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A Nested Sensor Array Focusing on Near Field Targets

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Abstract—A nested virtual array subband beamforming system is proposed for applications where broadband signal targets are located within the near field of the array. Subband multirate processing and near field beamforming techniques are used jointly for the nested array to improve the performances and reduce the computational complexity. A new noise model, namely the broadband near field spherically isotropic noise model, is also proposed for the optimization design of near field beamformers. It is shown that near field beamforming is essential for better distance discrimination of near field targets, reduced beampattern variations for broadband signals, and stronger reverberation suppression.

I. INTRODUCTION

Multiple sensors and sensor arrays are widely used for enhanced performances in signal detection, source localization, noise and interference suppression, and sensor networking and multisensor fusion [1]. Conventional array beamforming uses the simplified far field model assuming that all impinging signals at each sensor are plane waves. However, in many applications where the signal sources are located close to the sensor array, the wave front curvature can be significant within the array's aperture [2]. In these cases, far field assumption can result in severe performance loss and near field beamforming techniques have to be used [3]–[6]. This situation arises, for example, in microphone array applications in small rooms and automobiles where the size of the array is comparable to the distance between the array and the signal location. It is also found in the case of microelectromechanical system (MEMS)-based microarrays which electronically generate large virtual arrays [7]. Propagation delays are added to every element of the microarray as if the elements are spaced at the half (or quarter) wavelength of the operating frequency. In this scenario, signal targets are generally located well within the aperture of the virtual array,

especially for low frequencies, although the physical size of the microarray is very small.

In this paper, we propose a non-uniformly nested virtual array for microphone applications by adding synthesized propagation delays to a small-sized planar array or a MEMS-based microarray. The nested array is grouped into several subarrays, then near field beamforming and multirate subband processing are used jointly to improve the performance and reduce the complexity. A new optimization method is also proposed for the near field beamformer design using the broadband, near field, spherically isotropic noise model.

We show that near field beamforming is essential for most microphone applications where signal targets are located within the near field of the virtual array, even though the original array is very small. The non-uniformly nested approach can reduce the processing cost for broadband signals whose high-frequency-to-low-frequency ratio is much larger than 10:1. Comparing to conventional far field and/or full band beamforming methods, the proposed system achieves better performances in terms of better distance discrimination for near field targets, reduced beampattern variations for broadband signals, and stronger reverberation suppression.

II. THE NESTED VIRTUAL ARRAY

A small-sized uniform planar array is illustrated in Fig. 1. It has 5×5 elements located on the $x - z$ plane. The spacing of the array elements is 2.4 cm. The total size of the array is 9.6 cm \times 9.6 cm. Following the principle of adding propagation delays associated with a signal target, as proposed in [7], a physically small array can create a large virtual array to obtain sufficient spatial resolution covering the entire acoustical frequency band. Then array beamforming based on this method can be viewed as processing of

the virtual array. Consequently, beamformers are to be designed based on the virtual array.

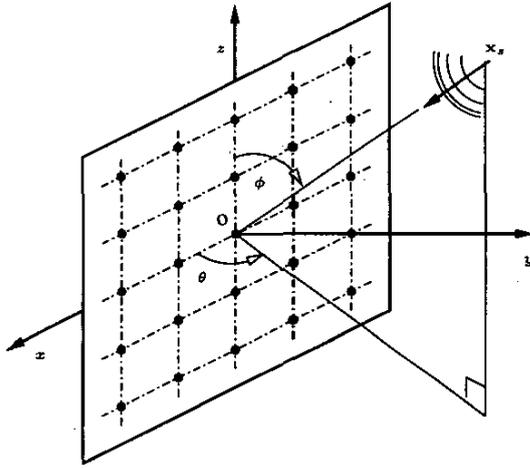


Fig. 1. The planar array with 5 x 5 elements.

