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Robust Near-field Narrowband Beamformer Against Steering Angle Mismatch and Distance Error Using Diagonal Loading Technique

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Abstract:- Steering angle mismatch and distance error severely degrade the performance of adaptive beamformer. This digression is more acute in near-field beamforming due to inconvenience of estimating signal's accurate location especially the radial distance. As the radial distance of signals vary in near-field which is constant in case of far-field. So robustness of near-field array against these errors is a must. Diagonal loading is the most popular and easeful method to increase the robustness of beamformer. This paper presents three robust techniques such as Fixed Diagonal Loading (FDL), Optimal Diagonal Loading (ODL) and Variable Diagonal Loading (VDL) for near-field narrowband beamformer and compares their performance with the optimal beamformer. From the investigation it's observed that the proposed robust techniques show superior performance than conventional with high directivity in the desired signal direction, low side lobe level and sharp interference and false signal rejection capability.

Keywords:- *(Beamforming, Near-field, Antenna-array, MVDR, FDL, ODL, VDL)*

I. INTRODUCTION

Beamforming nowadays are being the most emerging topic in signal processing scenario as its providing comprehensive application in the era of RADAR, SONAR, Air traffic control, Wireless and Satellite communication etc. Most of the literature about beamforming has done for far-field case. In far-field signal's radial distance is assumed at infinite distance so a far-field signal arrives at array are considered as plane wave front and that assumption simplify the analysis [1]. In near-field case signal is located at a limited distance that is near-field steering vector is a function of radial distance, elevation and azimuthal angle. So signal received by near-field array is not a plane wave front rather it spherical. A severe performance degradation occurs if a near-field signal is analyzed as plane wave. This paper investigates near field beamformer assuming source signal as spherical wave front.

Narrowband signal has higher sensitivity and longer range than the broadband. Interference effect on narrowband signal is also lower than wideband. In some application such as in mobile telephony, sound recording, microphone array etc. narrowband is more preferable than wideband [1]. Besides a broadband array require tapped delay line (TDL) filter in front of each element [2] that increases computational complexity. So this paper investigates about narrowband processing.

The optimal beamformer which is also known as Minimum variance distortionless response (MVDR) steered the main beam in desired signal direction, cancelling interference solving a constrained optimization problem. These constrained assumes desired signal position and direction. If any mismatch occurs that is if the signal directs from slightly different position or direction then performance of adaptive beamformer is hampered [3-5]. So a robust adaptive beamformer is requisite to remove these look direction disparity and distance error.

Many existing near-field research has done in [6-9] emphasizing only on the optimization of array response for some certain noise and interference environment. Robust and efficient antenna array processor against look direction error is discussed in [10] for far-field signals. Various far-field pattern synthesis techniques for robust broadband array processor are mentioned in [11]. Diagonal loading is the most used robust beamforming method and several diagonal techniques for far-field array processor are applied in [12]. These various loading method can be transferred for near-field array processor.

So the aim of this paper is to design a robust near-field narrowband FDL, ODL and VDL based array processor and to compare the array response pattern of these robust techniques with the adaptive beamformer. Simulation results show that any steering angle and distance disparity harshly demote the performance of optimal beamformer and ODL and VDL robust techniques restore the optimum performance. This paper also investigates that how look direction disparity and distance error affects on array signal power and SINR performance. Analysis shows that proposed ODL offers least signal cancellation rate at look direction error but in the presence of distance error proposed VDL performs better than ODL. VDL based robust beamformer maintains almost constant SINR over the array processor than robust FDL and ODL method.

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II. NEAR-FIELD SYSTEM MODEL

A signal is considered as near-field signal if the radial distance of signal from the reference be $r < 2D^2/\lambda$ where D denotes maximum dimension of antenna known as antenna aperture and λ be the wavelength of signal [13]. Let consider a linear antenna array with L elements and distance of each element from another be d also consider the origin of the coordinate system shown in Fig. 1 be the time reference.

