

BINAURAL MULTICHANNEL WIENER FILTER WITH DIRECTIONAL INTERFERENCE REJECTION

Elior Hadad¹, Daniel Marquardt², Simon Doclo², and Sharon Gannot¹

¹ Faculty of Engineering, Bar-Ilan University, Ramat-Gan, Israel

² University of Oldenburg, Department of Medical Physics and Acoustics and Cluster of Excellence Hearing4All, Oldenburg, Germany

{elior.hadad, sharon.gannot}@biu.ac.il {daniel.marquardt, simon.doclo}@uni-oldenburg.de

ABSTRACT

In this paper we consider an acoustic scenario with a desired source and a directional interference picked up by hearing devices in a noisy and reverberant environment. We present an extension of the binaural multichannel Wiener filter (BMWF), by adding an interference rejection constraint to its cost function, in order to combine the advantages of spatial and spectral filtering while mitigating directional interferences. We prove that this algorithm can be decomposed into the binaural linearly constrained minimum variance (BLCMV) algorithm followed by a single channel Wiener post-filter. The proposed algorithm yields improved interference rejection capabilities, as compared with the BMWF. Moreover, by utilizing the spectral information on the sources, it is demonstrating better SNR measures, as compared with the BLCMV.

Index Terms— Hearing aids, Binaural cues, LCMV and MWF Beamforming, Noise and interference cancellation.

1. INTRODUCTION

Speech understanding in noisy environments is still a major issue for many hearing aid users. Most state-of-the-art hearing aids nowadays contain multiple microphones, enabling the usage of multi-microphone speech enhancement algorithms, which have been shown to significantly improve speech quality and intelligibility compared to single-microphone algorithms. In a binaural system, the hearing-impaired person is fitted with two hearing aids where the microphone signals of both hearing aids are shared. The objective of a binaural speech enhancement algorithm is not only to selectively extract the desired source and to suppress directional interferences (e.g., competing speakers) and ambient background noise, but also to preserve the auditory impression for the hearing aid user. This can be achieved by preserving the binaural cues of the sound sources in the acoustic scene. For directional sources, preserving the interaural level difference (ILD) and the interaural time difference (ITD) can be achieved by preserving the so-called relative transfer function (RTF), which is defined as the ratio of the acoustical transfer functions relating the source and the two ears.

Several binaural speech enhancement algorithms aiming to preserve the binaural cues were developed in the last decade. In [1, 2] the beamformer utilizes two microphone signals (one at each side

of the head). An identical and real-valued spectral gain is applied in each side of the hearing aid, hence, preserving the ILD and ITD cues of all sources. This technique, however, typically suffers from artifacts, often attributed to single microphone speech enhancement algorithms, especially in low signal to noise ratio (SNR). Binaural noise reduction algorithms with cue preservation can also be constructed by applying a blind source separation (BSS) algorithm followed by spatialization stage to maintain the spatial information [3, 4, 5]. Alternatively, cue preservation can be obtained by extending the BSS cost function to incorporate spatial information [6]. In [7] the binaural cues of a desired source are preserved by applying multiple constraints and implementing a closed-form linearly constrained minimum variance (LCMV) beamformer with broad beam. In [8, 9] the binaural multichannel Wiener filter (BMWF) has been presented. It has been theoretically proven in [9] that in case of a single speech source the BMWF preserves the RTF of the desired source components while the binaural noise cues are not preserved. Several extensions of the BMWF, aiming to preserve the noise RTF and the interaural coherence (IC) of the noise component, were proposed in [9, 10]. Furthermore, it is well-known that the BMWF can be decomposed into a spatial filter, namely the binaural minimum variance distortionless response (BMVDR) and a single-channel Wiener postfilter [8].

