OPTIMAL BINAURAL LCMV BEAMFORMERS FOR COMBINED NOISE REDUCTION AND BINAURAL CUE PRESERVATION

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ABSTRACT

Besides noise reduction an important objective of binaural speech enhancement algorithms is the preservation of the binaural cues of both desired and undesired sound sources. Recently, the binaural Linearly Constrained Minimum Variance (BLCMV) beamformer has been proposed that aims to preserve the desired speech component and suppress the undesired directional interference component while preserving the binaural cues of both components. Since the performance of the BLCMV beamformer highly depends on the amount of interference rejection determined by the interference rejection parameter, in this paper we propose several performance criteria to optimize the interference rejection parameters for the left and the right hearing aid. Experimental results show how the performance of the BLCMV beamformer is affected by the different optimal parameter combinations.

Index Terms— Hearing aids, binaural cues, noise reduction, directional interference

1. INTRODUCTION

Noise reduction algorithms in hearing aids are crucial to improve speech understanding in background noise for hearing impaired persons. Binaural noise reduction algorithms that exploit the microphone signals from both the left and the right hearing aid are considered to be promising techniques for noise reduction, because in addition to spectral information spatial information can also be exploited [1, 2, 3, 4]. In addition to reducing noise and limiting speech distortion, another important objective of binaural noise reduction algorithms is the preservation of the listener's impression of the acoustical scene, in order to exploit the binaural hearing advantage and to avoid confusions due to a mismatch between the acoustical and the visual information. This can be achieved by preserving the binaural cues of all sound sources in the acoustical scene.

In [1] the binaural Speech Distortion Weighted Multi-channel Wiener Filter (MWF) has been presented. It has been theoretically proven in [5] that in the case of a single speech source, the binaural MWF preserves the binaural cues of the speech component but distorts the binaural cues of the residual noise component. To also preserve the binaural cues of the residual noise component, several extensions of the binaural MWF have been proposed for directional interferences [6] as well as for mixed noise fields [6, 7]. To better control the suppression and binaural cue preservation for directional interferences, a binaural extension of the monaural Linearly Constrained Minimum Variance (LCMV) beamformer in[8], namely the BLCMV has been presented in [9]. Since the performance of the LCMV beamformer highly depends on the choice of the so-called interference rejection parameter, for the monaural LCMV it has been proposed in [10] to decompose the LCMV filter as the weighted sum of two spatial subfilters. Using this decomposition, the interference rejection parameter, maximizing the output Speech to Interference + Noise Ratio (SINR) was derived in [10]. In this paper, we extend this approach to the binaural case and decompose the BLCMV as a trade-off beamformer. In contrast to the monaural case, for the binaural case not only the maximization of the output SINR is important but also the preservation of the Relative Transfer Function (RTF) of the speech component and the directional interference. In section 3 we will propose several optimization criteria, i.e. the SINR of the left, respectively right hearing aid or the binaural SINR, leading to different optimal interference rejection parameters for the left and the right hearing aid. The performance of the resulting filters with respect to objective measures is compared in Section 4.

2. CONFIGURATION AND NOTATION

Consider the binaural hearing aid configuration in Figure 1, consisting of a microphone array with M microphones on the left and the right hearing aid. The m-th microphone signal at the left hearing aid $Y_{0,m}(\omega)$ can be written in the frequency-domain as

$$Y_{0,m}(\omega) = X_{0,m}(\omega) + U_{0,m}(\omega) + N_{0,m}(\omega), \quad m = 1 \ldots M,$$
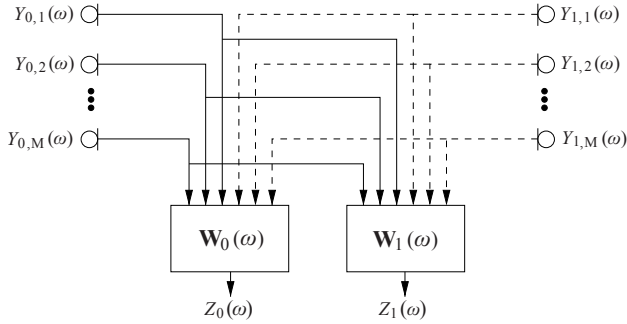
Fig. 1. Binaural hearing aid configuration

