Performance Analysis of Robust Acoustic Circular Microphone Array Beamformer

Nigar, Sarah
Department of Electrical and Electronic Engineering, Rajshahi University of Engineering and Technology (RUET)

Md. Faruk Hossain
Department of Electrical and Electronic Engineering, Rajshahi University of Engineering and Technology (RUET)

Md. Tarek Hossein
Department of Electrical and Electronic Engineering, Rajshahi University of Engineering and Technology (RUET)

Md. Shahel Zakaria
Department of Electrical and Electronic Engineering, Rajshahi University of Engineering and Technology (RUET)

https://doi.org/10.5109/7158002

出版情報：Proceedings of International Exchange and Innovation Conference on Engineering & Sciences (IEICES). 9, pp.361-367, 2023-10-19. 九州大学大学院総合理工学府
バージョン：

Performance Analysis of Robust Acoustic Circular Microphone Array Beamformer

Sarah Nigar[1*], Md. Faruk Hossain[1], Md. Tarek Hossein [1], Md. Shahel Zakaria [1]
1. Department of Electrical and Electronic Engineering, Rajshahi University of Engineering and Technology (RUET), Rajshahi-6204, Bangladesh
*Corresponding author email: sarahnigar1998@gmail.com

Abstract: *The robust acoustic microphone array beamformer is a relatively new instrument used in noisy environments to highlight a single sound source, like noise, interferences, reverberations etc. This paper proposes a robust uniform circular array (UCA) system with noise and interference sources. Compared to Frost with Optimal Diagonal Loading (ODL) and Frost with Fixed Diagonal Loading (FDL), both the FDL Frost and the ODL Frost experience performance drops in the look direction error. This model also provides adaptability against mismatch of arrival path by the suggested robust diagonal loading strategies, Frost with Variable Diagonal Loading (VDL) and Frost with New Variable Loading (NVL). The suggested robust beamformers can provide a high array gain and improved SINR in addition to being adaptive to the error of look direction. The frost with NVL gives the highest array gain among all the robust beamforming techniques. The proposed model uses MATLAB simulation.*

Keywords: Microphone array; Acoustic signal; Robust; Beamforming; Diagonal loading.

1. INTRODUCTION

The signal processing method is known as beamforming applied in audio and radio communications. Improving the desired signal quality while reducing interference and noise from other directions entails merging signals from several sensors (such as microphones or antennas). Beamforming is a technique used to enhance the signal-to-noise ratio (SNR) and concentrate the sensor array's sensitivity on a specific source or direction. From a given direction, this approach provides the expected frequency. This results in rejecting all other frequencies and the same frequency coming from different directions [1]. Communications sector Sonar, imaging, astrophysical exploration, radar, and geophysical research are just some array-processing applications that rely significantly on antenna array processors or beamformers. Cellular communication has attracted scientific interest in recent decades due to its extensive use in seismology [2].

A group of several microphones arranged in a specific geometric pattern is known as a microphone array. Because of their improved capabilities in signal recognition [3], adaption of origin [4], minimization of noise as well as interference [5], and other areas, microphone arrays are frequently utilized. The two primary processing operations on microphone arrays are beamforming of the array and adaption of origin and tracking [6].

A microphone array system finds locating the desired human voice challenging among the background noise and other speeches [2]. There is, therefore, no other option for a clear human voice but beamforming. The beamforming technique can extract the desired signal in a noisy environment [7]. The efficacy of the beamforming technique for high-frequency sounds decreases as the sound source's frequency rises because the time delays between microphones get smaller than before [8]. It cannot adequately account for spatially variable noise sources or respond to changes in the acoustic environment. Speech signal processing can use adaptive beamformers like Minimum Variance Distortion less Response (MVDR) [9]. However, in a noisy environment, it performs poorly. On stereo noise reduction, a strong MVDR is achieved [10]. In this case, the critical restriction is that the Direction of Arrival (DOA) mismatch cannot be considered [7].