In many acoustic conditions the desired source is contaminated by both additive noise and a directional interference (e.g., a competing speaker). To better control the suppression and binaural cue preservation of directional interferences, a binaural extension of the LCMV beamformer [11], named BLCMV was proposed in [12] and examined in [13]. In the proposed binaural criterion an interference rejection constraint was added to the basic cost function of the BMVDR [12]. The BLCMV is able to extract the desired source as received by the reference microphones while reducing noise and interference. In addition, the BLCMV is able to preserve the binaural cues of the desired source. The BLCMV can preserve the cues of the interference signals as well by constraining their contribution at the beamformer output to a small predefined value. In this contribution we ignore the interference cue preservation and constrain the interference output to be zero.

The BLCMV beamformer only utilizes spatial information without exploiting the spectral characteristics of the sources. Spectral filtering provides additional noise reduction at the cost of speech distortion, by exploiting the time-varying power spectral density (PSD) of the speech and the noise components.

In this paper we propose to add an interference rejection constraint to the BMWF cost function, similarly to the extension of the BMVDR to the BLCMV. Consequently, we combine the advantages

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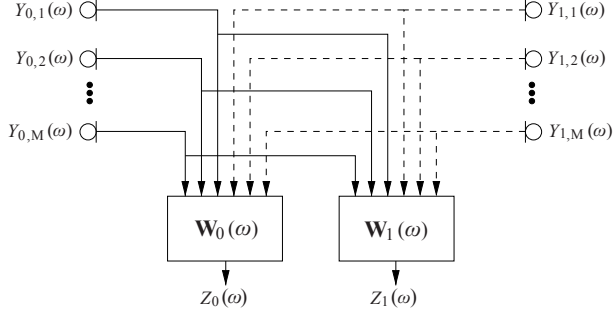


Fig. 1. General binaural processing scheme.

of spatial and spectral filtering while mitigating directional interference. This algorithm is denoted binaural multichannel Wiener filter with interference rejection (BMWF-IR). We show that the proposed BMWF-IR filter can be decomposed into the BLCMV filter followed by a single-channel Wiener post-filter. This decomposition into a spatial and spectral filter is advantageous since the spatial filter can be assumed time-invariant while the spectral filter can adapt to the fast changing PSD information. Experimental validations in an office scenario show that the proposed filter yields a better noise reduction than the BLCMV due to the additional spectral filtering, while the interference rejection is significantly larger than in the BMWF.

The paper is organized as follows. In Sec. 2, the binaural speech enhancement problem is formulated. We briefly review the BMWF and the BLCMV and introduce the BMWF-IR in Sec. 3. Sec. 4 outlines the relation between the BLCMV and the BMWF-IR. The proposed method is experimentally validated in Sec. 5. Conclusions are drawn in Sec. 6.

2. PROBLEM FORMULATION

We consider a simplified cocktail party scenario consisting of two speakers, one desired speaker and one interfering speaker, in a noisy and reverberant environment. A binaural hearing device is used, consisting of two hearing aids each equipped with M microphones as depicted in Fig. 1. We denote the m -th microphone signal at the left hearing aid in the frequency-domain as

$$Y_{0,m}(\omega) = X_{0,m}(\omega) + U_{0,m}(\omega) + N_{0,m}(\omega), \quad m = 1 \dots M,$$

with $X_{0,m}$ the desired source component, $U_{0,m}$ the interference source component and $N_{0,m}$ the additional background noise at the m -th microphone signal. The m -th microphone signal at the right hearing aid $Y_{1,m}(\omega)$ is defined similarly. The variable ω will henceforth be omitted for brevity. All microphone signals can be stacked in the $2M$ -dimensional vector \mathbf{Y} as

$$\mathbf{Y} = \mathbf{X} + \mathbf{U} + \mathbf{N} = \mathbf{X} + \mathbf{V}, \quad (1)$$

