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Combined Beamforming and Noise Cancellation

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Abstract – *This paper examines microphone-array-based, combined beamformer-noise canceller structures. The performance of the structures is evaluated using computer simulation as well as experimental measurements. The inter-operation of the beamformer and noise canceller is studied by measuring the SNR improvements offered by the respective components. An experimental procedure for evaluating output SNR is presented: the desired signal is captured from a set location in the recording environment. The noise signal is measured from a second (generally different) location. Results reveal an SNR improvement of up to 17 dB, and are compared to those stemming from conventional approaches.*

Keywords *– adaptive noise cancellation, microphone arrays, beamforming, generalized sidelobe canceller.*

I. BACKGROUND AND INTRODUCTION

The adaptive noise cancellation (ANC) process entails a scheme in which noise is subtracted from a received signal in an intelligent fashion to achieve a greater signal-to-noise ratio [1]. Figure 1 depicts the operation of the classical adaptive noise canceller.

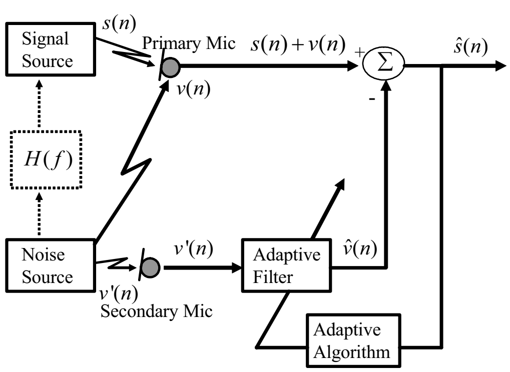

Figure 1: Classical adaptive noise cancellation.

A primary sensor is located in the vicinity of the desired signal, while a secondary sensor is positioned near the origin of the unwanted noise. The placement of the primary and secondary sensors is critical to the proper operation of the ANC. In some applications, it is not possible to place the secondary sensor near the noise source. Furthermore, if the temporal spectral content of the desired signal and interference is similar, the classical adaptive noise canceller may confuse (interchange) the desired signal from the interfering signal, leading to target signal suppression and noise enhancement. The addition of an intelligent front end may circumvent the latter two problems. A structure that exploits the spatial disparity between signal sources to perform spatial filtering is known as a beamformer [2] and potentially offers the intelligence required by the front end of the adaptive noise canceller.

The integration of a beamforming front-end into the adaptive noise cancellation process has been discussed as early as 1975, during which time Widrow [1] proposed adding an array-based fixed beamformer into the primary input of the noise canceller (Figure 2). The Griffiths-Jim beamformer [3], also known as the Generalized Sidelobe Canceller (GSC) expanded upon Widrow's structure by introducing a second beamformer that feeds the reference input of the noise canceller, shown in Figure 3. This beamformer, termed the "blocking matrix," is designed to block the target signal. Since the blocking matrix is a multiple-input-multiple-output device, the GSC also includes a multiple-input canceller, thus resulting in a more computationally complex structure. A structure that offers greater directivity than that of the Widrow structure without greatly increasing the complexity is presented in [4]. This structure includes a fixed beamformer steered to the noise source feeding the reference input, and is depicted in Figure 4.