That is why some robust beamforming approaches are addressed to overcome the problems mentioned earlier. These robust methods are known as the following: (1) Fixed Diagonal Loading (FDL); (2) Optimal Diagonal Loading (ODL); (3) Variable Diagonal Loading (VDL); (4) New Variable Loading (NVL) [11]. The FDL [12] and ODL [13] have already been discussed with their pros and cons. In this paper, VDL and NVL are proposed for their higher output gains and higher SINR. The suggested methods also maintain higher quality with the variation of different values of angle of disparity, the microphone element number, different values of interference direction, different noise power, and filter lengths than the techniques already proposed in [13].

Understanding the steering vector errors for NVL and VDL is unnecessary. As is customary for broadband beamformers, none of the techniques described in this study call for presteering delays after each sensor to compensate for the deviation between the look direction and the array's sensors [14]. A robust Uniform Circular Array (UCA) system has been proposed in this paper. While both the circular and rectangular arrays can scan 360 degrees azimuthally, the linear array can only scan 180 degrees. Therefore, circular and rectangular arrays help search objects in all directions (360 degrees) [15]. According to computer simulations, the suggested robust UCA-based beamformer improves the gain of the array by 0.8143 dB and 0.8769 dB at an angle of disparity of 3°, respectively, over the FDL Frost and ODL Frost techniques [7].

2. SYSTEM MODEL

Let us assume a wideband uniform circular array (UCA) with n elements to receive the expected signal and interference, echo, reverberation, and noise. Figure 1 represents a UCA system in which different signals impinge on it.

The array output is obtained by adding after being multiplied by the complex weights. Figure1 demonstrates the expression for the output of the array [11].

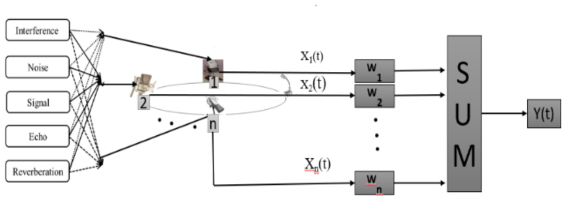

Figure 1. Several sound signal sources impinge on a uniform circular microphone array for signal processing.

Array Output is y_0 ,

$$y_o(t)=\begin{bmatrix} w_1 . & . & . w_n \end{bmatrix}\begin{bmatrix} x_1(t) \\ . \\ . \\ . \\ x_n(t) \end{bmatrix} \qquad (1)$$

$$y_o(t)=\sum_{i=1}^{n} w_i^* x_i(t)$$

$$= \underline{w}^* x(t) \qquad (2)$$

Where the complex conjugate is indicated by an *, the mathematical impression is made simpler using the conjugate of complex weights. Using vector notation to represent the array system's weights as [11],

$$\underline{w}=\begin{bmatrix} w_1, & w_2, & w_3,............w_n \end{bmatrix}^T \qquad (3)$$

Where the superscript T refers to the transposition of a vector or matrix.

The signals which are induced on all the elements are as [11],

$$\underline{x}(t)=\begin{bmatrix} x_1(t), & x_2(t), & x_3(t),..........x_n(t) \end{bmatrix}^T \qquad (4)$$

In an environment of loud noise as well as interference, the received signal matrix of correlation can be expressed as [7],

$$R_e = E|x(t)x^H(t)| \qquad (5)$$

Where the superscript H refers to the complex conjugate transposition of a vector or matrix.

Robust beamforming techniques, like different types of diagonal loading techniques, are a simple way to increase the robustness of the beamformer.

1.*Fixed Diagonal Loading (FDL):*

This robust method can mitigate signal cancellation due to the shortcomings of arrays by introducing a fixed value to the correlation matrix in the diagonal direction. The robust matrix of correlation is shown by

$$R_{FDL} = R + \beta * I \qquad (6)$$

Here, R is the correlation matrix without disparity angle and is the diagonal loading factor. I is the matrix of identity. The value of β equals 10, which denotes the system surrounding noise. [16]

2.*Optimal Diagonal Loading (ODL):*

The optimal diagonal method presumes the error to be constrained by a factor selected by the array construction, and the robust algorithm is shown by [17].

$$R_{ODL} = R + \beta * I \qquad (7)$$

where, loading factor:

$$\beta = \frac{\epsilon(\alpha_n^2 + P_d ||S_d||^2)}{||S_{ac}|| - \epsilon} \qquad (8)$$

The steering vector's distortion bound is calculated by:

$$\epsilon = max(||S_d - S_{ac}||) \qquad (9)$$

where, P_d is the desired signal power, S_d and S_{ac} are the norm of steering vector without and with look direction disparity, *squared is* the background noise power.