with $X_{0,m}$, the speech component, $U_{0,m}$, the interference component and $N_{0,m}$, the additional background noise in the m-th microphone signal. The m-th microphone signal at the right hearing aid $Y_{1,m}(\omega)$ is defined similarly. For conciseness we will omit the frequency variable ω in the remainder of the paper. We define the $2M$-dimensional signal vector $\mathbf{Y}$ as

$$\mathbf{Y} = [Y_{0,1} \ldots Y_{0,M} \, Y_{1,1} \ldots Y_{1,M}]^T. \qquad (1)$$

which can be written as $\mathbf{Y} = \mathbf{X} + \mathbf{U} + \mathbf{N}$, where $\mathbf{X}$, $\mathbf{U}$ and $\mathbf{N}$ are defined similarly as $\mathbf{Y}$. Considering a acoustical scenario with one desired speech source S_x and one undesired directional interference S_i, the directional components $\mathbf{X}$ and $\mathbf{U}$ can be further written as

$$\mathbf{X} = S_{\mathrm{x}}\mathbf{A}, \qquad \mathbf{U} = S_{\mathrm{i}}\mathbf{B} \qquad (2)$$

with $\mathbf{A}$ and $\mathbf{B}$ the Acoustic Transfer Function (ATF) of the speech component and directional interference, respectively. The ATFs of the speech component in the first microphone of the left and the right hearing aid are dentoted as A_0 and A_1. Furthermore, the ATFs of the directional interference in the first microphone of the left and the right hearing aid are denoted as B_0 and B_1. The correlation matrices of the individual components are defined as

$$\mathbf{R}_x = \mathcal{E}\left\{\mathbf{X}\mathbf{X}^H\right\} = P_s\mathbf{A}\mathbf{A}^H \qquad (3)$$

$$\mathbf{R}_u = \mathcal{E}\left\{\mathbf{U}\mathbf{U}^H\right\} = P_i\mathbf{B}\mathbf{B}^H \qquad (4)$$

$$\mathbf{R}_n = \mathcal{E}\left\{\mathbf{N}\mathbf{N}^H\right\}, \qquad (5)$$

with $P_s = \mathcal{E}\left\{|S_x|^2\right\}$ and $P_i = \mathcal{E}\left\{|S_i|^2\right\}$, the Power Spectral Densities (PSDs) of the speech source and the directional interference, respectively. Assuming statistical independence between the components, the correlation matrix of the microphone signal $\mathbf{R}_y$ can be written as

$$\mathbf{R}_y = \mathbf{R}_x + \underbrace{\mathbf{R}_u + \mathbf{R}_n}_{\mathbf{R}_v}, \qquad (6)$$

with $\mathbf{R}_v$, the correlation matrix of all undesired components. The Relative Transfer Function (RTF) of the speech component and the directional interference in the first microphone

of the left and the right hearing aid is defined as the ratio of the ATFs, i.e.,

$$\mathrm{RTF}_{\mathrm{x}}^{\mathrm{in}} = \frac{A_0}{A_1} \qquad \mathrm{RTF}_{\mathrm{u}}^{\mathrm{in}} = \frac{B_0}{B_1} \qquad (7)$$

The output signal at the left hearing aid Z_0 is equal to

$$Z_0 = \mathbf{W}_0^H\mathbf{Y} = \mathbf{W}_0^H\mathbf{X} + \mathbf{W}_0^H\mathbf{U} + \mathbf{W}_0^H\mathbf{V}. \qquad (8)$$

with $\mathbf{W}_0$ and $\mathbf{W}_1$, the filter in the left, respectively right hearing aid. The output signal at the right hearing aid Z_1 is defined similarly. The output RTF is defined as the ratio of the filtered speech component, respectively filtered directional interference at the left and the right hearing aid, i.e.,

$$\mathrm{RTF}_{\mathrm{x}}^{\mathrm{out}} = \frac{\mathbf{W}_0^H\mathbf{A}}{\mathbf{W}_1^H\mathbf{A}} \qquad \mathrm{RTF}_{\mathrm{u}}^{\mathrm{out}} = \frac{\mathbf{W}_0^H\mathbf{B}}{\mathbf{W}_1^H\mathbf{B}} \qquad (9)$$