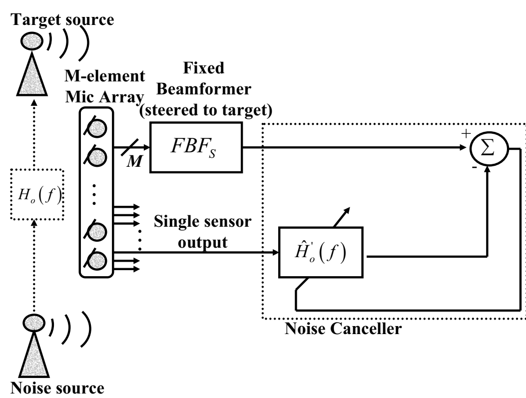

Figure 2: Array-based adaptive noise cancellation

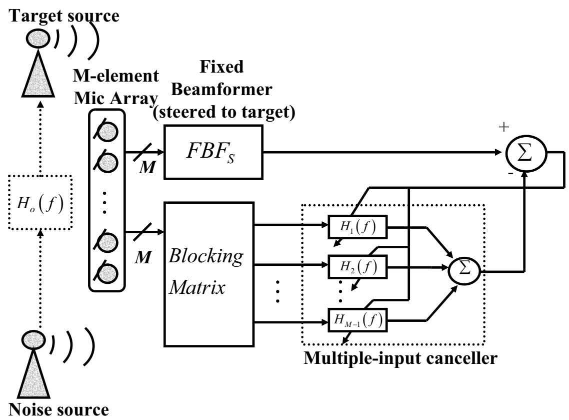

Figure 3: Generalized sidelobe canceller

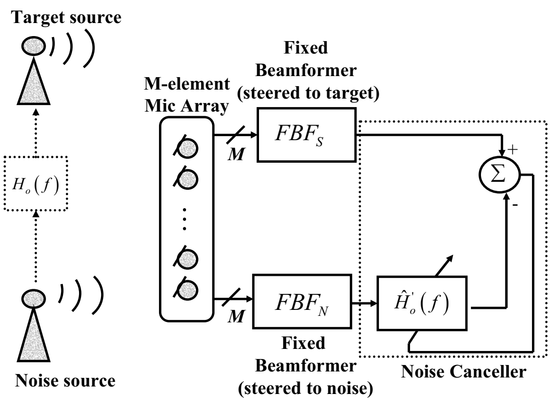

Figure 4: FBF-ANC structure

A number of researchers [5-7] have investigated beamformers from an experimental point-of-view. Specifically, [5] offers an experimental evaluation of a broadband beamformer-ANC structure. It is instructive to analyze the inter-operation involved when employing a beamformer in tandem with an adaptive noise canceller. The question of whether the use of a simple beamformer at the front end handicaps the performance of the adaptive noise canceller is particularly important.

II. ANECHOIC SIMULATION EVALUATION

The relationship between a front-end beamformer and cascaded adaptive noise canceller has first been studied in a computer simulation modeling lossless, anechoic, plane-wave propagation. A 9-element, uniformly-spaced linear array employing uniform weights of $1/9$ fed the beamformers comprising the front-ends of the three evaluated structures. The source signals were band-limited (300 Hz – 3.7 kHz) realizations of a white Gaussian process. The normalized LMS algorithms (NLMS) with a parameter of $\alpha = 0.1$ was chosen as the adaptive algorithm, with the adaptive filters consisting of 100 taps each. A delay of $L = 50$ samples was introduced into the target signal beamformer output in order to ensure that the transfer functions between primary and reference noise canceller inputs were causal. The simulation results reflect the assumption that a voice-activity-detection (VAD) module is present and accurate, such that adaptation is performed during "silent" (target-source-off) periods. Furthermore, the results given are post-convergence, such that the optimal Wiener filter is in place prior to evaluation. It is also assumed that the noise signal is statistically uncorrelated to the target signal.

To analyze the relationship between the performance of the front-end spatiotemporal beamformer(s) and that of the cascaded noise canceller(s), the SNR was computed at array input (denoted SNR_{array}), target-beamformer output (SNR_{BF}), and overall system output (SNR_{output}). The SNR improvement offered by the front-end beamformer is then given according to:

$$\Delta SNR_{BF} = SNR_{BF}\Big|_{dB} - SNR_{array}\Big|_{dB} \quad (1)$$

Likewise, the SNR improvement offered by the adaptive noise canceller component is:

$$\Delta SNR_{ANC} = SNR_{output}\Big|_{dB} - SNR_{BF}\Big|_{dB} \quad (2)$$

These SNR improvements were determined for various spatial separations (0-90 degrees) between target and noise sources. To that end, throughout the simulations, the target DOA was fixed at 0 degrees; the noise DOA was varied from 0 to 90 degrees. Figures 5-7 illustrate the manner in which the SNR improvements were computed. Figure 8 depicts the relationship between spatial separation and resulting SNR improvements.

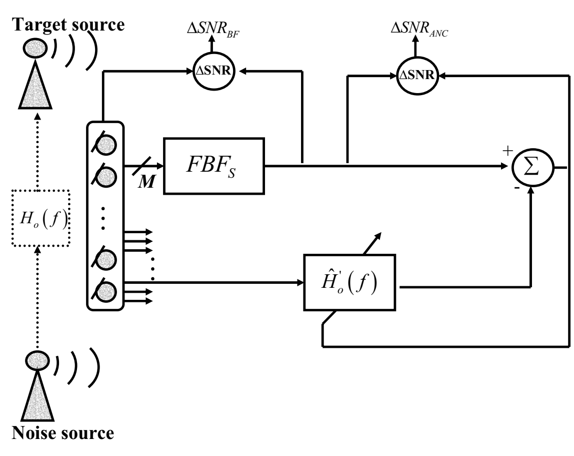

Figure 5: Contributions of beamformer and noise canceller to overall SNR improvement offered by Widrow structure