with $\mathbf{Y} = [Y_{0,1} \dots Y_{0,M} \ Y_{1,1} \dots Y_{1,M}]^T$. The vector $\mathbf{V} = \mathbf{U} + \mathbf{N}$ is defined as the total undesired component as received by the microphones, i.e., interference source plus background noise. \mathbf{X} , \mathbf{U} , \mathbf{V} and \mathbf{N} are defined similarly to \mathbf{Y} . We can further write $\mathbf{X} = S_d \mathbf{A}$ and $\mathbf{U} = S_u \mathbf{B}$, where S_d and S_u are the desired and interference source signals and \mathbf{A} and \mathbf{B} are the acoustic transfer functions (ATFs) relating the desired and interference components and the microphone array, respectively. The spatial correlation matrices of the desired,

interfering and noise components are defined as

$$\begin{aligned} \mathbf{R}_x &= \mathcal{E} \{ \mathbf{X} \mathbf{X}^H \} = P_s \mathbf{A} \mathbf{A}^H \\ \mathbf{R}_u &= \mathcal{E} \{ \mathbf{U} \mathbf{U}^H \} = P_u \mathbf{B} \mathbf{B}^H \\ \mathbf{R}_n &= \mathcal{E} \{ \mathbf{N} \mathbf{N}^H \}, \end{aligned} \quad (2)$$

where $\mathcal{E} \{ \cdot \}$ denotes the expectation operator, $P_s = \mathcal{E} \{ |S_d|^2 \}$ and $P_u = \mathcal{E} \{ |S_u|^2 \}$ the PSDs of the desired source and the directional interference, respectively. Assuming that the sources and the noise are uncorrelated, $\mathbf{R}_v = \mathbf{R}_u + \mathbf{R}_n$ and $\mathbf{R}_y = \mathbf{R}_x + \mathbf{R}_v$. Without loss of generality, the first microphone on the left hearing aid and the first microphone on the right hearing aid are chosen as the reference microphones. For conciseness, the reference microphone signals $Y_{0,1}$ and $Y_{1,1}$ at the left and the right hearing aid are denoted as Y_0 and Y_1 , and are equal to

$$Y_0 = \mathbf{e}_0^H \mathbf{Y}, \quad Y_1 = \mathbf{e}_1^H \mathbf{Y}, \quad (3)$$

where \mathbf{e}_0 and \mathbf{e}_1 are $2M$ -dimensional vectors with one element equal to 1 and 0 elsewhere, i.e., $\mathbf{e}_0(1) = 1$ and $\mathbf{e}_1(M+1) = 1$. The reference microphone signals can then be written as

$$\begin{aligned} Y_0 &= S_d A_0 + S_u B_0 + N_0 \\ Y_1 &= S_d A_1 + S_u B_1 + N_1. \end{aligned} \quad (4)$$

The RTFs of the desired source and the directional interference source in the reference microphones of the left and the right hearing aids are defined as the ratio of the ATFs, i.e.,

$$\text{RTF}_x^{\text{in}} = \frac{A_0}{A_1} \quad \text{RTF}_u^{\text{in}} = \frac{B_0}{B_1}. \quad (5)$$

3. BINAURAL NOISE REDUCTION ALGORITHMS

In this section we first briefly review the BMWF, BMVDR and the BLCMV. Then we extend the BMWF cost function with a term related to the rejection of the directional interference, resulting in the proposed BMWF-IR.

3.1. Binaural Multichannel Wiener filter (BMWF)

The BMWF produces a minimum mean square error (MSE) estimate of the desired source component at the reference microphone signals of both hearing aids [8]. The MSE cost functions for the filter \mathbf{W}_0 estimating the desired source component X_0 at the left hearing aid and for the filter \mathbf{W}_1 estimating the desired source component X_1 at the right hearing aid are given by

$$\begin{aligned} J_{\text{BMWF}}(\mathbf{W}_0) &= \mathcal{E} \{ \| [X_0 - \mathbf{W}_0^H \mathbf{X}] \|^2 + \mu \| \mathbf{W}_0^H \mathbf{V} \|^2 \} \\ J_{\text{BMWF}}(\mathbf{W}_1) &= \mathcal{E} \{ \| [X_1 - \mathbf{W}_1^H \mathbf{X}] \|^2 + \mu \| \mathbf{W}_1^H \mathbf{V} \|^2 \}, \end{aligned} \quad (6)$$