The output Signal to Interference + Noise ratio (SINR) of the left and the right hearing aid is defined as

$$\mathrm{SINR}_0^{\mathrm{out}} = \frac{\mathbf{W}_0^H\mathbf{R}_x\mathbf{W}_0}{\mathbf{W}_0^H\mathbf{R}_v\mathbf{W}_0} \qquad \mathrm{SINR}_1^{\mathrm{out}} = \frac{\mathbf{W}_1^H\mathbf{R}_x\mathbf{W}_1}{\mathbf{W}_1^H\mathbf{R}_v\mathbf{W}_1} \quad (10)$$

and the binaural output SINR is defined as the ratio of the averaged output PSDs of the speech and the noise component in the left and the right HA, i.e.,

$$\mathrm{SINR}^{\mathrm{out}} = \frac{\mathbf{W}_0^H\mathbf{R}_x\mathbf{W}_0 + \mathbf{W}_1^H\mathbf{R}_x\mathbf{W}_1}{\mathbf{W}_0^H\mathbf{R}_v\mathbf{W}_0 + \mathbf{W}_1^H\mathbf{R}_v\mathbf{W}_1}. \qquad (11)$$

The output Signal to Noise Ratio (SNR) is defined similarly by replacing $\mathbf{R}_v$ with $\mathbf{R}_n$ in (10) and (11). The output Signal to Interference Ratio (SIR) is defined by replacing $\mathbf{R}_v$ with $\mathbf{R}_u$ in (10) and (11).

3. BINAURAL LCMV

In [9] the BLCMV beamformer has been proposed, which aims to minimize the overall output power of the left and the right hearing aid subject to the constraints of preserving the desired speech component and suppressing the directional interference by a prespecified amount determined by the interference rejection parameters. The complex-valued parameters η_0 and η_1 are the interference rejection parameters for the left and the right hearing aid which can in principle be freely chosen. For the scenario in Section 2, the optimization criteria for the left and the right hearing aid are given by

$$\min_{\mathbf{W}_0} \mathbf{W}_0^H\mathbf{R}_y\mathbf{W}_0 \quad \text{subject to} \quad \mathbf{C}^H\mathbf{W}_0 = \mathbf{b}_0, \qquad (12)$$

$$\min_{\mathbf{W}_1} \mathbf{W}_1^H\mathbf{R}_y\mathbf{W}_1 \quad \text{subject to} \quad \mathbf{C}^H\mathbf{W}_1 = \mathbf{b}_1, \qquad (13)$$

with

$$\mathbf{C} = \begin{bmatrix} \mathbf{A} & \mathbf{B} \end{bmatrix}, \quad \mathbf{b}_0 = \begin{bmatrix} A_0^* \\ \eta_0^* B_0^* \end{bmatrix}, \quad \mathbf{b}_1 = \begin{bmatrix} A_1^* \\ \eta_1^* B_1^* \end{bmatrix}. \quad (14)$$

Note that the optimization criterion in (12), (13) and (14) can also be written in terms of the RTFs of the speech component and the directional interference. However, for the sake of readability we will use the ATF formulation for the following discussion. The filters minimizing (12) and (13) can be computed as [9]

$$\mathbf{W}_0 = \mathbf{R}_y^{-1}\mathbf{C}\left[\mathbf{C}^H\mathbf{R}_y^{-1}\mathbf{C}\right]^{-1}\mathbf{b}_0 \qquad (15)$$

$$\mathbf{W}_1 = \mathbf{R}_y^{-1}\mathbf{C}\left[\mathbf{C}^H\mathbf{R}_y^{-1}\mathbf{C}\right]^{-1}\mathbf{b}_1 \qquad (16)$$