Here we propose a harmonically nested virtual array for wideband telephony applications covering the G.722 [8] frequency band of [50, 7000] Hz. It consists of several harmonically nested subarrays as illustrated in Fig. 2. Each subarray is a uniform planar array whose signals are generated by delaying the signals received by the original array elements. Each subarray covers an octave subband: from $B_1 = [3.6, 7.2]$ kHz to $B_7 = [0.05, 0.1175]$ kHz. The subband of the i -th subarray is $B_i = B_{i-1}/2$ for $i = 2, 3, \dots, 6$. The three high frequency subarrays Sub1 to Sub3 each has 5×5 elements with $\lambda/2$ spacing; the low frequency subarrays Sub4 and Sub5 each has 9×9 elements with $\lambda/4$ spacing, where λ is the wavelength of the high frequency edge of the corresponding subband. Sub6 and Sub7 share the same elements of Sub5. The reason for quarter-wavelength spacing at Sub4 and Sub5 is that near field beamforming generally requires smaller spacing to avoid spatial aliasing [9] than the half-wavelength spacing required by far field beamforming. Besides, it is also found [5] that smaller spacing could result in better performances for near field beamformers, especially for larger arrays observing greater wave front curvature.

For the virtual array illustrated in Fig. 2, the total number of the synthesized elements is 17×17 . The size of the virtual array is as large as $1.56 \text{ m} \times 1.56 \text{ m}$, although the physical size of the original array is very small. Consequently, the wave front curvature is

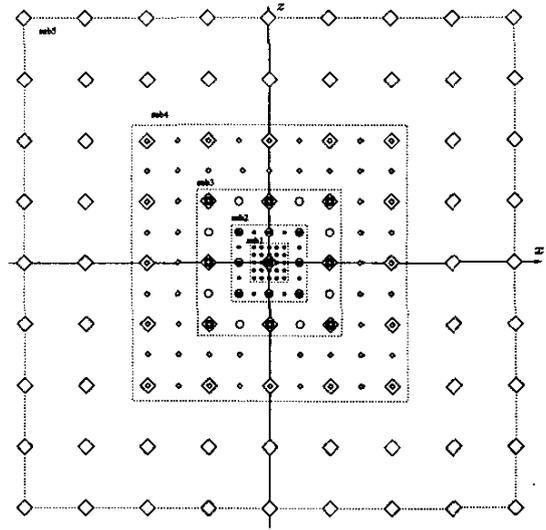


Fig. 2. The geometry of the virtual array generated by the small array in Fig. 1. Subarrays are harmonically nested to cover the acoustic band of [50, 7200] Hz. The subarrays 1 to 3 each has 5×5 elements with $\lambda/2$ spacing; the subarrays 4 and 5 each has 9×9 elements with $\lambda/4$ spacing. Sub6 and Sub7 share the elements of Sub5.

significant for signals located within the radial distance of D_a^2/λ , where D_a is the size of the subarray. This is the case for many microphone array applications in small enclosures. The near field propagation model and near field beamforming techniques are required in these scenarios. It will be shown in Fig. 4 that conventional far field beamforming can not provide adequate spatial directivity in the near field target region, and near field beamforming results in much better performances.

The nested virtual array is processed by the subband multirate beamformers shown in Fig.3. The array input signals are first sampled at a high frequency $F_s = 16$ kHz, then subbanded by an analysis filter $H_l(z)$ and decimated to a lower frequency F_l , where $F_1 = F_s$, and $F_{l+1} = F_l/2$ for $l = 1, 2, \dots, 6$. Each subarray is then processed by a broadband near field beamformer designed for the corresponding subband. The outputs of the beamformers are interpolated and combined via the synthesis filters $G_l(z)$. The use of the multirate subband processing results in the same normalized frequency passband for every subarray, that is $B = [0.225, 0.45]$, to be specific. However, to focus on a fixed near field location, each subband beamformer has to be designed individually. This is due to the fact that the size of each subarray and the radial distance of the focal point are