3.*Variable Diagonal Loading (VDL):*

The variable loading factor is determined by utilizing a scaled inverse of the original correlation matrix R, which possesses enhanced adaptability to account for imperfections within the array [17].

$$R_{VDL} = R + R^{-1} * \beta * I \qquad (10)$$

Where, loading factor:

$$\beta = \frac{\epsilon(\alpha_n^2 + P_d ||S_d||^2)}{||S_{ac}|| - \epsilon} \qquad (11)$$

The steering vector's distortion bound is calculated by:

$$\epsilon = max(||S_d - S_{ac}||) \qquad (12)$$

Where, P_d = desired signal power, S_d = norm of the vector of steering without disparity of look direction [18], S_{ac} = steering vector'norm with disparity of look direction, α_n^2 = background noise power.

4.*New Variable Loading (NVL):*

In NVL technique [19], Correlation matrix considering look direction error:

$$R_{VDL} = R + R^{-1} * \mu * I \tag{13}$$

Where,loading factor

$$\mu = 1 + \gamma \tag{14}$$

$$\gamma = min[v * \frac{p}{||R_{fac} - v*I||^2}, v] \tag{15}$$

$$v = \frac{tr(R_{fac})}{L} \text{ and } p = ||R_{fas} - R_{fac}||_F \tag{16}$$

Array output power in vector form:

$$P(w) = w^H R w \tag{17}$$

Where, R_{fas} *and* R_{fac} are respectively given by equation (17) with R replaced by the matrix of correlation of broadband array R_{as} Without error and by R_{ac} with error.

tr(.) and $||\ .\ ||_F$ respectively represent the operator trace and Frobenius norm of a matrix.

The UCA VDL and NVL procedures are being proposed in place of the ODL technique and depend on the steering vector's signal power, noise power, and norm with and without look direction disparity.

An antenna array's ability to capture more radiation intensity in a chosen direction than an isotropic antenna array is known as array gain. It offers a wideband receiving array with diversity. It may be computed using [7],

$$G_T = 10\log n + G_{ee} \tag{18}$$

Where, G_{ee} is the gain of arrays of each *n*-th element, G_T is the total gain of the array of the microphones.

3.PERFORMANCE ANALYSIS

The proposed diagonal loading-based UCA system's performance is assessed using various beamforming approaches simultaneously without and with mismatch scenarios. By adjusting various beamformer parameters, variations in performance are noticed. The microphone array captures sound frequencies between 20 Hz and 20 kHz that are perceptible to humans. 8 kHz is the sampling frequency.

As a result, the aliasing effect carried on by undersampling will be eliminated. 1000 shots are snapped. The velocity of the sound signal is 340 m/s. 3 seconds are required to get the signal. The accepted thermal noise temperature is 300 K. Two voice-recorded signals and one recorded laughter signal are loaded to start the procedure. The section of the laughter audio that is loaded is regarded as interference.

The first speech signal is incident at an azimuth angle of -20 degrees and an elevation angle of 0 degrees. The second voice signals azimuth angle is -10 degrees and elevation angle is 10. 20 degrees of azimuth and 0 degrees of elevation are the angles of interference signal.

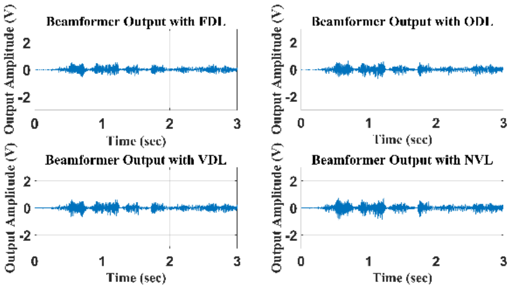

Figure2: Output amplitude comparison among Frost with FDL, ODL, VDL, and NVL beamforming techniques.

