method for CCAA.

Beamforming technique	Output power in dB for different disparity angle				
	Without disparity	1° disparity	2° disparity	3° disparity	4° disparity
SCB	0	−28.9566	−42.4559	−50.5586	−56.3727
RCB [22, 26]	0	−9.3917	−19.8354	−27.2182	−32.7652
Novel Loading Method [23]	0	−1.6779	−5.494	−9.7793	−13.8011
Proposed VDL technique	**0**	−0.0484	−0.1685	−0.3611	−0.625

Power receipt by the CCAA beamformer at actual signal with the variation of different disparity angle directions using different methods is shown in Table 1. From Table 1, it is clear that power receipt by the proposed CCAA beamformer is approximately −0.0484 dB, which is much higher than the SCB, RCB and beamformer discussed in [23]. As an interference signal is considered in −25°, from Fig. 5 and Fig. 6, it is also observed that a sharp attenuation occurs at −25° for all the robust beamformers. However, from Fig. 6, one can easily understand that in comparison to the other existing roust beamformer, the proposed beamformer shows higher interference cancellation capability.

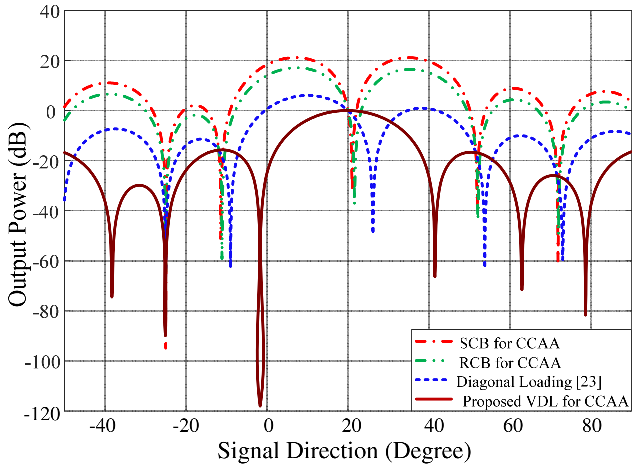

Figure 5. Comparison of the Power pattern of SCB, RCB, Diagonal loading method [23] and proposed VDL method for CCAA beamformer with 1° look direction error (assume signal direction $= 20°$ and actual signal direction $= 21°$) and in the presence of an interfering signal at $-25°$.

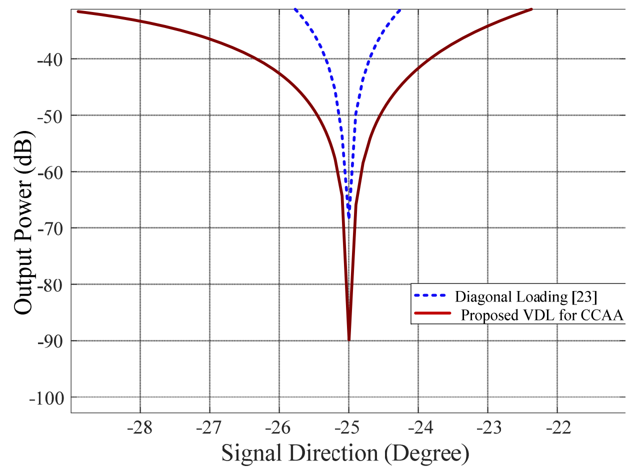

Figure 6. Comparison of the interference cancellation capability CCAA based beamformer with Diagonal Loading Technique [23] and proposed VDL technique.

