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ROBUSTNESS AND DISTANCE DISCRIMINATION OF ADAPTIVE NEAR FIELD BEAMFORMERS

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ABSTRACT

A robust adaptive beamformer is proposed using the near field regionally constrained adaptive approach that designs a set of linear constraints by filtering on a low rank subspace of the near field signal over a spatial region and a wide frequency band. This method can accurately control the beamformer response over the designed spatial-temporal region using a small number of linear constraint vectors and improve the robustness against target location errors. Meanwhile, this method enhances the capability of the near field beamformer in distance discrimination without additional constraints so that interference impinging at the same direction as the desired signal but at a different distance can be effectively suppressed.

1. INTRODUCTION

Microphone array beamformers are widely used for speech enhancement due to their performance and convenience. Recently, near field beamforming has attracted great interests in array signal processing for multimedia communications in small rooms and automobiles, where signal targets are located close to the array and reverberation imposes significant performance degradation. As a rule of thumb, near field beamforming is required to avoid performance degradation when the signals are located within the radial distance of R_a^2/λ, where R_a is the size of the array and λ is the wavelength of the operating frequency [1, 2].

The majority of near field beamforming techniques are fixed-weight or "statically" adaptive beamforming methods which are either designed for specified beamformer responses [2] or optimized for certain noise and interference environment [3,4]. Studies on dynamically adaptive near field beamformers remain very scarce although it is well known that dynamically adaptive beamformers can achieve better performance than fixed-weight beamformers of comparable sizes [5,6]. Adaptive beamformers suffer from severe performance loss due to location errors of signal targets and other array imperfections [7]. The robustness problem becomes more pronounced in near field adaptive beamformers than in conventional far field beamformers because the three-dimensional near field signal location is more difficult to estimate than the Directions of Arrival (DOA) in far field cases. The accuracy in distance estimation is particularly low [8] resulting in unacceptable performance of near field adaptive beamformers.

In this paper, we propose a regionally constrained beamforming method for near field robust adaptive beamformer design. We extend the idea of the far field eigenvector constrained LCMV (Linearly Constrained Minimum Variance) beamforming [9, 10] to the near field scenario. We establish a direct relationship between the desired near field target region and the eigen-structure of a near field signal distributed over this target region and develop a low rank subspace representation for the near field regional signal. By filtering on this signal subspace, we propose a systematic constraint design method which can accurately control the beamformer response over the target region using a small number of constraint vectors. The beamformer's robustness against location errors is then achieved via unit gain constraints over the target region and signals outside the target region are suppressed.

Another advantage of the proposed near field beamformer is its capability in distance discrimination. The potential of distance discrimination of near field beamforming has not been fully exploited in the literature of near field array processing. Ryan and Goubran [3] have proposed a method that imposes a soft null constraint on the far field interference in order to suppress it through array gain optimization. They have shown that compromised far field interference reduction can be obtained by trading the robustness of the beamformer and the gain at the near field focal point. The proposed regionally constrained method achieves better distance discrimination while maintaining the robustness of the beamformer. This is inherently achieved with the proper design of the constrained region without additional null constraints. Design examples of a nine-element equi-spaced linear array is presented that demonstrates the improved performances of the regionally constrained adaptive near field beamformers.

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2. PROPOSED ROBUST NEAR FIELD BEAMFORMING

Consider a broadband array beamformer with M elements and K taps attached at each element. The elements of the array are located at $\{\mathbf{x}_m = (r_m, \theta_m, \phi_m), m = 1, 2, \ldots, M\}$ in a spherical coordinate system, where r_m, θ_m and ϕ_m denote the radial distance, azimuth angle and elevation angle, respectively. Without loss of generality, the coordinate system is defined such that its origin is at the phase center of the array. If the signal target is located at $\mathbf{x}_s = (r_s, \theta_s, \phi_s)$ with $r_s < R_a^2/\lambda$, where R_a is the largest array dimension and λ is the operating wavelength, then the near field propagation model is required and the near field steering vector of the array beamformer is defined as an N-dimensional ($N = MK$) vector [11]

$$\mathbf{a}(\mathbf{x}_s, f) = \frac{r_s}{e^{j2\pi f r_s/c}} \left[\frac{e^{j2\pi f r_{1s}/c}}{r_{1s}}, \cdots, \frac{e^{j2\pi f (r_{ms}/c - k)}}{r_{ms}}, \cdots, \frac{e^{j2\pi f (r_{Ms}/c - K+1)}}{r_{Ms}} \right]^T, \quad (1)$$