Frost with FDL, Frost with ODL, Frost with VDL, and Frost with NVL are compared in Figure 2. This statistic makes it evident that Frost with VDL and Frost with NVL beamformers offer better quality noise and interference suppression compared to the other techniques. The following lists the parametric variations for the various beamforming techniques.:

A. *Array Gain at Variation with Number of Microphone Elements*

A sample period of 3 seconds is employed with UCMA of 16 microphone elements where adjacent microphones are spaced at λ/2, λ being 0.0982m.

Array gain with the variation in the microphone elements number is shown in Table 1 at disparity angle |-3|°. 1e-4 W is the white noise power. The azimuth angle of the interference signal direction is 20°. The highest array gain is found with Frost with NVL, according to Table 1 and Figure 3. With 16 microphone array elements, the gain of arrays of Frost with NVL is maximum compared with the Frost with VDL, Frost with ODL, and Frost with FDL of about 0.0046 dB, 0.0613 dB, and 0.3753 dB, respectively at |-3|°disparity. It can also be noticed that the quality of minimization of noise and interference for Frost with VDL and NVL is better than that of the other beamforming techniques, as shown in Figure 4.

Table 1. Comparison of Gain of Arrays with Variation of Microphone Elements Number.

Beamforming Technique	Array Gain in dB				
	8	***10***	***12***	***14***	***16***
Frost with FDL	6.2262	6.2015	6.2000	6.1784	6.1620
Frost with ODL	6.4216	6.4367	6.4498	6.4573	6.4760
Frost with VDL	6.5155	6.5274	6.5307	6.5258	6.5327
Frost with NVL	6.5063	6.5563	6.5637	6.5479	6.5373

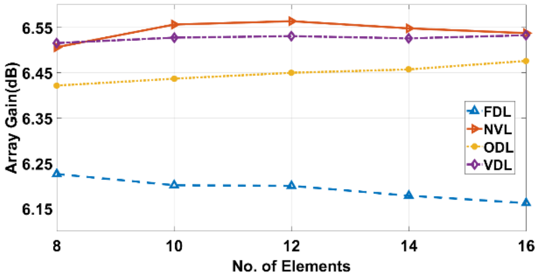

Figure 3. Comparison of the gain of arrays for different numbers of elements among FDL Frost, ODL Frost, VDL Frost, and NVL Frost.

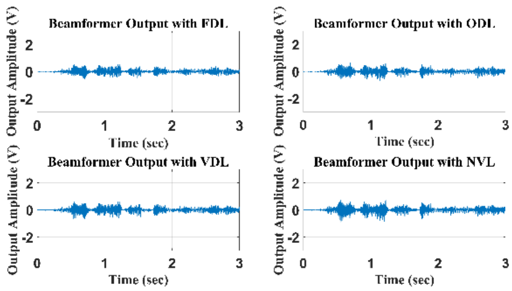

Figure 4. Output Amplitude Comparison among FDL Frost, ODL Frost, VDL Frost, and NVL Frost with 12 Antenna.

B. *Variation with Different Values of Direction of Interference*

The array gain at a variation of |-3|° is shown in TABLE II. There are 16 elements in this microphone array. Frost with NVL yields the highest gain according to Table 2 and Figure 5. Frost with NVL has a higher array gain at a 20° angle of interference than Frost with VDL, Frost with ODL, and Frost with FDL, which are respectively 0.0046 dB, 0.0613 dB, and 0.3753 dB. The array gain increases as the deviation of the direction of interference is further from the direction of the desired signal. Therefore, Frost with NVL provides more excellent noise and interference reduction quality with this variation from Figure 6.

Table 2. Comparison of array gain with Different values of Interference Direction.