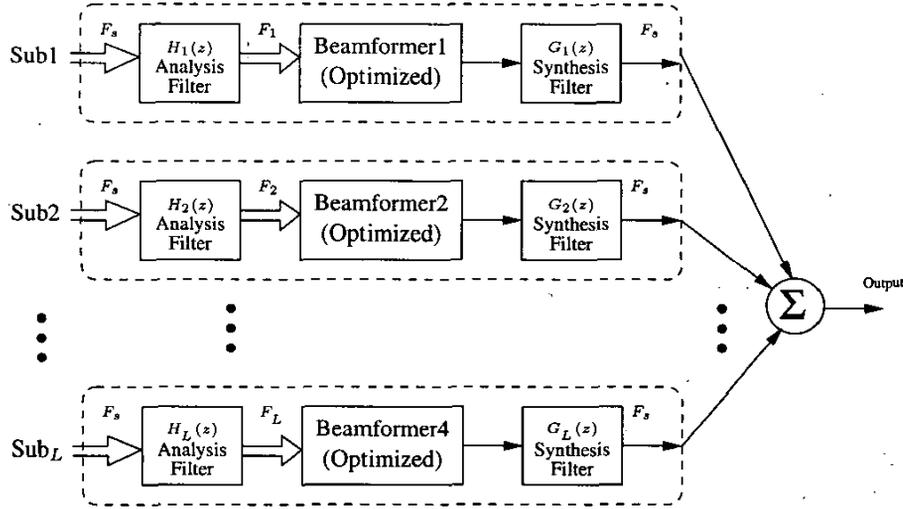


Fig. 3. Subband multirate beamforming scheme for the nested virtual array. The sampling frequencies are: $F_s = 16$ kHz, $F_1 = F_s$, $F_{l+1} = F_l/2$ for $l = 1, 2, \dots, L$. The number of subbands $L \approx \log_2(f_2/f_1)$. Near field beamformers are designed for each subband using constrained optimization under near field spherically isotropic noise field.

different in terms of the corresponding wavelength.

The advantage of the nested array multirate subband beamforming technique is its reduced complexity. With multirate subband processing, the high-to-low frequency ratio of each subband reduces to 2:1. Therefore, the number of taps in each subband beamformer can be reduced substantially comparing to a full band beamformer. Non-uniform nesting of the subarrays also reduces the number of active elements in the virtual array in comparison to a uniform sampling scheme, because half-wavelength sampling at the highest frequency is grossly over sampled for lower frequencies. Therefore, nested array subband beamforming can reduce system complexity without performance loss.

III. NEAR FIELD BEAMFORMING

Now we propose a new optimization method for the design of the near field broadband beamformers. After multirate subband processing, the high-to-low frequency ratio of each subband reduces to 2:1. Therefore, the number of taps in each beamformer can be reduced substantially. Denote the number of elements by M and the number of taps per element by K . We have $N = MK$ degrees of freedom for the beamformer optimization. The Linearly Constrained Minimum Variance method is used. That is

$$\min_{\mathbf{w}} \mathbf{w}^H \mathbf{R} \mathbf{w}, \quad (1)$$

$$\text{subject to } \mathbf{C}^H \mathbf{w} = \mathbf{f}, \quad (2)$$

where \mathbf{w} is the concatenated weight vector, \mathbf{R} is the $N \times N$ covariance matrix of the input signals, \mathbf{C} is the constraint matrix, and \mathbf{f} is the unit gain response vector. If the dimension of \mathbf{C} is $N \times P$, then the constraint (2) is a set of P linear equations controlling the beamformer response. The constraint equation (2) is designed by the eigenvector method [10]. Only a small number of constraints are required to enforce a unit gain over the desired temporal passband at the spatial focal point. Beamformer weights are then optimized under the broadband, near field, spherically isotropic noise field where a large number of independent random noises are uniformly distributed over a spheroid Ω with radius r_s . The covariance of the noise field observed at the sensor array is then

$$\mathbf{Q} = \frac{1}{\Omega} \frac{1}{B} \int_{\Omega} \int_B S(f) \mathbf{a}(\mathbf{x}_s, f) \mathbf{a}^H(\mathbf{x}_s, f) df d\mathbf{x}_s, \quad (3)$$