where μ provides a tradeoff between noise reduction and speech distortion¹. The filters minimizing $J_{\text{BMWF}}(\mathbf{W}_0)$ and $J_{\text{BMWF}}(\mathbf{W}_1)$ are given by

$$\begin{aligned} \mathbf{W}_{0,\text{BMWF}} &= (\mathbf{R}_x + \mu \mathbf{R}_v)^{-1} \mathbf{r}_{x,0} \\ \mathbf{W}_{1,\text{BMWF}} &= (\mathbf{R}_x + \mu \mathbf{R}_v)^{-1} \mathbf{r}_{x,1} \end{aligned} \quad (7)$$

¹Note that by introducing μ , the more general binaural *speech distortion weighted* multichannel Wiener filter (SDW-MWF) is addressed. For conciseness it is abbreviated in this paper as BMWF.

with $\mathbf{r}_{x,0} = \mathbf{R}_x \mathbf{e}_0$ and $\mathbf{r}_{x,1} = \mathbf{R}_x \mathbf{e}_1$. Applying the Woodbury identity to (7), the optimal filters can be decomposed into a (spatial) BMVDR filter followed by a single-channel (spectral) Wiener filter, i.e.,

$$\begin{aligned} \mathbf{W}_{0,\text{BMWF}} &= W_{0,\text{post}} \mathbf{W}_{0,\text{BMVDR}} = \underbrace{\frac{\rho_{\text{BMVDR}}}{\mu + \rho_{\text{BMVDR}}}}_{W_{0,\text{post}}} \underbrace{\frac{\mathbf{R}_v^{-1} \mathbf{A}}{\gamma_a} A_0^*}_{\mathbf{W}_{0,\text{BMVDR}}} \\ \mathbf{W}_{1,\text{BMWF}} &= W_{1,\text{post}} \mathbf{W}_{1,\text{BMVDR}} = \underbrace{\frac{\rho_{\text{BMVDR}}}{\mu + \rho_{\text{BMVDR}}}}_{W_{1,\text{post}}} \underbrace{\frac{\mathbf{R}_v^{-1} \mathbf{A}}{\gamma_a} A_1^*}_{\mathbf{W}_{1,\text{BMVDR}}} \end{aligned} \quad (8)$$

with $\gamma_a = \mathbf{A}^H \mathbf{R}_v^{-1} \mathbf{A}$ and $\rho_{\text{BMVDR}} = P_s \gamma_a$ is the output SNR of the BMVDR [8]. Note that the left and right BMVDR filters are parallel and hence preserve the binaural cues of the desired source. The left and the right postfilters are identical and real-valued, i.e., $W_{0,\text{post}} = W_{1,\text{post}}$. Therefore, the binaural postfilter does not distort the binaural cues.

3.2. Binaural LCMV (BLCMV)

The BLCMV consists of two beamformers designed to reproduce the desired source component of both reference microphone signals, while canceling the directional interference and minimizing the overall noise power [12]. The BLCMV is an extension of the BMVDR beamformer by adding an interference rejection constraint to the BMVDR cost function², i.e.,

$$\begin{aligned} \min_{\mathbf{W}_0} \mathbf{W}_0^H \mathbf{R}_v \mathbf{W}_0 \quad \text{subject to} \quad \mathbf{C}_0^H \mathbf{W}_0 &= \mathbf{b}_0, \\ \min_{\mathbf{W}_1} \mathbf{W}_1^H \mathbf{R}_v \mathbf{W}_1 \quad \text{subject to} \quad \mathbf{C}_1^H \mathbf{W}_1 &= \mathbf{b}_1, \end{aligned} \quad (9)$$