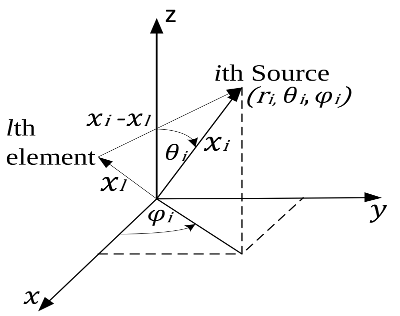

Fig.1: Near field coordinate system.

Let the focal point of a *ith* near field signal is $(r_i\ \theta_i\ \phi_i)$, *here* r_i denotes radial distance, θ_i is the angle of elevation and ϕ_i be the azimuth angle. Assuming that the signal from that focal point directs towards the array and time taken by this spherical wave front to reach the array and measured from the *lth* element to origin is given by [14]

$$\tau_{il}(r_i\ \theta_i\ \phi_i) = (|\,x_i - x_l\,| - |\,x_i\,|)\,/\,c \quad (1)$$

Where

$$x_i = r_i\,(\sin\theta_i \cos\phi_i + \sin\theta_i \sin\phi_i + \cos\theta_i\,) \quad (2)$$

be the position vector of *ith* signal source. Similarly x_l denotes position vector of *lth* element and c is the speed of propagation of spherical wave front. For L elements antenna array let signal induced on array is $x_1(t), x_2(t)\ldots\ldots\ldots\ldots x_L(t)$. In vector notation induced signal $x(t)$ of array is given by

$$x(t) = [x_1(t), x_2(t)\ldots\ldots\ldots\ldots x_L(t)]^T \quad (3)$$

If the distance between *lth* element and *ith* source be r_{il} then induced signal at *lth* element is given by [15]

$$x_l(t) = r_i * s_i(t+\tau_{il})\,/\,r_{il} + n_l(t) \quad (4)$$

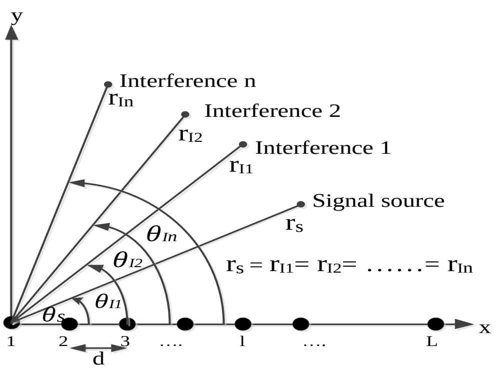

Fig. 2: Direction of arrival (DOA) of signals keeping radial distance as constant.

Here $n_l(t)$ denotes total noise of *lth* element and $E[n_k(t)\ n_l(t)] = 0$ for $k \neq l$ and $E[n_k(t)\ n_l(t)] = \sigma_n^2$ for $k=l$ means that noise of each element is uncorrelated with another also this noise signal is uncorrelated with source signal. Here σ_n^2 denotes noise power.

In this paper array response pattern, signal power and SINR are investigated at two point of view. Firstly power pattern, signal power and SINR are analyzed in the presence of look direction error that is steering angle is varied keeping radial distance of signal as constant shown in Fig. 2. Secondly the same parameters are observed against distance error that is the radial distance of signal is changed while the signals steering angle is constant like that of Fig. 3

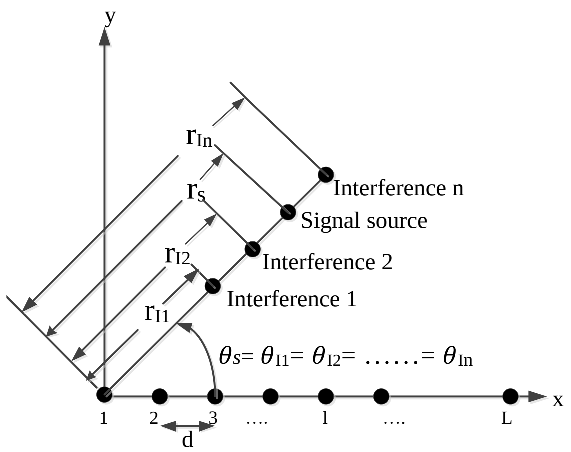

Fig. 3: Distance discrimination of signals while angle of arrival is constant.