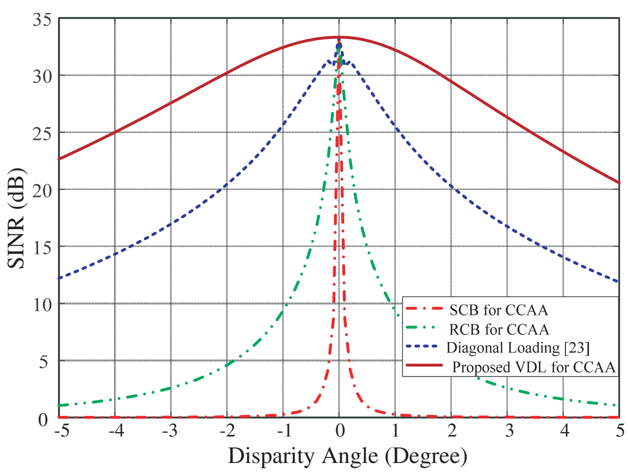

Figure 7. SINR comparison of CCAA based SCB, RCB, Beamformer in [23] and proposed VDL beamformer.

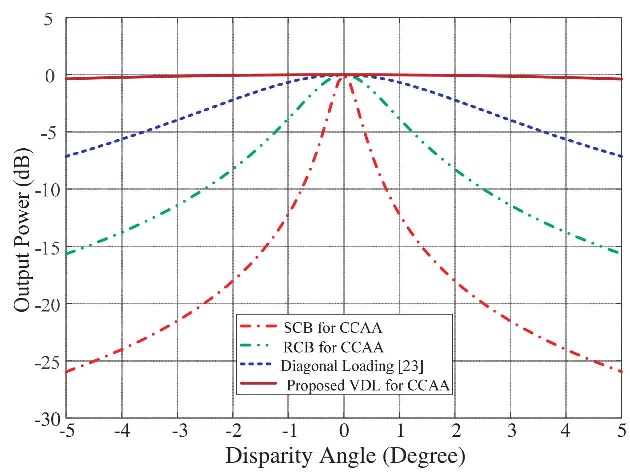

Figure 8. Power pattern comparison of CCAA based SCB, RCB, Beamformer in [23] and proposed VDL beamformer.

Figures 7 and 8 represent the performance of CCAA beamformer using different robust techniques with the variation of disparity angle between actual signal direction and steering direction. From those two figures, one can observe that with the increase in the disparity angle both the output power and SINR of SCB are decreased very much. Though the performance of the system is degraded due to look direction disparity, it is observed that the performance of CCAA processor is improved by using VDL technique which is much higher than the existing loading techniques.

Figure 9(a) is a representation of output SINR versus noise power, and Fig. 9(b) is a representation of output SINR versus SNR of the CCAA system. Both figures are plotted for SCB, RCB, Loading technique in [23] and the proposed beamformer in the presence of noise, interference and look direction error. From those two figures, one can observe that the proposed beamformer with VDL technique can maximize the SINR compared to the existing techniques.