with

$$\mathbf{C}_0 = \mathbf{C}_1 = \mathbf{C} = [\mathbf{A} \quad \mathbf{B}] \quad \mathbf{b}_0 = \begin{bmatrix} A_0^* \\ 0 \end{bmatrix} \quad \mathbf{b}_1 = \begin{bmatrix} A_1^* \\ 0 \end{bmatrix}, \quad (10)$$

where $\mathbf{b}_0, \mathbf{b}_1$ are set to constrain the desired source component at the beamformers output to $A_0 S_d$ and $A_1 S_d$, for the left and right beamformers respectively, and to constrain the interference source component to zero. Filters solving (9) are equal to:

$$\begin{aligned} \mathbf{W}_0 &= \mathbf{R}_v^{-1} \mathbf{C} \left[\mathbf{C}^H \mathbf{R}_v^{-1} \mathbf{C} \right]^{-1} \mathbf{b}_0 \\ \mathbf{W}_1 &= \mathbf{R}_v^{-1} \mathbf{C} \left[\mathbf{C}^H \mathbf{R}_v^{-1} \mathbf{C} \right]^{-1} \mathbf{b}_1. \end{aligned} \quad (11)$$

Substituting (10) into (11), these filters can be written as

$$\begin{aligned} \mathbf{W}_{0,\text{LCMV}} &= \frac{A_0^*}{\gamma_a (1 - \Gamma)} \begin{bmatrix} \mathbf{R}_v^{-1} \mathbf{A} - \Gamma \frac{\gamma_a}{\gamma_{ab}} \mathbf{R}_v^{-1} \mathbf{B} \\ \frac{\gamma_a}{\gamma_{ab}} \mathbf{R}_v^{-1} \mathbf{B} \end{bmatrix} \\ \mathbf{W}_{1,\text{LCMV}} &= \frac{A_1^*}{\gamma_a (1 - \Gamma)} \begin{bmatrix} \mathbf{R}_v^{-1} \mathbf{A} - \Gamma \frac{\gamma_a}{\gamma_{ab}} \mathbf{R}_v^{-1} \mathbf{B} \\ \frac{\gamma_a}{\gamma_{ab}} \mathbf{R}_v^{-1} \mathbf{B} \end{bmatrix}, \end{aligned} \quad (12)$$

where $\gamma_{ab} = \mathbf{A}^H \mathbf{R}_v^{-1} \mathbf{B}$, $\gamma_b = \mathbf{B}^H \mathbf{R}_v^{-1} \mathbf{B}$ and $\Gamma = \frac{|\gamma_{ab}|^2}{\gamma_a \gamma_b}$ with $0 \leq \Gamma \leq 1$. Again, the filters for the left and the right hearing aid are parallel such that the RTF of the desired source is preserved³, i.e., $\text{RTF}_x^{\text{out}} = \text{RTF}_x^{\text{in}}$.

²Note that we can replace \mathbf{R}_v in these LCMV criteria with \mathbf{R}_n or with \mathbf{R}_y . Ideally, without model-errors all criteria coincide [14].

³Note that the beamformer assigns a perfect null towards the interference, therefore, $\text{RTF}_x^{\text{out}}$ is undefined. In [12] cue preservation of the interference source is obtained by a nontrivial constraint on its respective RTFs.

3.3. BMWF with Interference Rejection (BMWF-IR)

Similar to the extension of the BMVDR we now propose to extend the BMWF cost function in (6) with a constraint related to the rejection of the directional interference source component, i.e.,

$$\begin{aligned} \min_{\mathbf{W}_0} J_{\text{BMWF}}(\mathbf{W}_0) \quad \text{subject to} \quad \mathbf{W}_0^H \mathbf{B} &= 0, \\ \min_{\mathbf{W}_1} J_{\text{BMWF}}(\mathbf{W}_1) \quad \text{subject to} \quad \mathbf{W}_1^H \mathbf{B} &= 0. \end{aligned} \quad (13)$$