where $B = [f_1, f_2]$ is the normalized frequency band, $S(f)$ is the power spectrum density of the noises, $\mathbf{a}(\mathbf{x}_s, f)$ is the near field steering vector defined by

$$\mathbf{a}(\mathbf{x}_s, f) = \frac{r_s}{e^{j2\pi f r_s/c}} \left[\frac{e^{j2\pi f r_s/c}}{r_{1s}}, \dots, \frac{e^{j2\pi f (r_{ms}/c - k)}}{r_{ms}}, \dots, \frac{e^{j2\pi f (r_{Ms}/c - K + 1)}}{r_{Ms}} \right]^T, \quad (4)$$

and $r_{ms} = |\mathbf{x}_m - \mathbf{x}_s|$ is the distance from the point \mathbf{x}_s to the m -th element of the array located at \mathbf{x}_m .

The covariance matrix in (1) is defined as

$$\mathbf{R} = \alpha \mathbf{Q} + \gamma \mathbf{I}, \quad (5)$$

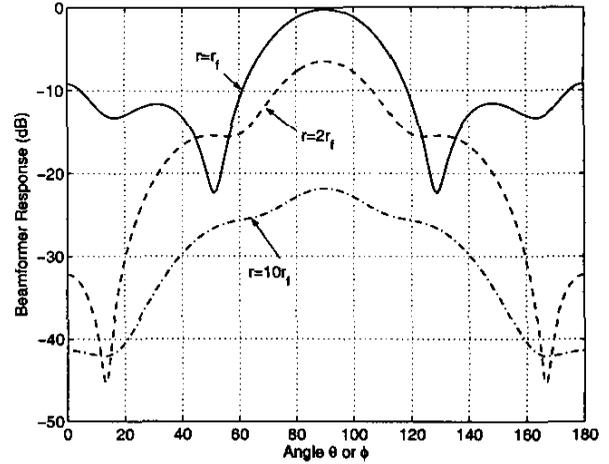
where α is a design parameter used to trade off white noise gain for noise suppression, and γ is a small constant representing the power of background white noises. The solution to the constrained optimization problem is well-known:

$$\mathbf{w} = \mathbf{R}^{-1} \mathbf{C} (\mathbf{C}^H \mathbf{R}^{-1} \mathbf{C})^{-1} \mathbf{f}. \quad (6)$$

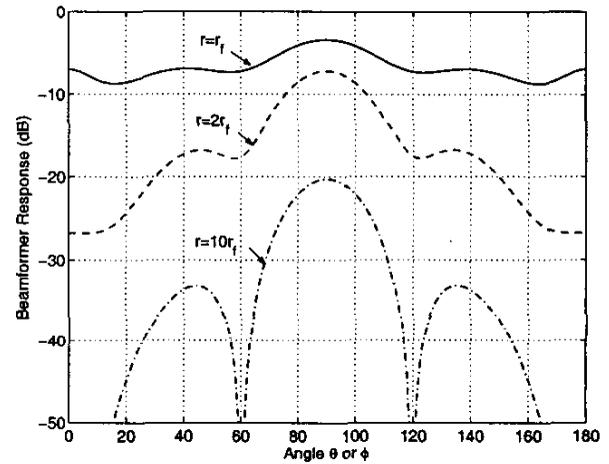
The novelty of the proposed optimization method is the use of the broadband, near field, spherically isotropic noise model. Optimization under the far field spherically isotropic noise model has been reported in [5]. A narrow band near field spherically isotropic noise model has also been used in [3]. However, the broadband, near field, spherically isotropic noise model provides a more accurate approximation to the effect of reverberation. It is also more convenient than the conventional image model [11] which is dependent on the physical sizes and characteristics of the environment.