Total array correlation matrix R of this near-field processor is given by

$$R = P_s\, S_0^H\, S_0 + P_i\, S_i^H\, S_i + \sigma_n^2 I \quad (5)$$

Here P_s be the power of the signal of interest, S_0 denotes look direction steering vector, S_i is the steering vector at the interference direction, P_i be the interference power and I denotes identity matrix.

III. BEAMFORMING TECHNIQUES

Techniques of beamformer defines the performance of beamforming array processor. Conventional beamformer shows maximum response in the look direction but can't detect and nullify interference sources. Optimal array processor has the ability to sense and cancel out these directional interferences but at steering vector mismatch it provides worst performance. It considers actual signal of interest (SOI) as interference and create null in that direction. Robust FDL, ODL and VDL can recover these problems. In this section Optimal, FDL, ODL and VDL techniques are described shortly.

A. *Optimal Beamformer*

Optimal or MVDR beamformer maximizes output SINR without the knowledge of interference power and direction with only knowing SOI direction [16]. The weight of optimal beamformer is selected as

$$w = R^{-1} S_0 / S_0^H R^{-1} S_0 \qquad (6)$$

Here R denotes total array correlation matrix and weight w is the solution of the following optimization problem

$$\underset{w}{\text{minimize}} \quad w^H R\, w$$
$$\text{Subject to} \quad w^H S_0 = 1$$

This constraints minimizes noise and interference power, keeping unity response at SOI direction. Minimization of noise and interference maximizes output SNR.

B. Fixed Diagonal Loading Method

Optimal beamformer can't provide precise performance at steering vector errors. FDL techniques recover the problem of this optimal beamformer by updating the array correlation matrix diagonally with a fixed value

$$R_{FDL} = R + \xi * I \qquad (7)$$

ξ denotes FDL factor and the value of this constant is fixed to $10\sigma_n^2$. To determine this value is a challenging task which is discussed in [17].

C. Robust Optimal Diagonal Loading Technique

ODL performs better than FDL in near-field array processor against direction of arrival and distance error. Array correlation matrix for ODL is given by [18]

$$R_{ODL} = R + \xi * I \qquad (8)$$

The constant ξ for ODL computed using SOI power, noise power, norm of steering vector with and without considering steering vector mismatch and defined as

$$\xi = \varepsilon\,(\sigma_n^2 + P_s \,\|S_0\|^2) / \|S_{ac}\| - \varepsilon \qquad (9)$$

Where $\|S_0\|$ and $\|S_{ac}\|$ are the norm of steering vector without and with considering the DOA and Distance error. The distortion bound of steering vector, ε is given by [19]

$$\varepsilon = \max(\|S_0 - S_{ac}\|) \qquad (10)$$

D. Robust Variable Diagonal Loading

Correlation matrix for VDL is defined as

$$R_{VDL} = R + R^{-1} * \xi * I \qquad (11)$$

VDL correlation matrix is updated using inverse of original correlation matrix that provides superior weight adaption capabilities against steering vector error. The constant ξ is calculated [20] using (9) and (10).

IV. PERFORMANCE EVALUATION

Array power pattern of near-field narrowband based optimal, robust FDL, ODL, and VDL beamformer against signals incidence angle and radial distance of signals are analyzed in this section. Output power and SINR variation against DOA and distance error are also shown.