Beamforming Technique	Array Gain in dB				
	5	*10*	*15*	*20*	*25*
Frost with FDL	6.1072	6.1470	6.1520	6.1620	6.1642
Frost with ODL	6.0476	6.3216	6.4262	6.4760	6.4991
Frost with VDL	5.9757	6.3133	6.4606	6.5327	6.5683
Frost with NVL	5.9669	6.3107	6.4627	6.5373	6.5745

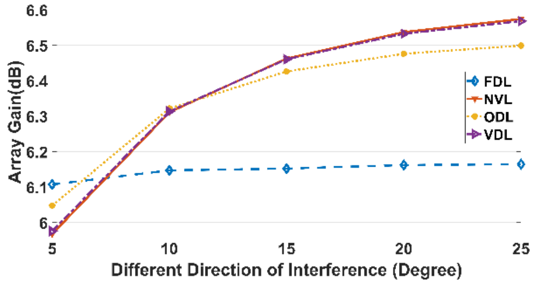

Figure 5. Comparison of Array Gain for different values of interference direction among Frost with FDL, Frost with ODL,VDL Frost, and NVL Frost.

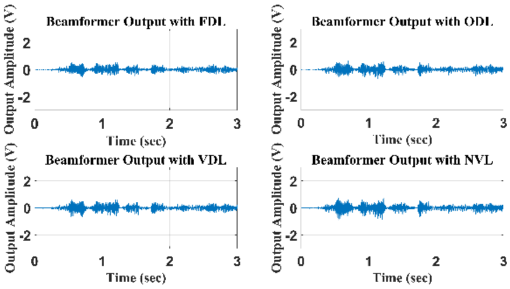

Figure 6. Output Amplitude Comparison among FDL Frost, ODL Frost,VDL Frost, and NVL Frost with interference at 15° in azimuth.

C. *Variation with Different Values of Noise Power*

Table 3. presents an array gain at |-3|° and different noise power. In this instance, 16 microphone array elements and 20° azimuth angle of the interference are taken. Figure 7 illustrates array gain with varying noise power for FDL Frost, ODL Frost, and Frost with VDL and NVL. Frost has more significant array gain than the other techniques when using an NVL beamformer.

Table 3.Comparison of Array Gain with Different values of Noise Power.

Beamforming Technique	Array Gain in dB				
	1e-4 (W)	*1.5e-4 (W)*	*2e-4 (W)*	*2.5e-4 (W)*	*3e-4 (W)*
Frost with FDL	6.1620	6.2007	6.2286	6.2505	6.2688
Frost withODL	6.4760	6.4779	6.4797	6.4815	6.4832
Frost withVDL	6.5327	6.5344	6.5361	6.5377	6.5392
Frost withNVL	6.5373	6.5389	6.5405	6.5419	6.5433

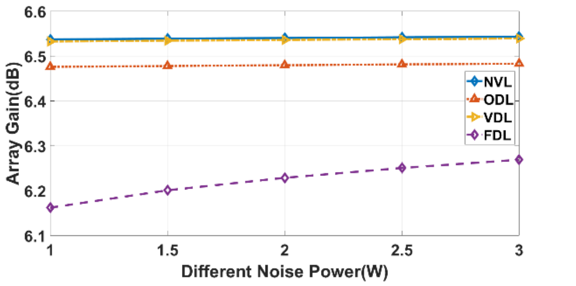

Figure 7. Comparison of Array Gain for Different values of Noise Power among Frost with FDL, ODL, VDL and NVL.

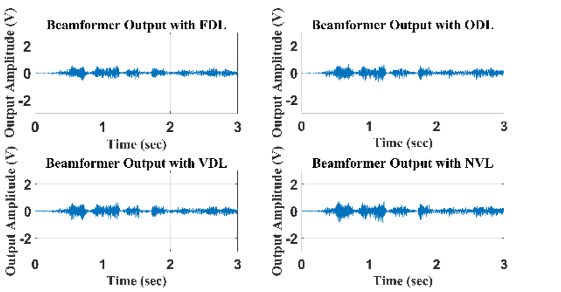

Figure 8. Output Amplitude Comparison among FDL Frost, Frost with ODL, Frost with VDL, and Frost with NVL with 1e-4 noise power.

Figure 8 demonstrates the better quality of minimization of noise as well as interference of the suggested robust Frost with an NVL beamformer. .