Due to the linear constraints on the speech component and the directional interference, the output RTFs can be easily computed and are equal to Hence, the RTF of the speech component is always preserved, independent of the choice of the interference rejection parameters η_0 and η_1. Moreover, the RTF of the the directiona

$$\mathrm{RTF}_{\mathrm{x}}^{\mathrm{out}} = \frac{A_0}{A_1}, \qquad \mathrm{RTF}_{\mathrm{u}}^{\mathrm{out}} = \frac{\eta_0 B_0}{\eta_1 B_1}. \qquad (17)$$

3.1. The BLCMV as an Trade-off Beamformer

As mentioned before, the noise reduction and binaural cue preservation performance of the BLCMV highly depend on the choice of the interference rejection parameters η_0 and η_1. Extending the analysis of the monaural LCMV in [10] to the BLCMV, we propose to write the filters in (15) and (16) as a weighted sum of two spatial sub-filters $\bar{\mathbf{W}}_0$ and $\bar{\mathbf{W}}_1$ using (14). The BLCMV filters for the left and the right hearing aid in (15) and (16) can now be written as

$$\mathbf{W}_0 = A_0^*\bar{\mathbf{W}}_0 + \eta_0^* B_0^*\bar{\mathbf{W}}_1 \qquad (18)$$

$$\mathbf{W}_1 = A_1^*\bar{\mathbf{W}}_0 + \eta_1^* B_1^*\bar{\mathbf{W}}_1, \qquad (19)$$

with

$$\left[\bar{\mathbf{W}}_0 \quad \bar{\mathbf{W}}_1\right] = \mathbf{R}_y^{-1}\mathbf{C}\left[\mathbf{C}^H\mathbf{R}_y^{-1}\mathbf{C}\right]^{-1}. \qquad (20)$$

By plugging (18) and (19) into (10), the output SINR at the left and the right hearing aid is equal to

$$\mathrm{SINR}_0^{\mathrm{out}} = \frac{P_s|A_0|^2}{|A_0|^2h_0 + |\eta_0|^2|B_0|^2h_1 + 2\Re\{\eta_0^*A_0B_0^*h_{01}\}} \qquad (21)$$

$$\mathrm{SINR}_1^{\mathrm{out}} = \frac{P_s|A_1|^2}{|A_1|^2h_0 + |\eta_1|^2|B_1|^2h_1 + 2\Re\{\eta_1^*A_1B_1^*h_{01}\}}, \qquad (22)$$

with

$$h_0 = \bar{\mathbf{W}}_0^H\mathbf{R}_v\bar{\mathbf{W}}_0, \; h_1 = \bar{\mathbf{W}}_1^H\mathbf{R}_v\bar{\mathbf{W}}_1, \; h_{01} = \bar{\mathbf{W}}_0^H\mathbf{R}_v\bar{\mathbf{W}}_1 \qquad (23)$$

and $\Re\{\cdot\}$, denoting the real part of a complex number. The trade-off parameters η_0^{max} and η_1^{max}, maximizing the output SINR of the left, respectively right hearing aid can be computed by setting the derivative of (21) with respect to η_0, respectively (22) with respect to η_1 to 0 and are equal to

$$\eta_0^{\mathrm{max}} = -\frac{A_0 h_{01}}{B_0 h_1}, \qquad \eta_1^{\mathrm{max}} = -\frac{A_1 h_{01}}{B_1 h_1}, \qquad (24)$$

similar to the expressions given in [10]. However, since in general $\eta_0^{\mathrm{max}} \neq \eta_1^{\mathrm{max}}$, the RTF of the directional interference is not preserved. By plugging (24) in (17), the output RTF of the directional interference is equal to,

$$\mathrm{RTF}_{\mathrm{u}}^{\mathrm{out}} = \frac{\mathbf{W}_0^H\mathbf{B}}{\mathbf{W}_1^H\mathbf{B}} = \frac{\eta_0^{\mathrm{max}}B_0}{\eta_1^{\mathrm{max}}B_1} = \frac{A_0}{A_1}. \qquad (25)$$