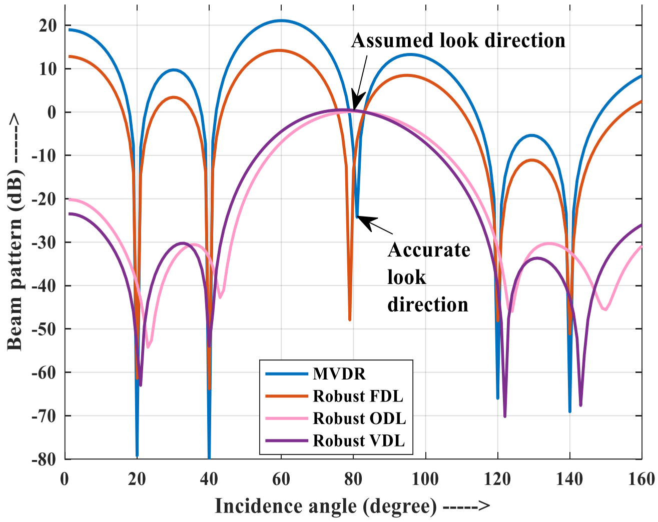

Fig. 4: Array power pattern with 1^0 look direction error when elements no. of the array = 50, signal power = 1.0, assumed signals position (r, θ, φ) = (11λ, 80^0, 90^0), position of accurate signal (r, θ, φ) = (11λ, 81^0, 90^0), interference no. = 4, power of each interference = 10, interference position: (11λ, 20^0, 90^0), (11λ, 40^0, 90^0), (11λ, 120^0, 90^0), (11λ, 140^0, 90^0), noise power = 0.01.

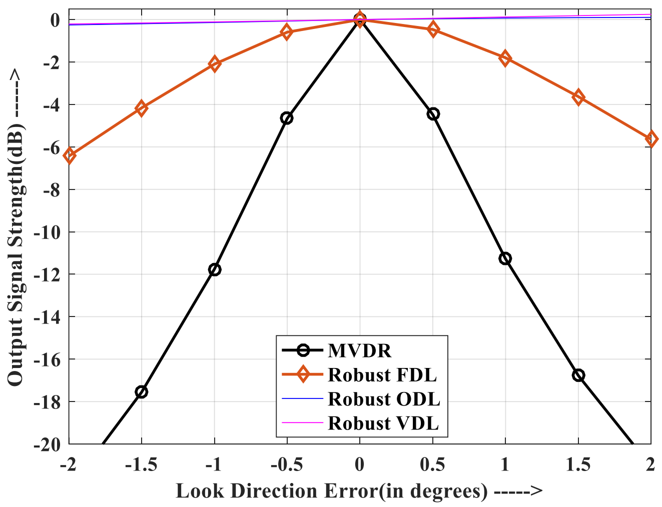

Fig. 5: Output signal power variation against look direction error when elements no. of the array = 50, signal power = 1.0, interference no. = 4, power of each interference = 10, interference position: (11λ, 20^0, 90^0), (11λ, 40^0, 90^0), (11λ, 120^0, 90^0), (11λ, 140^0, 90^0), noise power = 0.01.

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Fig. 4 shows power pattern of MVDR and three robust FDL, ODL and VDL beamformer with respect to signals incidence angle. MVDR is unable to overcome look direction error it takes accurate look direction as interference i.e. create null at exact signal direction. FDL can't recover the problem of optimal beamformer rather it acts like that of MVDR. ODL and VDL provide robustness against look direction error i.e. if signals position is slightly deviated from its accurate position ODL and VDL don't take it as error rather these show maximum array response in accurate signal direction. While providing robustness VDL performs better than ODL as ODL can't generate null at exact interference direction (e.g. fourth interference positioned at 140^0 in Fig. 4) but VDL has almost done.

Fig. 5 shows output signal strength variation of four beamformer against signals steering angle error. MVDR which is not robust shows worst performance. For the conventional MVDR beamformer the output signal decays at a large rate with increasing the look direction error. It is observed from this figure that the proposed robust techniques provides less signal cancellation. Fig. 6 clarifies that ODL based robust beamformer has less signal power variation i.e. less signal cancellation rate. Table 1 displays a comparison of signal strength variation for different beamforming techniques. Fig.7 expresses output SINR change with look direction error. Conventional MVDR beamformer has sharp SINR changes with error in incidence angle. VDL performs best among these three robust beamformer in terms of SINR variation.