IV. PERFORMANCE

The performance of near field beamforming is compared to that of far field beamforming in Fig. 4. All beampatterns were evaluated at 400 Hz covered by the 5-th subarray. Both beamformers were designed using the optimization method in (6) with $\alpha = 0$ and $\gamma = 0.01$. The near field beamformer was focused at $\mathbf{x}_f = (0.96\text{m}, 90^\circ, 90^\circ)$. Figure 4(a) shows the beampatterns evaluated at three radial distances from the array center. It is clear that the near field beamformer provided good directivity at the focal point ($r = r_f$) while attenuating 10 dB or more at sidelobes and far away locations. The far field beamformer, on the other hand, had a look direction at $(90^\circ, 90^\circ)$ without distance discrimination. Its beampatterns shown in Fig. 4(b) illustrates that little spatial directivity was obtained for near field areas at distances $r = r_f$ and $r = 2r_f$. Good directivity was exhibited at the far away distance of $r \geq 10r_f$. But propagation attenuation was also large at a further distance. Severe performance degradation by far field beamforming exhibited over the near field target region, especially at low frequencies. Obviously, far field beamforming is not suitable for signals located in the near field of the array.



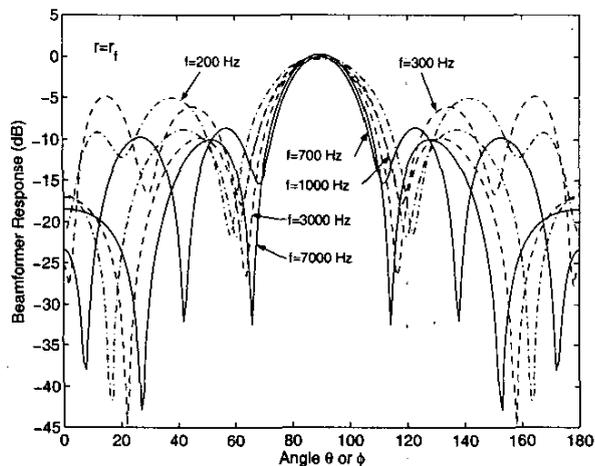
(a) Near Field Beamformer



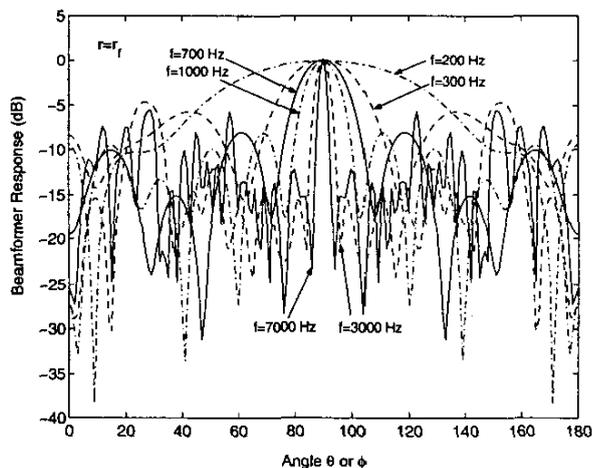
(b) Far Field Beamformer

Fig. 4. Performance comparison of the near field and far field beamformers of subband 5 with 9×9 elements and 25 taps per element. Weights are optimized under white noises. The array responses are evaluated with $f = 400$ Hz and $r_f = 0.96$ cm.

When subband multirate technique is used jointly with near field beamforming, it further improves the performance in terms of reduced beampattern variations. Figure 5 compares the mainlobe bandwidths of the subband beamformer to that of the full band beamformer. Both beamformers used the same nested array and the near field optimization method with $\alpha = 10$ and $\gamma = 0.01$. The focal point of both



(a) Nested Array Subband Beamformer



(b) Nested Array Full Band Beamformer

Fig. 5. Comparison of the mainlobe beam width obtained by subband and full band beamformers. Both beamformers use the same 17×17 nested array and near field beamforming techniques with the focal point at $\mathbf{x}_f = (0.96 \text{ m}, 90^\circ, 90^\circ)$.

beamformers was $\mathbf{x}_f = (0.96 \text{ m}, 90^\circ, 90^\circ)$. The radius of the noise field r_s was selected within $3r_f$ to $10r_f$. The subband beamformer used 25 taps per element. The full band beamformer used 51 taps per element. The beampatterns were evaluated at $r = r_f$ and several frequencies across the passband. The mainlobe beam width of the full band beamformer, as shown in Fig.5(b) widens proportionally as the frequency decreases. The