Hence, the directional interference is perceived as coming from the direction of the speech source, which is obviously undesired. To determine the interference rejection parameters that maximize the output SINR and preserve the RTF of the directional interference, we propose to maximize the binaural output SINR in (11) subject to the constraint that $\eta = \eta_0 = \eta_1$. By plugging (18) and (19) into (11), the binaural output SINR is equal to

$$\mathrm{SINR}^{\mathrm{out}} = \frac{P_s|A_0|^2 + P_s|A_1|^2}{g} \qquad (26)$$

with

$$g = (|A_0|^2 + |A_1|^2)h_0 + |\eta|^2(|B_0|^2 + |B_1|^2)h_1 + \qquad (27)$$
$$2\Re\{\eta^*(A_0B_0^* + A_1B_1^*)h_{01}\}$$

and $\eta = \eta_0 = \eta_1$. Setting the derivative of (26) with respect to η to 0, the trade-off parameter η^{max}, maximizing the binaural output SINR, is equal to

$$\eta^{\mathrm{max}} = -\frac{(A_0B_0^* + A_1B_1^*)h_{01}}{(|B_0|^2 + |B_1|^2)h_1}. \qquad (28)$$

Please note that the derived expressions for the optimal interference rejection parameters can also be written in terms of the RTF of the speech component and the directional interference.

3.2. Optimal Parameter Combinations

Based on the previous derivations, we can now define 3 combination for the interference rejection parameters η_0 and η_1, maximizing the output SINR in the left hearing aid, the output SINR in the right hearing aid or maximizing the binaural output SINR without distorting the RTF of the directional interference. Especially for binaural hearing aid users with a strong better ear effect, the maximization of the better ear output SINR could be beneficial.

1. To maximize the output SINR at the left hearing aid, the optimal parameter combination denoted as BLCMV[η_0^{max}] is equal to

$$\eta_0 = \eta_1 = \eta_0^{\mathrm{max}}. \qquad (29)$$

2. To maximize the output SINR at the right hearing aid, the optimal parameter combination denoted as BLCMV[η_1^{max}] is equal to

$$\eta_0 = \eta_1 = \eta_1^{\mathrm{max}}. \qquad (30)$$

3. To maximize the binaural output SINR, the optimal parameter combination denoted as BLCMV[$\eta^{\max}$] is equal to

$$\eta_0 = \eta_1 = \eta^{\max}. \tag{31}$$

4. EXPERIMENTAL RESULTS

In this section we present simulation results for a cafeteria scenario to compare the performance of the BLCMV[$\eta_0^{\max}$], BLCMV[$\eta_1^{\max}$] and BLCMV[$\eta^{\max}$].

4.1. Setup

Binaural Behind-The-Ear Impulse Responses (BTE-IR) measured in a cafeteria from [11] have been used to generate the microphone signals of the desired speech component and the directional interference. The left and the right HA are equipped with 2 microphones. From the left hearing aid, both microphones have been used and from the right hearing aid, the frontal microphone has been used, therefore in total 3 microphone signals for each filter are available. The desired speaker was located in front of the listener at a distance of $1\,$m and the undesired interference was located at $-45°$ at a distance of $1.2\,$m. The additional background noise was recorded ambient noise from the cafeteria taken from the same database. The global input SIR at the first microphone in the left HA was equal to $-5\,$dB and the global input SNR at the first microphone in the left HA was equal to $0\,$dB. The signals were processed at $f_s = 16\,$kHz using an weighted overlap-add (WOLA) framework with a block size of $N = 512$ samples and an overlap of 75% between successive blocks. The signal had a length of $35\,$s. Since we aim to evaluate the performance of the BLCMV with different parameter settings, we disregard the influence of estimation errors and compute the signal statistics directly from the underlying input components. Elaborated methods for estimating the RTFs in multiple speaker scenarios can be found in [8]. The correlation matrices are calculated according to (3) - (6) and the RTF vector of the speech component and the directional interference is then calculated from $\mathbf{R}_x$ and $\mathbf{R}_u$ as in [6]. The average of the logarithmic values of the output SINR, SNR and SIR over all frequency bands denoted as output gSINR, gSNR and gSIR are used as performance measure. The RTF preservation capabilities of the BLCMV have been evaluated in [9] and are omitted due to space constraints.