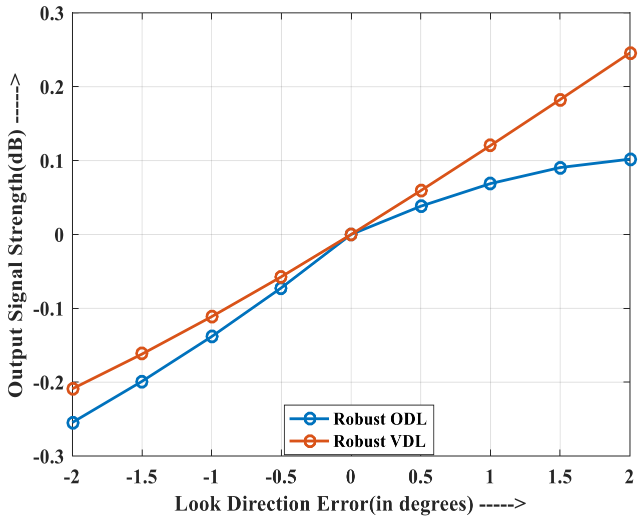

Fig. 6: Output signal power variation of proposed ODL and proposed VDL against look direction error when elements no. of the array = 50, signal power = 1.0, interference no. = 4, power of each interference = 10, interference position: (11λ, 20^0, 90^0), (11λ, 40^0, 90^0), (11λ, 120^0, 90^0), (11λ, 140^0, 90^0), noise power = 0.01.

Table 1: Output signal strength variation against DOA angle error of conventional MVDR and proposed robust FDL, ODL and VDL techniques

Beamforming techniques	**Output signal strength variation in dB for several DOA error**				
	Without error	**0.5^o disparity**	**1^o disparity**	**1.5^o disparity**	**2^o disparity**
MVDR	0	-4.477	-11.28	-16.78	-21.07
FDL	0	-0.468	-1.802	-3.633	-5.642
ODL	0	0.0382	0.0689	0.0905	0.102
VDL	0	0.0593	0.1203	0.1827	0.2457

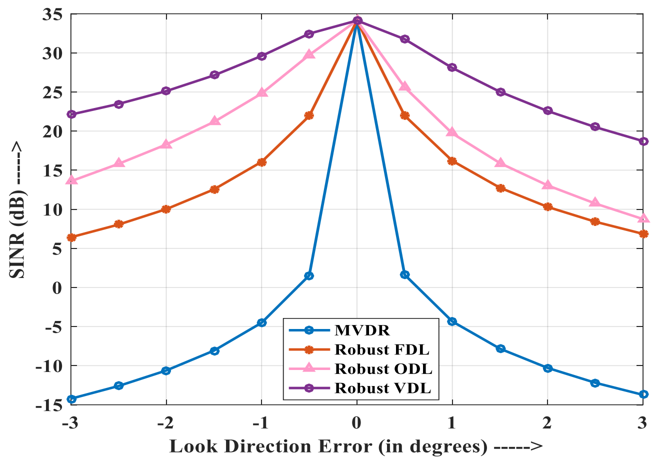

Fig. 7: Output SINR variation against look direction error when elements no. of the array = 50, signal power = 1.0, interference no. = 4, power of each interference = 10, interference position: (11λ, 20^0, 90^0), (11λ, 40^0, 90^0), (11λ, 120^0, 90^0), (11λ, 140^0, 90^0), noise power = 0.01.

Near-field beamforming array processor is not only the function of signals incidence angle but also of signals radial distance. This section discusses the performance of conventional optimal beamformer against signals radial distance error and how the problems of this optimal beamformer can be overcome using various robust techniques.