The Lagrangian for the left beamformer cost function is equal to

$$\mathcal{L}(\mathbf{W}_0) = \{ \mathbf{W}_0^H (\mathbf{R}_x + \mu \mathbf{R}_v) \mathbf{W}_0 - \mathbf{W}_0^H \mathbf{r}_{x,0} - \mathbf{r}_{x,0}^H \mathbf{W}_0 + P_s |A_0|^2 + \lambda \mathbf{W}_0^H \mathbf{B} - \lambda^* \mathbf{B}^H \mathbf{W}_0 \} \quad (14)$$

where λ is a Lagrange multiplier. Setting the derivative with respect to \mathbf{W}_0^H to 0 yields

$$\nabla_{\mathbf{W}_0^H} \mathcal{L}(\mathbf{W}_0) = (\mathbf{R}_x + \mu \mathbf{R}_v) \mathbf{W}_0 - \mathbf{r}_{x,0} + \lambda \mathbf{B} = 0. \quad (15)$$

By satisfying the constraints in (13) the Lagrange multiplier λ can be computed as:

$$\lambda = \frac{\mathbf{B}^H (\mathbf{R}_x + \mu \mathbf{R}_v)^{-1} \mathbf{r}_{x,0}}{\mathbf{B}^H (\mathbf{R}_x + \mu \mathbf{R}_v)^{-1} \mathbf{B}}. \quad (16)$$

The criterion for the right beamformer is similarly formulated. The optimal left beamformer is hence equal to

$$\begin{aligned} \mathbf{W}_{0,\text{BMWF-IR}} &= \mathbf{W}_{0,\text{BMWF}} \\ &\quad - \frac{(\mathbf{R}_x + \mu \mathbf{R}_v)^{-1} \mathbf{B}^H (\mathbf{R}_x + \mu \mathbf{R}_v)^{-1} \mathbf{r}_{x,0}}{\mathbf{B}^H (\mathbf{R}_x + \mu \mathbf{R}_v)^{-1} \mathbf{B}} \mathbf{B}. \end{aligned} \quad (17)$$

Similarly, the optimal right beamformer is equal to

$$\begin{aligned} \mathbf{W}_{1,\text{BMWF-IR}} &= \mathbf{W}_{1,\text{BMWF}} \\ &\quad - \frac{(\mathbf{R}_x + \mu \mathbf{R}_v)^{-1} \mathbf{B}^H (\mathbf{R}_x + \mu \mathbf{R}_v)^{-1} \mathbf{r}_{x,1}}{\mathbf{B}^H (\mathbf{R}_x + \mu \mathbf{R}_v)^{-1} \mathbf{B}} \mathbf{B}. \end{aligned} \quad (18)$$

Hence, by assigning a null towards the directional interference the output of the BMWF-IR filter corresponds to a subtraction of a component, related to the directional interference, from the standard BMWF.

4. RELATIONSHIP BETWEEN BMWF-IR AND BLCMV

In this section we show that the BMWF-IR in (17) and (18) can be decomposed into the BLCMV followed by a single-channel Wiener postfilter. Reformulating the filters in (17) and (18) yields

$$\begin{aligned} \mathbf{W}_{0,\text{BMWF-IR}} &= P_s A_0^* \left[(\mathbf{R}_x + \mu \mathbf{R}_v)^{-1} \mathbf{A} - \frac{\lambda_{ab}^*}{\lambda_b} (\mathbf{R}_x + \mu \mathbf{R}_v)^{-1} \mathbf{B} \right] \\ \mathbf{W}_{1,\text{BMWF-IR}} &= P_s A_1^* \left[(\mathbf{R}_x + \mu \mathbf{R}_v)^{-1} \mathbf{A} - \frac{\lambda_{ab}^*}{\lambda_b} (\mathbf{R}_x + \mu \mathbf{R}_v)^{-1} \mathbf{B} \right] \end{aligned} \quad (19)$$