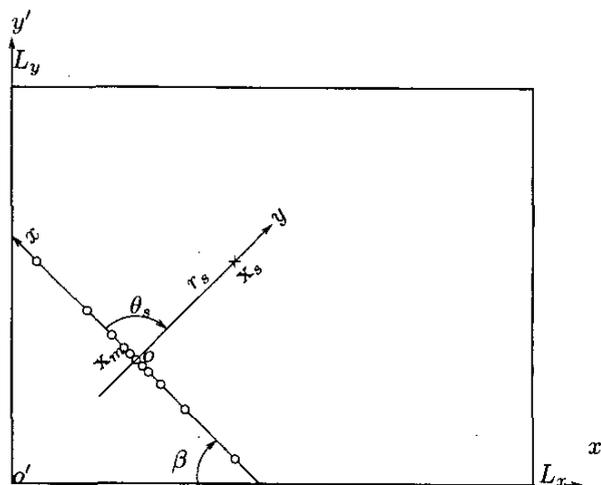


Fig. 6. The nested virtual array in a reverberant room. The reverberation time of the room is $T_{60} \approx 300 \text{ ms}$. The angle $\beta = 45^\circ$, and $r_f = 1.0 \text{ m}$. The figure is not to scale.

beam width variations is too large to provide adequate directivity at low frequencies. The nested array subband beamformer reduced the 3-dB mainlobe beam width variations to within 15° , as shown in Fig. 5(a). It is satisfactory in the applications although it is not strictly constant beam width across the entire passband. The nested array subband method provides the compromise solution between performance and system complexity.

The proposed near field subband beamforming method can also eliminate room reverberation to a satisfactory level. We show the de-reverberation performance by simulated experiment. The simulated room had a size of $5.0 \text{ m} \times 4.0 \text{ m} \times 3.0 \text{ m}$. The nested array was located on the $x - z$ plane in the room, as shown in Fig. 6. The angle between the x axis and the wall is $\beta = 45^\circ$. The phase center of the array was at point o located at $(1.0 \text{ m}, 1.0 \text{ m}, 1.0 \text{ m})$ on the $x' - y' - z'$ coordinates. The impulse response of the room was simulated by the image model [11]. The reflection coefficients of the walls were 0.9, and those of the ceiling and floor were 0.7. The reverberation time of the simulated room was approximately $T_{60} \approx 300 \text{ ms}$. An audio signal source was located in front of the array on the y axis with the radial distance being 1.0 m . The reverberant signals were generated by convolution of the clean signal with the impulse responses.

The reverberant signals were processed by the nested array subband beamformers and their output Signal-to-Interference-and-Noise Ratio (SINR) of each subband

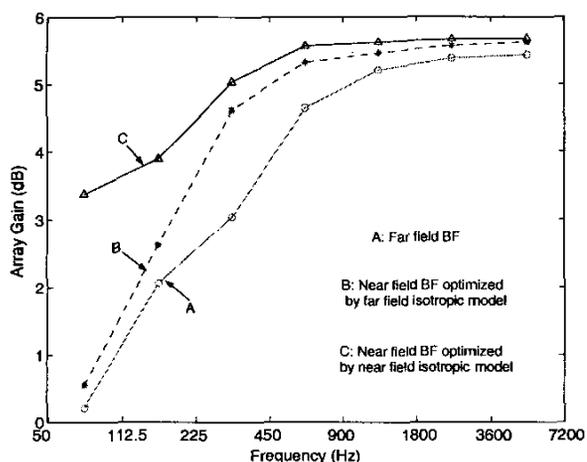


Fig. 7. De-reverberation performances of the nested array subband beamformers. (A) the far field beamformer; (B) the near field beamformer optimized under the far field spherically isotropic noise model; (C) the near field beamformer optimized under the near field spherically isotropic noise model.

were computed, as illustrated in Fig. 7. Comparing curves (B) and (C) to curve (A), it is clear that near field beamformers has better de-reverberation gain than that of the far field beamformer. Furthermore, the use of the near field spherically isotropic noise model for the near field beamformer design improves the performance significantly in lower frequency subbands. This is due to the improved distance discrimination of the near field beamformer of the lower subband arrays.