D.*Variation with Different Filter Length*

At |-3|° with the variation of filter length, the array gain is shown in TABLE IV . 16 microphone array elements are used in this case, and the direction of interference is at a 20° azimuth angle. Figure 9 shows array gain for Frost with FDL, ODL Frost, Frost with VDL, and Frost with NVL with various filter lengths. When implementing an NVL beamformer, Frost is greater than the others regarding array gain for any filter length. Figure 10 also represents the improved quality of noise minimization and interference of the suggested robust Frost with NVL beamformer.

Table 4. Comparison of Array Gain with Different Filter Length.

Beamforming Technique	Array Gain in dB				
	5	10	15	20	25
Frost with FDL	6.0557	6.0325	6.1025	6.1620	6.1838
Frost with ODL	6.1892	6.2785	6.3826	6.4760	6.5350
Frost with VDL	6.1723	6.3179	6.4461	6.5327	6.5833
Frost with NVL	6.1692	6.3217	6.4524	6.5373	6.5866

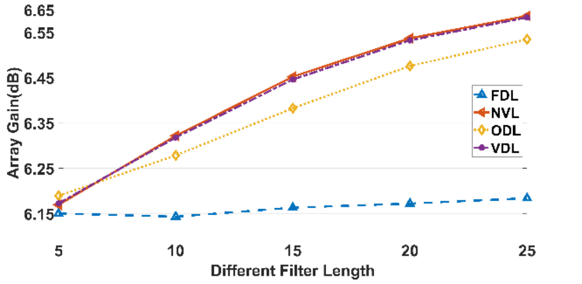

Figure 9. Comparison of array gain for Different Filter Length among FDL Frost,ODL Frost,VDL Frost, and NVL Frost.

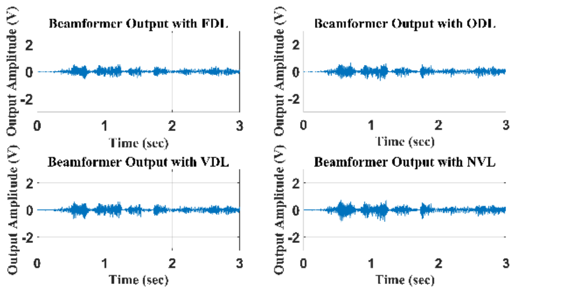

Figure 10. Output Amplitude Comparison among Frost with FDL, Frost with ODL, Frost with VDL, and Frost with NVL with 20 Filter Length.

E.*Variation with Different Disparity*

All beamforming techniques converge on the same result in the absence of mismatches. As the disparity increases, all techniques degrade, but Frost with NVL degrades the least and still yields the highest gain. It can be noticed that the difference between Frost with NVL and Frost with FDL is 0.1708 dB. Additionally, the mismatch is 0.0698 dB higher than the Frost with ODL and 0.0431 dB more significant than the Frost with VDL.

Tables 5 and 6 compare array gain with Frost with FDL, Frost with ODL, Frost with VDL, and Frost with NVL techniques.

Table 5. Comparison of Array Gain with Variation of Positive Angle of Disparity

Beamforming Technique	Array Gain in dB			
	No disparity	*|1|° disparity*	*|2|° disparity*	*|3|° disparity*
Frost with FDL	7.8174	7.5239	7.3943	7.2906
Frost with ODL	7.8155	7.6367	7.4953	7.3754
Frost with VDL	7.8165	7.6939	7.5963	7.4764
Frost with NVL	7.8174	7.7092	7.6184	7.4985

Table 6. Comparison of array gain with Variation of Negative Angle of Disparity.

Beamforming Technique	Array Gain in dB			
	No disparity	|-*1*|° *disparity*	|-*2*|° *disparity*	|-*3*|° *disparity*
Frost with FDL	7.8174	7.5937	7.4788	7.3926
Frost with ODL	7.8155	7.6944	7.5778	7.4936
Frost with VDL	7.8165	7.7514	7.6341	7.5203
Frost with NVL	7.8174	7.7709	7.6782	7.5634

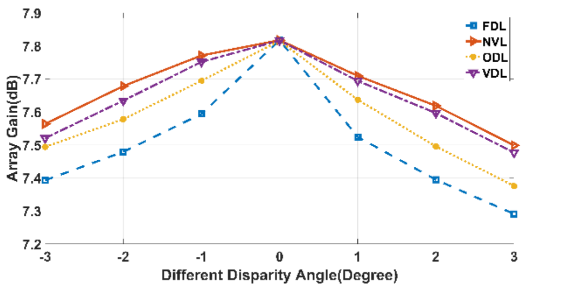

Figure 11. Array Gain Comparison for Different Angle of Disparity among Frost with FDL, Frost with ODL, Frost with VDL, and Frost with NVL.