where $\lambda_a = \mathbf{A}^H (\mathbf{R}_x + \mu \mathbf{R}_v)^{-1} \mathbf{A}$, $\lambda_{ab} = \mathbf{A}^H (\mathbf{R}_x + \mu \mathbf{R}_v)^{-1} \mathbf{B}$ and $\lambda_b = \mathbf{B}^H (\mathbf{R}_x + \mu \mathbf{R}_v)^{-1} \mathbf{B}$. By applying the Woodbury identity to (19) the filters can be written as:

$$\begin{aligned} \mathbf{W}_{0,\text{BMWF-IR}} &= \frac{P_s A_0^*}{\mu + P_s \gamma_a (1 - \Gamma)} \left[\mathbf{R}_v^{-1} \mathbf{A} - \Gamma \frac{\gamma_a}{\gamma_{ab}} \mathbf{R}_v^{-1} \mathbf{B} \right] \\ \mathbf{W}_{1,\text{BMWF-IR}} &= \frac{P_s A_1^*}{\mu + P_s \gamma_a (1 - \Gamma)} \left[\mathbf{R}_v^{-1} \mathbf{A} - \Gamma \frac{\gamma_a}{\gamma_{ab}} \mathbf{R}_v^{-1} \mathbf{B} \right]. \end{aligned} \quad (20)$$

Note that the left and right BMWF-IR are parallel as well. These expressions can be further simplified by noting that the BLCMV outputs are given by:

$$\begin{aligned} S_{0,x,o} &= P_s |A_0|^2 & S_{0,v,o} &= |A_0|^2 [\gamma_a (1 - \Gamma)]^{-1} \\ S_{1,x,o} &= P_s |A_1|^2 & S_{1,v,o} &= |A_1|^2 [\gamma_a (1 - \Gamma)]^{-1}. \end{aligned} \quad (21)$$

Hence, using (21) the BMWF-IR can be decomposed into the (spatial) BLCMV filter followed by a single-channel (spectral) Wiener postfilter, i.e.,

$$\begin{aligned} \mathbf{W}_{0,\text{BMWF-IR}} &= W_{0,\text{post}} \mathbf{W}_{0,\text{LCMV}} = \frac{\rho_{\text{BLCMV}}}{\mu + \rho_{\text{BLCMV}}} \mathbf{W}_{0,\text{LCMV}} \\ \mathbf{W}_{1,\text{BMWF-IR}} &= W_{1,\text{post}} \mathbf{W}_{1,\text{LCMV}} = \frac{\rho_{\text{BLCMV}}}{\mu + \rho_{\text{BLCMV}}} \mathbf{W}_{1,\text{LCMV}}, \end{aligned} \quad (22)$$

where $\rho_{\text{BLCMV}} = \frac{S_{0,x,o}}{S_{0,v,o}} = \frac{S_{1,x,o}}{S_{1,v,o}} = P_s \gamma_a (1 - \Gamma)$ is the output SNR of the BLCMV⁴. Again, the left and right postfilters are identical and real-valued, i.e., $W_{0,\text{post}} = W_{1,\text{post}}$, leading to identical signal to interference ratio (SIR) and SNR improvement for each frequency bin (but not necessarily for the respective wideband measures). Therefore, the binaural postfilter does not distort the binaural cues. The relationship between the BMWF and the BMVDR is well-known [8]. From the above derivations, it can be deduced that a similar relationship holds between the BLCMV and the BMWF-IR as well. Note that this relation holds also for the monaural case.