V. CONCLUSION

A nested planar array subband beamforming system has been proposed for applications where broadband signal targets are located within the near field of the array. The nested array consists of non-uniformly spaced virtual sensors generated by adding synthesized propagation delays to a small-sized 5×5 -element linear array. Subband multirate processing and near field beamforming techniques are then used jointly to improve the performances and reduce the computational complexity. A new noise model, namely the broadband near field spherically isotropic noise model, was also proposed for the optimization design of near field beamformers. The proposed nested array system can also be implemented by a microelectromechanical system (MEMS)-based microarray with the same principle.

We have shown that near field beamforming is essen-

tial for most applications due to the large size of the virtual array, even though the original array is physically small. Comparing to conventional far field and/or full band beamforming methods, the proposed system achieves better distance discrimination for near field targets. It reduces beampattern variations for broadband signals to the extent that occurs within an octave frequency band. It also improves sound quality via reverberation suppression in small enclosures.

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REFERENCES

- [1] R. C. Luo, C.-C. Yih, and K. L. Su, "Multisensor fusion and integration: approaches, applications, and future research directions," *IEEE Sensors Journal*, Vol. 2, No. 2, pp. 107–119, April, 2002.
- [2] J. G. Ryan, "Criterion for the minimum source distance at which plane-wave beamforming can be applied," *J. Acoust. Soc. Amer.*, vol. 104, no.1, pp.595–598, July 1998.
- [3] T. D. Abhayapala, R. A. Kennedy, and R. C. Williamson, "Noise modeling for nearfield array optimization," *Electronics Letters*, vol.35, no.10, pp. 764–765, 13 May 1999.
- [4] M. Dahl, and I. Claesson, "Acoustic noise and echo canceling with microphone array," *IEEE Trans. Vehicular Technology*, vol.48, no.5, pp. 1518–1526, Sep. 1999.
- [5] J.G. Ryan, and R. A. Goubran, "Array optimization applied in the near field of a microphone array," *IEEE Trans. Speech and Audio Processing*, vol.8, no.2, pp. 173–176, March 2000.
- [6] J.G. Ryan, and R.A. Goubran, "Application of Near-Field Optimum Microphone Arrays to Hands-free Mobile Telephony," *IEEE Transactions on Vehicular Technology*, Vol. 52, No. 2, pp. 390–400, March 2003.
- [7] S. Chowdhury, M. Ahmadi, and W. C. Miller, "Design of a MEMS Acoustical Beamforming Sensor Microarray," *IEEE Sensors Journal*, vol.2, No. 6, pp. 617–627, Dec. 2002.
- [8] P. Mermelstein, "G.722, a new CCITT coding standard for digital transmission of wideband audio signals," *IEEE Communications Magazine*, Vol. 26, No. 1, pp. 8–15, Jan. 1988.
- [9] T. D. Abhayapala, R. A. Kennedy, and R. C. Williamson, "Spatial aliasing for near-field sensor arrays," *Electronics Letters*, vol.35, no.10, pp. 764–765, 13 May 1999.
- [10] Y. R. Zheng, R. A. Goubran, and M. El-Tanany, "On constraint design and implementation for broadband adaptive array beamforming," *IEEE ICASSP*, Orlando, FL, USA, May 2002. vol.3, pp. 2917–2920.
- [11] J. B. Allen, and D. A. Berkley, "Image method for efficiently simulating small room acoustics," *J. Acoust. Soc. Amer.*, vol.65, no.4, pp.943–950, Apr. 1979.
- [12] Y. R. Zheng, "Spatial-temporal subband beamforming for near-field array processing." *Ph.D. dissertation, Dept. of Systems and Computer Engineering, Carleton University., Ottawa, Canada. Sep. 2002.*