4.2. Performance

The output gSINR values for different parameter settings are depicted in Table 1. As expected, the BLCMV[$\eta_0^{\max}$] maximizes the left output gSINR, the BLCMV[$\eta_1^{\max}$] maximizes the right output gSINR and the BLCMV[$\eta^{\max}$] maximizes the binaural output gSINR. The performance difference between BLCMV[$\eta_0^{\max}$] and BLCMV[$\eta^{\max}$] is rather small, whereas the BLCMV[$\eta_1^{\max}$] shows a significant worse performance for the left and the right binaural output gSINR. Furthermore, the output gSNR values are depicted in Table 2. The relation of the performance differences for the discussed parameter combinations are very similar as for the output

gSINR. Again, the BLCMV[$\eta_0^{\max}$] and the BLCMV[$\eta^{\max}$] show a very similar performance and the performance of the BLCMV[$\eta_1^{\max}$] is significantly worse for the left and the binaural output gSNR. Again, as for the gSINR, the BLCMV[$\eta_1^{\max}$] maximizes the right output gSNR.

The output gSIR is depicted in Table 3. For the left, the right and the binaural output gSIR, the BLCMV[$\eta^{\max}$] shows the best performance and again the BLCMV[$\eta_0^{\max}$] values are very similar. Similarly as before, the BLCMV[$\eta_1^{\max}$] shows a significantly decreased performance since η_1^{max} is calculated only based on the right output gSINR. Due to the smaller input gSIR in the left HA, more interference rejection is applied if the interference rejection parameters $\eta_0^{\max}$ or $\eta^{\max}$ are used.

	$\text{gSINR}_0^{\text{out}}$	$\text{gSINR}_1^{\text{out}}$	$\text{gSINR}^{\text{out}}$
BLCMV[$\eta_0^{\max}$]	**1.1**	-0.1	0.5
BLCMV[$\eta_1^{\max}$]	-3.3	**1.2**	-1.7
BLCMV[$\eta^{\max}$]	0.9	0.3	**0.6**

Table 1. Output gSINR of the BLCMV beamformer in dB. The input gSINR at the left HA is equal to $-7.3\,$dB, the input gSINR at the right HA is equal to $-2.3\,$dB and the binaural input gSINR is equal to $-5.5\,$dB.

	$\text{gSNR}_0^{\text{out}}$	$\text{gSNR}_1^{\text{out}}$	gSNR^{out}
BLCMV[$\eta_0^{\max}$]	**2.4**	0.4	1.3
BLCMV[$\eta_1^{\max}$]	0.3	**2.5**	0.8
BLCMV[$\eta^{\max}$]	2.2	0.8	**1.5**

Table 2. Output gSNR of the BLCMV beamformer in dB. The input gSNR at the left HA is equal to $0\,$dB, the input gSNR at the right HA is equal to $-0.3\,$dB and the binaural input gSNR is equal to $-0.1\,$dB.

	$\text{gSIR}_0^{\text{out}}$	$\text{gSIR}_1^{\text{out}}$	gSIR^{out}
BLCMV[$\eta_0^{\max}$]	7.6	11.5	9.0
BLCMV[$\eta_1^{\max}$]	1.2	7.8	3.2
BLCMV[$\eta^{\max}$]	**7.9**	**11.7**	**9.2**

Table 3. Output gSIR of the BLCMV beamformer in dB. The input gSIR at the left HA is equal to $-5\,$dB, the input gSIR at the right HA is equal to $4.2\,$dB and the binaural input gSIR is equal to $-2.5\,$dB.

5. CONCLUSION

In this paper we derived several optimal choices for the interference rejection parameter in the BLCMV beamformer subject to the constraint that the RTF of the speech component and the directional interference is preserved. The performance of the different parameter choices has been investigated using objective measures and the results have been compared. To achieve a better understanding of the performance results, a comprehensive theoretical analysis of the objective performance dependent on the interference rejection parameters is of significant importance and remains a topic for future research.

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