5. EXPERIMENTAL VALIDATION

In this section we present experimental validation results comparing the performance of the BMVDR, BMWF, the BLCMV and the BMWF-IR. To verify the theoretical analysis presented in Sec. 3 and Sec. 4, we have used actual impulse responses (IRs) and artificial sources, hence circumventing any estimation errors issues⁵. The algorithms were evaluated using the binaural behind-the-ear impulse responses (BTE-IRs) drawn from [16]. Both hearing aids are equipped with two microphones at each side. The tradeoff parameter μ for the BMWF and for the BMWF-IR was set to 1. The test scenario comprised one desired source at $\theta_x = -30^\circ$ and 1m from the listener, one interference source at $\theta_v = 45^\circ$ and 1m from the listener and a diffuse noise. The reverberation time is approximately 400 ms. Two different stationary signals with speech-shaped PSDs were chosen as the desired and interference input signals. A cylindrically isotropic noise field was simulated by averaging the anechoic BTE-IR from [16]. The noise PSD was modelled as speech-shaped noise as well.

We will compare the performance of the considered algorithms in terms of (wideband) SIR and SNR. The SIR is defined as the ratio

⁴It is easy to verify that $\rho_{\text{BLCMV}} \leq \rho_{\text{BMVDR}}$, consequently, the BMVDR outperforms BLCMV in terms of SNR improvement.

⁵Note that for implementing the algorithm it is sufficient to estimate the relative ATF's rather than the ATF's of the desired source and the directional interference. Relative ATF estimation procedures can be found in [11, 12, 15]. The noise correlation matrix can be estimated in speech non-active time segments. Further detailed can be found in [12] and are omitted due to space constraints.

of the average PSDs of the desired and interference sources over all frequency bands. The SNR is defined as the ratio of the average PSDs of the desired source and the noise.

The results for various input SNRs and SIRs are summarized in Table 1 and Table 2, respectively. First, it can be observed from Table 1 that the SIR improvement of the BLCMV and the BMWF-IR is very high for all scenarios (indicated with ∞ in the tables).

SNR in	SIR in	Δ SIR			
		BMVDR	BMWF	BLCMV	BMWF-IR
0	-10	28.6	30	∞	∞
0	10	8.2	8.7	∞	∞
16	0	39.0	39.2	∞	∞

Table 1. Wideband SIR improvements in dB relative to the left signal as obtained by the BMVDR, BMWF, BLCMV and BMWF-IR beamformers for various input SIRs and input SNRs.

It can be observed from Table 2 that the BMWF shows the best SNR improvement for all scenarios compared with the other considered algorithms. The SNR improvement of the BMVDR is higher than the SNR improvement of the BLCMV resulting from the additional constraint in the BLCMV (and theoretically shown in Footnote 4). For low input SIRs, the SNR improvements of the BMWF-IR and the BMWF are comparable. This may be attributed to the marginal contribution of the competing signal to the overall interference. BMVDR, BMWF and BMWF-IR outperform the BLCMV with respect to SNR improvement. For high input SNR, the SNR improvement performance for the four algorithms is comparable.

SNR in	SIR in	Δ SNR			
		BMVDR	BMWF	BLCMV	BMWF-IR
0	-10	5.08	6.58	4.66	6.32
0	10	6.81	8.20	4.66	6.32
16	0	4.79	4.91	4.66	4.78

Table 2. Wideband SNR improvements in dB relative to the left signal as obtained by the BMVDR, BMWF, BLCMV and BMWF-IR beamformers for various input SIRs and input SNRs.

Note that the SNR performance of the BLCMV does not depend on either the SIR or the SNR input levels, since it utilizes only the ATF's of the sources and the coherence of the noise. The improvement in the *wideband* SNR measure of the BMWF-IR, as compared with the BLCMV, is attributed to the subsequent single-channel Wiener postfilter.

6. CONCLUSION

In this paper we proposed a novel binaural beamformer that is designed to estimate a desired source and reject a directional interference in a noisy and reverberant environment. The proposed algorithm is capable of steering a null towards the interference, therefore yielding an improved interference rejection as compared with the BMWF. Moreover, since the algorithm also utilizes the spectral information of the sources, it is able to achieve a larger SNR improvement as compared with the BLCMV.

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