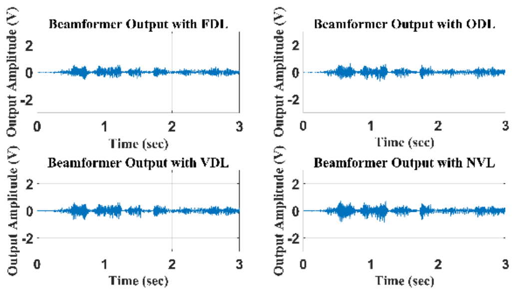

Figure 12. Output amplitude comparison among FDL Frost, Frost with ODL, Frost with VDL, and Frost with NVL at |-1|° disparity.

Figure 12 demonstrates that the quality of reduction of noise and interference by Frost with NVL is superior.

F. *SINR at Different Different Disparity*

The SINR of the input in this case is 0.2859 dB. Table 7 displays the output SINR for various DOAs. The Frost with NVL delivers superior results than other approaches for all disparity angles.

Table 7. Comparison of SINR with Variation of Angle of Disparity.

Beamforming Technique	Output SINR in dB			
	No disparity	|-*1*|° *disparity*	|-*2*|° *disparity*	|-*3*|° *disparity*
Frost with FDL	1.4739	1.4293	1.3881	1.3449
Frost with ODL	1.4736	1.4374	1.3979	1.3535
Frost with VDL	1.4735	1.4432	1.4041	1.3627
Frost with NVL	1.4739	1.4542	1.4136	1.3752

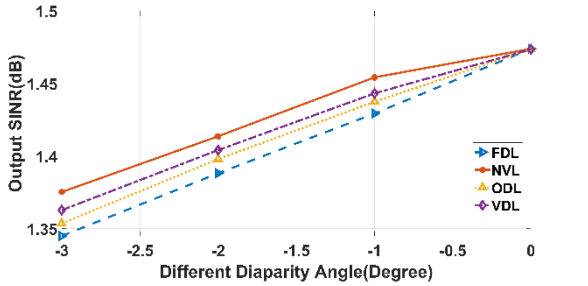

Figure 13. Output SINR Comparison for Different Disparity Angle among FDL Frost,ODL Frost, VDL Frost, and NVL Frost.

Frost beamformer with NVL always has a larger SINR than FDL frost and ODL frost and Frost with VDL, which are 0.0303 dB, 0.0217 dB, and 0.0125 dB, respectively, at |-3|° angle of disparity and noise power of 1e-4 W.

4.CONCLUSION

The robustness of a uniform circular microphone array (UCA) beamformer with the error of look direction has been examined in this research work. Numerical simulation has demonstrated that the frost with VDL and NVL robust technique beamformers achieves greater SINR and output signal strength than the FDL and ODL beamformers. The NVL one has the highest array gain and SINR. The reduction of interference direction by the Frost with FDL and ODL beamformers could be more satisfactory when comparing the difference between the original signals' directions and paths of steering. It has been observed that the suggested robust UCA has a better quality of minimizing noise and interference by altering different parameters.

5.REFERENCES

[1] B. D. Van Veen, K. M. Buckley, “Beamforming: a Versatile Approach to Spatial Filtering,” *IEEE ASSP Magazine*, vol. 5, no. 2, pp. 4-24, 1988.

[2] M. S. Hossain, M. M. Rashid, M. R. Islam, and M. F. Ali, “Convolution constrained robust beamforming techniques for broadband microphone array”, *International Conference on Electrical & Electronic Engineering (ICEEE)*, 2015.