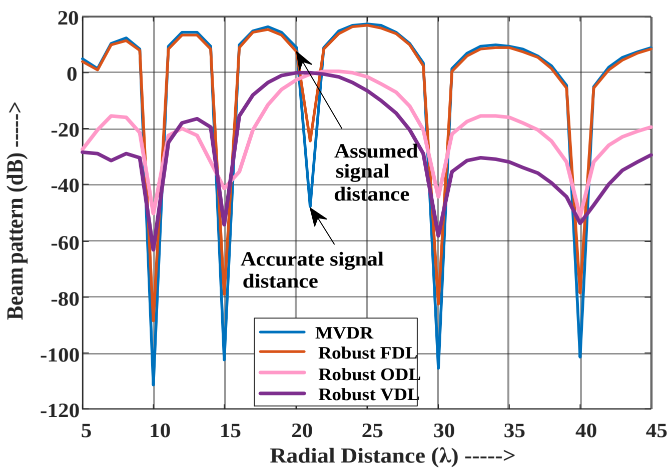

Fig. 8: Array power pattern with 1λ look direction error when elements no. of the array = 70, signal power = 1.0, assumed signals position (r, θ, φ) = (20λ, 50^0, 90^0), position of accurate signal (r, θ, φ) = (21λ, 50^0, 90^0), interference no. = 4, power of each interference =

10, interference position: (10λ, 50^0, 90^0), (15λ, 50^0, 90^0), (30λ, 50^0, 90^0), (40λ, 50^0, 90^0), noise power = 0.01.

Fig. 8 compares the beampattern of various beamformer. Conventional MVDR can't differentiate the assumed and accurate signal's distance i.e. when incidence signal is slightly deviated from its accurate distance MVDR beamformer can't provide maximum response rather it takes this deviation as interference and create null at accurate position.

Output signal strength and output SINR variation against signals radial distance are shown at Fig. 9 and Fig. 11 respectively. Robust ODL and VDL performs better than MVDR and FDL method. Fig. 10 clarify the performance of robust ODL and VDL. VDL shows less signal power variation compared to ODL and VDL display positive power error in according with the distance error. Table 2 compares the signal strength of various beamformer in the presence of distance error. One can observes from Fig.11 that the proposed VDL based robust beamformer has comparatively slower SINR degradation property.

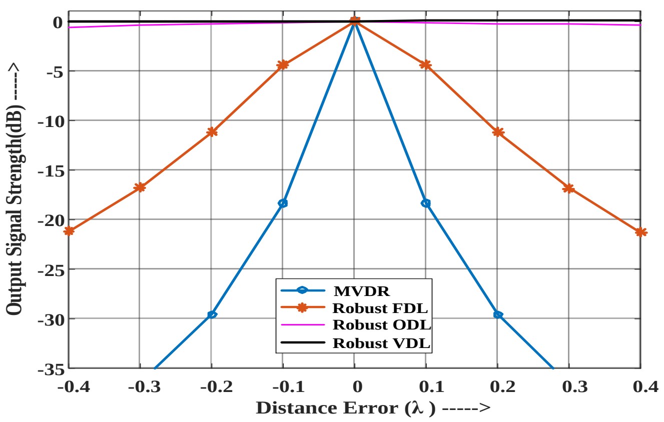

Fig. 9: Output signal strength variation against look direction error when elements no. of the array = 70, signal power = 1.0, interference no. = 4, power of each interference = 10, interference position: (10λ, 50^0, 90^0), (15λ, 50^0, 90^0), (30λ, 50^0, 90^0), (40λ, 50^0, 90^0), noise power = 0.01.

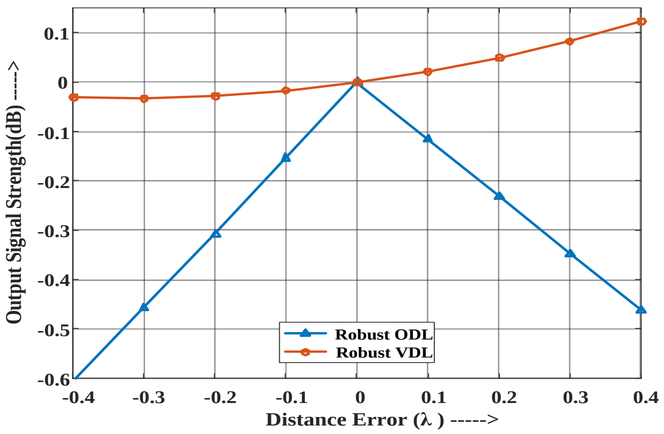

Fig. 10: Comparison of ODL and VDL robust techniques while measuring output signal strength against signals distance error when elements no. of the array = 70, signal power = 1.0, interference no. = 4, power of each interference = 10, interference position: (10λ, 50^0, 90^0), (15λ, 50^0, 90^0), (30λ, 50^0, 90^0), (40λ, 50^0, 90^0), noise power = 0.01.