where the superscript $(\cdot)^T$ represents transpose, and f is the frequency, c is the propagation speed, $r_s = |\mathbf{x}_s|$ and $r_{ms} = |\mathbf{x}_m - \mathbf{x}_s|$ are the distances from the signal source to the phase center of the array and the m-th element, respectively. Let the input vector of the array beamformer be the concatenated snapshot samples grouped into an N-dimensional vector denoted as $\mathbf{u}(k)$, where k is the time instance. The beamformer output $y(k)$ can be expressed in matrix form as $y(k) = \mathbf{w}^H\mathbf{u}(k)$, where $\mathbf{w}$ is the concatenated weight vector of the beamformer, and the superscript $(\cdot)^H$ represents complex conjugate transpose. Using the LCMV method, the near field adaptive beamformer tries to minimize the output power subject to some constraints. That is

$$\min_{\mathbf{w}} \left\{ \mathbf{w}^H \mathbf{R}_{\mathbf{uu}} \mathbf{w} \right\}, \quad (2)$$

subject to

$$\mathbf{C}^H \mathbf{w} = \mathbf{h}, \quad (3)$$

where $\mathbf{R}_{\mathbf{uu}}$ is the $N \times N$ covariance matrix of the concatenated input vector, *i. e.*, $\mathbf{R}_{\mathbf{uu}} = E\{\mathbf{u}(k)\mathbf{u}^H(k)\}$ with $E\{\cdot\}$ being the expectation operator. The matrix $\mathbf{C}$ is the constraint matrix and $\mathbf{h}$ is the desired response vector. If the dimension of $\mathbf{C}$ is $N \times L$, then (3) is a set of L linear constraint equations controlling the beamformer response.

Assume the signal source is spread over a spatial region $\Omega = (\pm\Delta r, \pm\Delta\theta, \pm\Delta\phi)$ around the estimated focal point $\mathbf{x}_F = (r_F, \theta_F, \phi_F)$, as shown in Fig. 1 for a linear array. Denote the signal source sample vector by $\mathbf{s}(k)$ and its power spectrum density by $S(\mathbf{x}, f)$ having a normalized angular frequency band B. The source sample covariance matrix observed at the array beamformer is

$$\begin{aligned} \mathbf{R}_{\mathbf{ss}} &= E\{\mathbf{s}(k)\mathbf{s}^T(k)\} \\ &= \frac{1}{\mathbf{\Omega}} \frac{1}{B} \int_{\mathbf{\Omega}} \int_B S(\mathbf{x}, f) \mathbf{a}(\mathbf{x}, f) \mathbf{a}^H(\mathbf{x}, f) df d\mathbf{x}, \end{aligned} \quad (4)$$

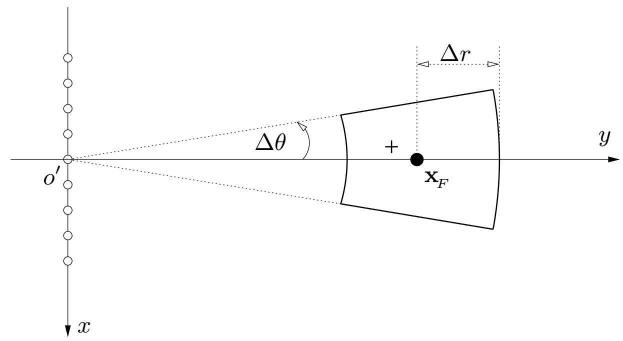


Fig. 1. The constrained region for a linear array is $\Omega = \{\pm\Delta r, \pm\Delta\theta\}$. The presumed focal point is $\mathbf{x}_F$. The figure is not to scale.

where $\mathbf{a}(\mathbf{x}, f)$ is the near field steering vector defined in (1). Assume a flat spectrum of the signal source within the frequency band B and the constrained region Ω. The covariance matrix $\mathbf{R}_{\mathbf{ss}}$ defined in (4) can be computed numerically by selecting I points in the spatial region Ω and J points in the frequency band B.

$$\mathbf{R}_{\mathbf{ss}} = \frac{1}{P} \sum_{i=1}^{I} \sum_{j=1}^{J} \mathbf{a}(\mathbf{x}_i, f_j) \mathbf{a}^H(\mathbf{x}_i, f_j) = \frac{1}{P} \mathbf{A}\mathbf{A}^T, \quad (5)$$

where $P = IJ$, and $\mathbf{A}$ is a real matrix formed by the real and imaginary parts of the sampled steering vector $\mathbf{a}(\mathbf{x}_i, f_j)$ at the point $(\mathbf{x}_i, f_j)$.