[3] H. Wang and L. Y. Wang, “Multi-sensor adaptive heart and lung sound extraction”, in Proc. *IEEE Sensors Conf.*, Toronto, ON, Canada, pp. 1096–1099, Oct. 2003.

[4] A. A. Handzel and P. S. Krishnaprasad, “Biomimetic sound-source localization,” *IEEE Sensors J.*, vol. 2, no. 6, pp. 607–616, Dec. 2002.

[5] C. Marro, Y. Mahieux, and K. U. Simmer, *IEEE Transaction on Speech Audio Processing*, vol. 6, no3, pp.240–259, May 1998.

[6] Y. R. Zheng, R. A. Goubran ,M.Tanany, and H. Shi, “A Microphone Array System for Multimedia Applications With Near-Field Signal Targets”,*IEEE sensors journal*, vol. 5, no. 6, Dec. 2005.

[7] M. T. Hossein, N. Ahmed, M. S. Hossain, "Performance Investigation of Acoustic Microphone Array Beamformer to Enhance the Speech Quality," in *2021 International Conference on Automation, Control and Mechatronics for Industry 4.0 (ACMI)*, Rajshahi, Bangladesh, July 2021, pp. 1–4.

[8] S. Wooh and Y. Shi, "Optimum beam steering of linear phased arrays", *Wave Motion*, vol. 29, no. 3, pp. 245-265, 1999.

[9] J. Jensen, S. Karimian-Azari, M. Christensen and J. Benesty, "Harmonic beamformers for speech enhancement and dereverberation in the time domain", *Speech Communication*, vol. 116, pp. 1-11, 2020.

[10] W. Lobato and M. Costa, "Worst-Case-Optimization Robust-MVDR Beamformer for Stereo Noise Reduction in Hearing Aids", *IEEE/ACM Transactions on Audio, Speech, and Language Processing*, vol. 28, pp. 2224-2237, 2020.

[11] M. S. Hossain, G. N. Milford, M. C. Reed, and L. C. Godara ,"Efficient robust broadband antenna array processor in the presence of look direction errors," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 2,pp. 718–727, Feb. 3.

[12] M. T. Hossein, M. S. Hossain, and M. F. Reza. "Performance analysis of acoustic microphone array beamformer in the presence of the interfering signal." *2016 2nd International Conference on Electrical, Computer & Telecommunication Engineering (ICECTE).* IEEE, 2016.

[13] M. Ali, M. Hossain, and M. Reza, "Variable Diagonal Loading Based Robust Concentric Hexagonal Antenna Array with Low Side Lobe Level Using Tapering Windows", *Progress In Electromagnetics Research C*, vol. 103, pp. 251-263, 2020.

[14] O. L. Frost, "An algorithm for linearly constrained adaptive array processing," *Proc. IEEE,* vol. 60, no. 8, pp. 926–935, Aug. 1972.

[15] P. Ioannides and C. A. Balanis, "Uniform Circular and Rectangular Arrays for Adaptive Beamforming Applications", *IEEE antennas and wireless propagation letters*, vol.4,2005.

[16] J. Lin, Q. Peng, and H. Shao, "Near field robust adaptive beamforming based on worst-case performance optimization," *in Int. J. Elect. And Comp. Eng.*, vol. 27, no. 1, pp. 489 –495, 2006.

[17] M. S. Hossain, L. C. Godara and M. R. Islam, "Robust and efficient broadband beamforming algorithms in the presence of steering angle mismatch using variable loading," *IEEE Third Latin-American Conference on Communications*, pp. 1-5, 2011.

[18] M. F. Reza, M. S. Hossain, M. T. Hossein and M. M. Rashid, "Robust Uniform Concentric Circular Array Beamforming in the Existence of Look Direction Disparity," *2nd International Conference on Electrical, Computer & Telecommunication Engineering (ICECTE)*,2016.

[19] M. R. Islam, L. C. Godara and M. S. Hossain, "Robust near field broadband beamforming in the presence of steering vector mismatches," *WAMICON IEEE Wireless & Microwave Technology Conference*, pp. 1-6, 2012.