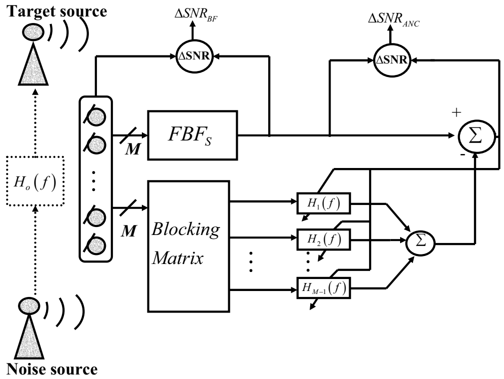

Figure 6: Contributions of beamformer and noise canceller to overall SNR improvement offered by GSC structure

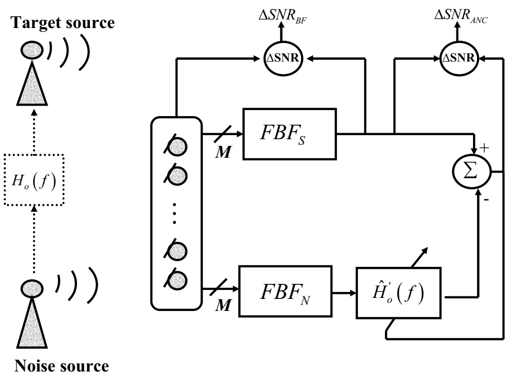

Figure 7: Contributions of beamformer and noise canceller to overall SNR improvement offered by FBF-ANC structure

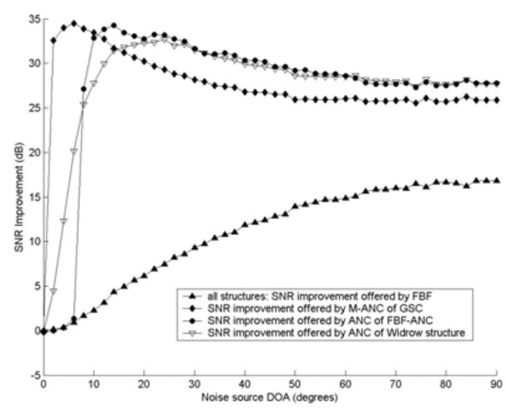

Figure 8: SNR improvements of beamformer and noise canceller components of the GSC, FBF-ANC, and Widrow structures

III. EVALUATION IN A REAL ENVIRONMENT

In order to evaluate the SNR improvements in a realistic scenario, an experimental evaluation has been performed. A (reverberant) conference-room environment has been chosen as the setting, with loudspeakers (playing white, Gaussian noise) acting as the sound sources. The data acquisition unit consists of a circular, sector-based, 6-element microphone array, a pre-amplifier, a multi-channel computer sound card, and recording software.

A semi-circular area (radius of *2m*) around the microphone array has been evaluated. The objective of the evaluation is to determine, for the three aforementioned structures, the improvement in signal-to-noise ratio from signal acquisition point (microphone array) to system output point.

It is important to note that since the investigation employed real (as opposed to simulated) data, the evaluation cannot be performed with desired signal source and noise source playing simultaneously. The signal processing consisted of two stages; In the first stage, the noise (and only the noise) is captured with the array, and beamformed accordingly. The adaptive algorithm then computes the optimal transfer function between the two beamformer outputs. The captured noise is then fed back into the converged structure, and the output noise power is measured. In the second stage, the target signal (and only the target signal) is recorded with the array and subsequent components. The recorded signal is then applied to the converged structure being evaluated, and once again, the output signal power is recorded. The output SNR is then easily determined by combining the results of the two stages. Note that since the system is linear, the latter procedure is valid. Figure 9 depicts the output signal-to-noise ratios of the three structures for various target-noise separation: the target DOA was fixed at 0 degrees, while the noise DOA was increased in increments of 30 degrees up to 180 degrees.

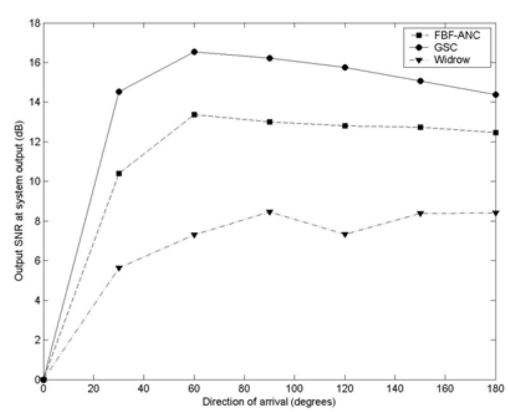

Figure 9: Experimentally obtained output signal-to-noise ratios for the GSC, FBF-ANC, and Widrow structures

IV. DISCUSSION

A beamformer is a spatiotemporal structure that thrives on spatial separation between target and noise sources. The beampattern function generally decreases as one moves away from the target DOA. Since the amount of noise leaked through the target beamformer decreases as the noise source moves away from the target source, the SNR at the target beamformer output will increase for increased target-noise separation.