We have found [12] that the covariance matrix $\mathbf{R}_{\mathbf{ss}}$ can be represented by a low rank approximation consisting of its largest eigenvalues. The singular values σ_n of $\mathbf{A}$ are related with the eigenvalues λ_n of $\mathbf{R}_{\mathbf{ss}}$ by $\lambda_n = \sigma_n^2/P$ for $n = 1, 2, \cdots, N$. Therefore, a low rank L approximation of $\mathbf{A}$ corresponds to the same rank representation of $\mathbf{R}_{\mathbf{ss}}$. An efficient design of constraint equation $\mathbf{C}^T\mathbf{w} = \mathbf{h}$ can be obtained as

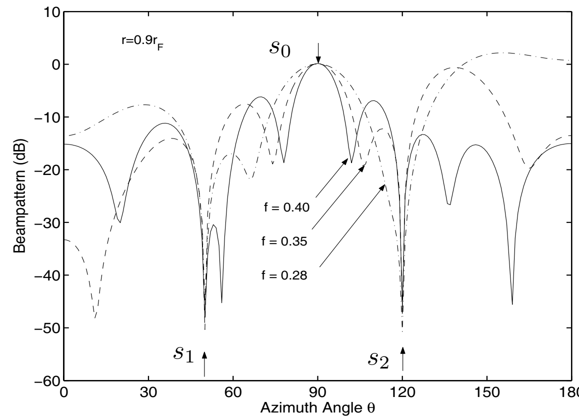
$$\begin{aligned} \mathbf{C} &= \mathbf{V}_L \\ \mathbf{h} &= \mathbf{\Sigma}_L^{-1} \mathbf{U}_L^T \mathbf{g}. \end{aligned} \quad (6)$$

where $\mathbf{\Sigma}_L$ is the diagonal matrix consisting of the L largest singular values. The columns of $\mathbf{V}_L$ and $\mathbf{U}_L$ are, respectively, the L corresponding columns of the singular vectors, and $\mathbf{g}$ is the desired response vector for the constrained region. Detailed design procedures can be found in [12].

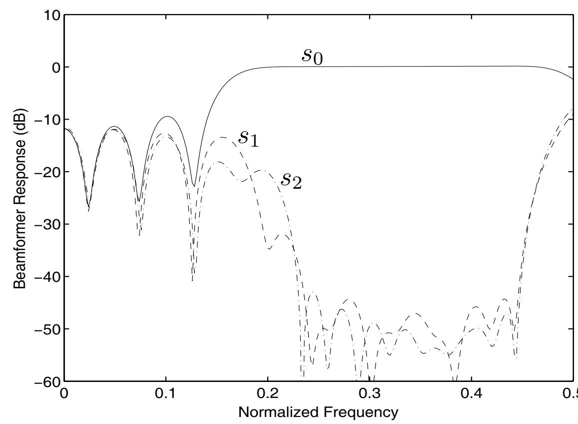
3. DESIGN EXAMPLE AND PERFORMANCE EVALUATION

As an example, a nine-element microphone array is used to demonstrate the performances of the proposed near field regionally constrained adaptive beamformer. The normalized frequency band of interest is $B = [0.22, 0.44]$. Each element has $K = 25$ taps. The array elements are uniformly placed along the x axis with $\lambda/2$ spacing, where λ is the wavelength of the high frequency edge of the frequency band. Thus the size of the array is $R_a = 4\lambda$. The presumed focal point is well within the near field of the array at $\mathbf{x}_F = (r_F, \theta_F, \phi_F) = (5\lambda, 90°, 90°)$. The near field regionally constrained adaptive beamformer was designed with the constrained frequency band being B and the constrained region Ω being as $\Delta r = 0.1 r_F, \Delta\theta = 4°$ and $\Delta\phi = 0$. The elevation angle $\Delta\phi$ does not affect the constraint design due to the fact that linear arrays on x-axis have no resolution on the elevation angle. The resulting beamformer used $L = 78$ degrees of freedom for the constraints. There are 147 degrees of freedom left for dynamic adaptation. Figure 2 shows the beamformer's performance when it's adapted to the presence of one desired signal s_0 and two interfering signal sources s_1 and s_2. All signals were uncorrelated, band-limited to B, and with a power of 20 dB above the background noise. The desired signal was slightly off the focal point at $(0.9r_F, 88°, 90°)$. The two interfering signals s_1 and s_2 were located at $(r_F, 50°, 90°)$ and $(r_F, 120°, 90°)$, respectively. The beampatterns in Fig. 2(a) illustrate that the proposed beamformer was able to preserve the desired signal with unit gain while place deep nulls at the interfering signal locations. The frequency responses in Fig. 2(b) shows that it had a flat response within the pass band at the desired signal location and more than 40 dB attenuation at the interfering signal locations. This demonstrates that the designed regional constraints had efficient control of the beamformer responses over the entire pass band. The proposed beamformer achieved an array gain of 25.6 dB at the output. Similar beampatterns and frequency responses were obtained when the desired signal was located at any point within the constrained region, including the presumed focal point.