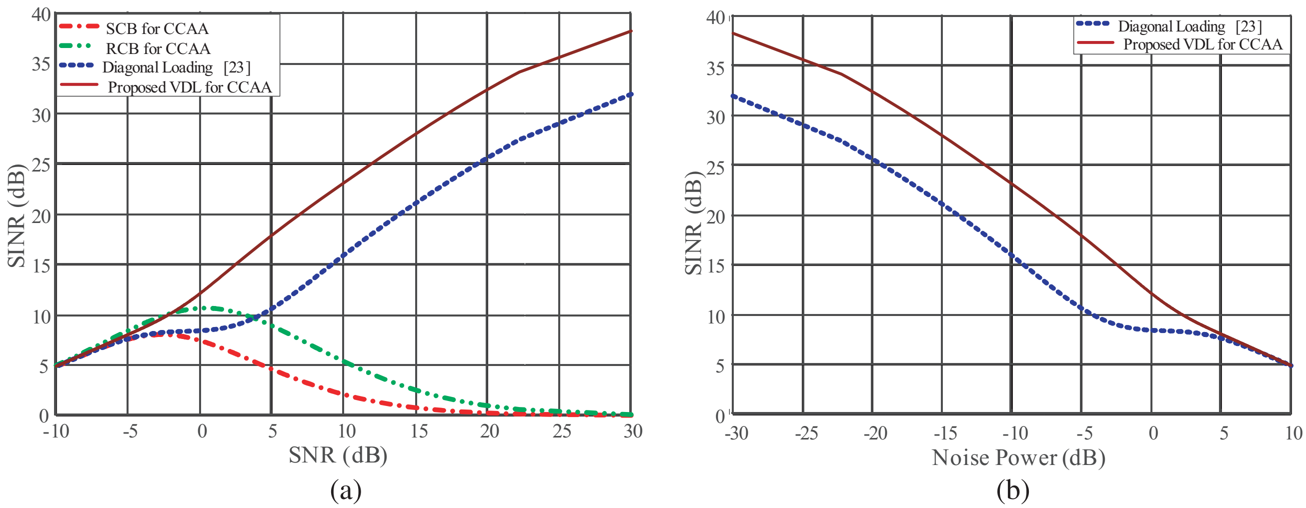

Figure 9. Output SINR variation of CCAA based robust beamformers (a) with the variation of the input SNR, (b) with the variation of noise power in the presence 1° look direction error.

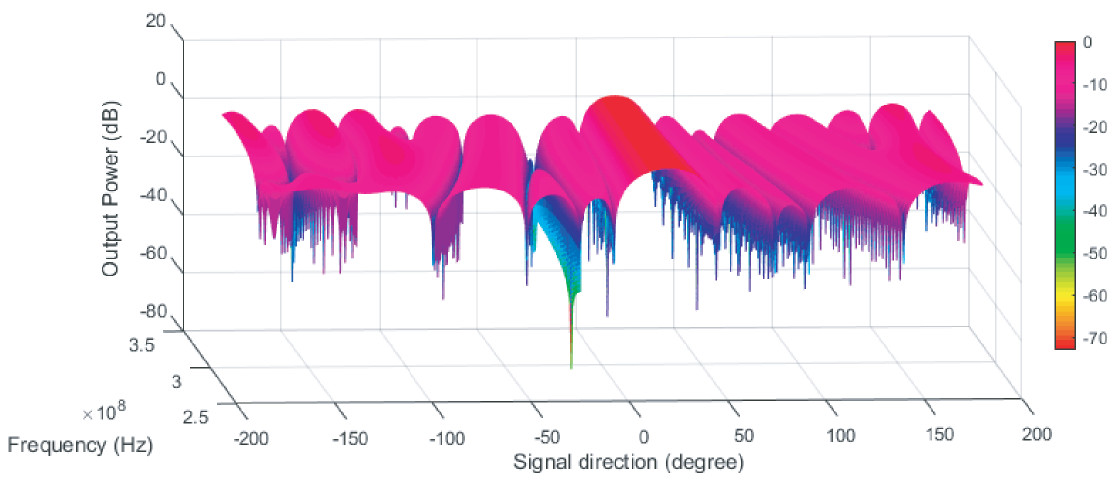

Figure 10. 3-D power pattern of the CCAA processor with respect to signal directions and frequency variation.

Figure 10 presents the 3-D power pattern of the proposed CCAA processor. To present this figure, a directional interference signal is considered at an angle $-25°$ and steering angle direction at 20°. From Fig. 10, one can observe how the performance of CCAA beamformer is varied with the variation of the system frequency.

5. CONCLUSION

The performance of robust CCAA processor is addressed in this paper. As shown in this work, SCB has the ability to detect and attenuate directional interference, but its performance is degraded if any disparity occurs between original signal direction and steering direction. A robust beamformer using VDL technique has been proposed in this paper for CCAA system. It has been observed that the proposed robust CCAA beamformer enhances the output power 28.9 dB, 9.34 dB and 1.63 dB at 1° disparity angle compared to the SCB based CCAA processor and CCAA processor with techniques used in [22, 26] and [23], respectively. Moreover, the proposed beamformer has better interference cancellation capability than the beamformer in [23].

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