Table 2: Output signal strength variation against distance error of conventional MVDR and proposed robust FDL, ODL and VDL techniques

Beamforming techniques	Output signal strength variation in dB for several distance error				
	Without error	0.1λ disparity	0.2λ disparity	0.3λ disparity	0.4λ disparity
MVDR	0	-18.37	-29.59	-36.47	-41.40
FDL	0	-4.41	-11.25	-16.86	-21.28
ODL	0	-0.1162	-0.2321	-0.3474	-0.4622
VDL	0	0.0215	0.0493	0.0834	0.1237

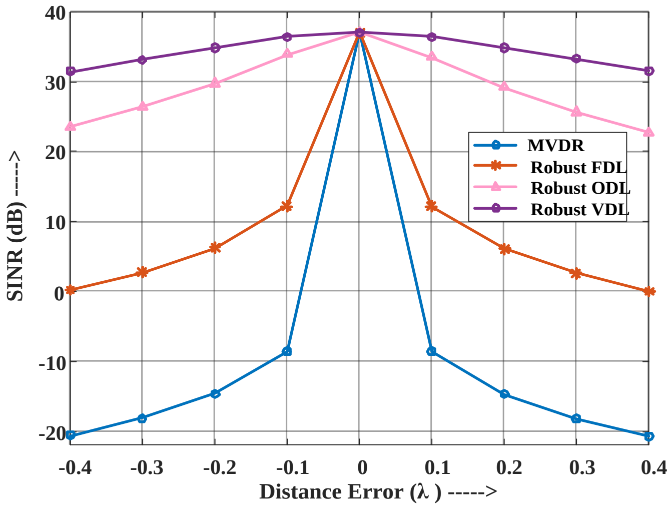

Fig. 11: Output SINR variation against look direction error when elements no. of the array = 70, signal power = 1.0, interference no. = 4, power of each interference = 10, interference position: (10λ, 50^0, 90^0), (15λ, 50^0, 90^0), (30λ, 50^0, 90^0), (40λ, 50^0, 90^0), noise power = 0.01.

V. CONCLUSION

In this paper three robust beamforming techniques are discussed to remove the problems of conventional MVDR beamformer as severe performance degradation of MVDR beamformer occurs in the presence of steering angle mismatch and distance error. MVDR beamforming array processor provides maximum array response in the desired signal direction creating null at each interference position but this performance don't sustain if the signals position is displaced from its previous position. MVDR takes the signal displacement as interference signal i.e. provides null at accurate signals position. This paper proposes three robust beamforming techniques FDL, ODL and VDL. Fig. 4 and Fig. 8 elucidates that FDL can't provide maximum radiation pattern at accurate signal position but it has less signal and SINR cancellation rate than MVDR. ODL and VDL techniques can sense any slight steering angle variation or any slight radial distance changes but don't receive it as interference or false signal rather continues to maintain maximum array response in accurate signal direction. Fig.4 confirms that at look direction error VDL performs better than ODL as ODL don't indicate null at exact interference direction. Table 1 shows that at 2^0 error output signal power variation of ODL and VDL are 0.1020 dB and 0.2457 dB respectively i.e. ODL based beamformer has least signal cancellation rate. But from Table 2 one can observe that output power variation for ODL based beamformer is -0.4622 dB and for VDL is 0.1237 dB at 0.4 disparity i.e. at distance error VDL beamformer has little power change. Fig. 7 and Fig. 11 prove that VDL has higher capability to retain constant SINR over the array processor.

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