An adaptive noise canceller is a purely temporal device that relies on correlation between its primary and reference inputs to convert the adaptive filter input to the desired signal. Intuitively, the correlation between beamformer outputs decreases as the steering DOA's of the beamformers move away from each other.

For very small separations between target and noise sources, the noise canceller suffers from a large amount of target signal leakage in the reference input, leading to significant target signal distortion. Once there is sufficient separation between target and noise, however, the noise canceller is able to significantly enhance the output signal by removing the noise present in the target beamformer output. This is clearly shown in Figure 8. Note that the three evaluated structures differ in the minimum amount of target-noise separation required to avoid significant target signal distortion. It is not surprising that the GSC requires only approximately 5 degrees of separation, while the FBF-ANC and Widrow structure require 15 and 25 degrees, respectively; The GSC is designed to prevent target signal leakage in the reference input. Note, however, that the FBF-ANC and Widrow structures offer greater SNR improvements in their noise canceller portions after the critical separation is reached. This is because the GSC, by attenuating a range of DOA's, has effectively reduced the correlation between noise in the reference input and noise in the primary input. Furthermore, note that for all structures, beyond the critical separation, the SNR improvement offered by the noise canceller(s) decreases as the separation increases. Once again, this is because as the target-noise separation increases, the correlation between the noise in the primary input and noise in the reference input decreases.

From Figure 8, one sees the co-operative effort of the beamformer and noise-canceller portions: the noise canceller provides greater signal enhancement in cases where the target beamformer output is heavily corrupted by noise. On the other hand, when the noise canceller is not able to offer as much enhancement, the beamformer "picks up the slack" by offering greater directivity.

The experimental results shown in Figure 9 reflect the presence of two complicating factors: uncorrelated noise components in the data acquisition unit, and the effect of signal reverberation on algorithm performance. It is well-known that the noise reduction offered by an ANC is intimately related to the level of uncorrelated noise components in the primary and reference input [8]. The noise canceller is obviously not able to remove uncorrelated noise in its primary input. Background noise, as well as noise introduced in the microphones, pre-amplifiers, and in the analog-to-digital conversion process contributes to lowering the SNR improvement offered by the structures.

Perhaps more detrimental to the performance of the algorithms is the effect of reverberation: multi-path signal propagation. Reverberation lowers the directivity offered by the beamformers by introducing multiple DOA's into the propagating wavefield. Components arriving in the sidelobes of the beamformer are undesirably passed. It has been shown [1] that the SNR at the output of an adaptive noise canceller is inversely related to the SNR at the reference input; Therefore, one desires to have a low signal-to-noise ratio at the reference sensor. Reverberation leads to target signal leakage in the output of the blocking matrix (or fixed beamformer steered to the noise DOA in the case of the FBF-ANC structure), thus increasing the SNR at the reference sensor.

It is not surprising that among the three evaluated structures, the Widrow structure offers the least SNR improvement: the reference input obviously contains a significant target signal component. The GSC offers the greatest SNR due to the lower level of target signal in the reference input. However, the gains are not as high as predicted by the computer simulations. Once again, this is due to the multi-path target signal reflections being leaked through the blocking matrix. It is interesting to consider the contrast between the design of the FBF-ANC and GSC structures: While the GSC attempts to minimize the target signal in the reference ANC input, the FBF-ANC focuses on maximizing the noise component. Note that under Widrow's postulation, the two should yield similar results. To that end, the FBF-ANC offers very reasonable SNR gains and avoids the complexity increase incurred by including the multiple-input canceller of the GSC.

V. CONCLUSION

The combination of a beamformer and an adaptive noise canceller leads to a spatiotemporal structure that operates with its two components cooperating with one another. The SNR gain offered by the ANC is proportional to the amount of noise present in the target beamformer output.

Experimental recordings and subsequent processing reveal the possibility of achieving the SNR gains produced by the GSC with a substantially less complex structure such as the FBF-ANC. In an anechoic signal environment, the GSC is able to rid the reference input entirely of the target signal by forming a deep null in the direction of the target source. However, in a real environment, multiple reflections leading to multiple target DOA's inevitably result in some level of target signal leakage. A structure that attempts to minimize the SNR at the reference sensor by maximizing the noise component achieves comparable results at substantially lower cost.

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