For comparison, a near field point-constrained adaptive beamformer was designed using the eigenvector constraint method [9] resulting in 18 constraint vectors to ensure unit gain at the focal point and over the frequency band. A near field fixed beamformer was also designed by optimization under the far field spherically isotropic noise field [3]. Both used the same nine-element array with the same parameters. Several regionally constrained adaptive beamformers were also designed using different constraint regions. The array gain sensitivity of the beamformers were evaluated as functions of source locations, shown in Fig. 3. Fig. 3(a) plotted the array gain sensitivity as a function of the radial distance which is a measure of robustness against the location error as well as the capability of distance discrimination of near field beamformers. The solid line shows that the point-constrained adaptive beamformer is very sensitive to distance errors. It has strong capability of discriminating signals but is very sensitive to small errors. The regionally constrained beamformers, shown in the dash-dot line and dot line, show that the unit gain is preserved in the constrained ranges. Meanwhile, they achieved 15 dB attenuation at distances outside their constrained range. This means that the proposed beamformer has greatly improved robustness against distance error while maintaining sufficient distance discrimination outside the target region. In comparison, the dashed line shows that the fixed beamformer is robust but has no advantage in distance discrimination.



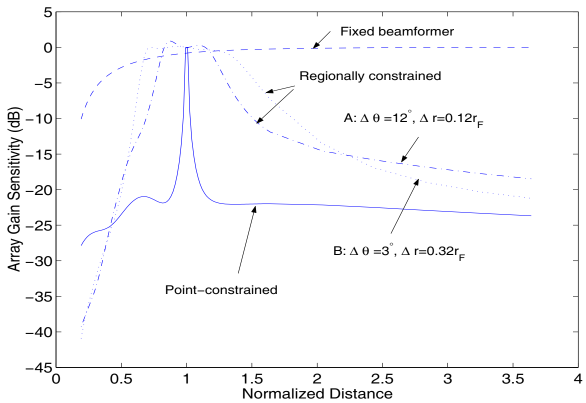
(a) Beampattern



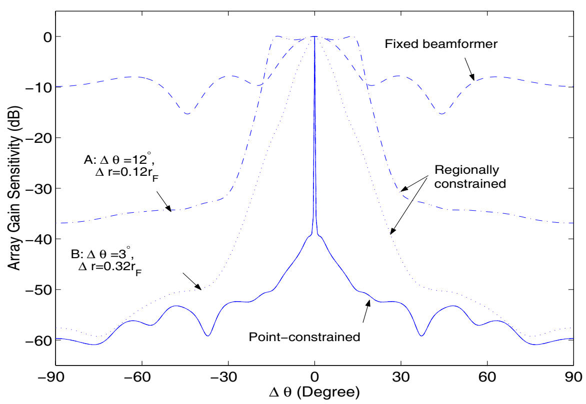
(b) Frequency response

Fig. 2. Spatial and frequency responses of the regionally constrained beamformer. The constrained region is $\Delta r = 0.1 r_F$ and $\Delta\theta = 4°$ around the focal point. The desired signal s_0 is off the focal point at $(0.9r_F, 88°, 90°)$ and the interfering signals s_1 and s_2 are located at $(r_F, 50°, 90°)$ and $(r_F, 120°, 90°)$, respectively.

The array gain sensitivity versus the DOA θ is plotted in Fig. 3(b) with the radial distance $r = r_F$. The point-constrained adaptive beamformer had a very sharp spike at the look direction, as shown by the solid line. A small DOA error would result in dramatic reduction of the array gain to below -40 dB. The proposed regionally constrained adaptive beamformers maintained a high array gain in the target DOA region of while achieving strong attenuation outside the target region. The fixed beamformer, although very robust against



(a) Distance discrimination, evaluated at $\theta = \theta_F$



(b) Robustness against DOA error, evaluated at $r = r_F$

Fig. 3. Array gain sensitivity as functions of the source location. All beamformers have 9 equi-spaced elements covering the frequency band $B = [0.22, 0.44]$. The size of the arrays is 4λ and the focal point is $\mathbf{x}_F = (5\lambda, 90°, 90°)$, with λ being the wavelength of th high frequency edge. Distances are normalized with respect to r_F.

the DOA error, does not provide adequate attenuation outside the target region.

4. CONCLUSION

We have proposed a design method for robust regionally constrained adaptive near field beamformers by filtering the low rank subspace of near field signals with a broad frequency band and over a specified spatial region. The designed near field beamformer uses a small number of degrees of freedom for the constraint vectors and is dynamically adaptive to the changing environment. It achieves robustness against target location errors while maintaining excellent distance discrimination. We have shown, via a nine-element linear microphone array example, that the proposed beamformer can preserve the desired signal of large distance and DOA errors while suppressing interfering signals located at different distances with the same DOA as the desired signal.

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