



HAL
open science

Binaural Integrated Active Noise Control and Noise Reduction in Hearing Aids

Romain Serizel, Marc Moonen, Jan Wouters, Søren Holdt Jensen

► **To cite this version:**

Romain Serizel, Marc Moonen, Jan Wouters, Søren Holdt Jensen. Binaural Integrated Active Noise Control and Noise Reduction in Hearing Aids . IEEE Transactions on Audio, Speech and Language Processing, 2013, 21 (5), pp.1113-1118. hal-01393937

HAL Id: hal-01393937

<https://hal.science/hal-01393937>

Submitted on 9 Nov 2016

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Binaural Integrated Active Noise Control and Noise
Reduction in Hearing Aids¹

Romain Serizel², Marc Moonen²,
Jan Wouters³ and Søren Holdt Jensen⁴

November 2012

Accepted for publication in the IEEE Transactions on Audio, Speech
and Language Processing

¹This report is available by anonymous ftp from *ftp.esat.kuleuven.be* in the directory *pub/sista/rserizel/reports/12-113.pdf*

²K.U.Leuven, Dept. of Electrical Engineering (ESAT), Research group SCD (SISTA) Kasteelpark Arenberg 10, 3001 Leuven, Belgium, Tel. +32 16 32 9607, Fax +32 16 321970, E-mail: *romain.serizel@esat.kuleuven.be*. This research work was carried out at the ESAT Laboratory of Katholieke Universiteit Leuven, in the frame of K.U.Leuven Research Council CoE EF/05/006 Optimization in Engineering (OPTeC), PFV/10/002 (OPTeC), Concerted Research Action GOA-MaNet, the Belgian Programme on Interuniversity Attraction Poles initiated by the Belgian Federal Science Policy Office IUAP P6/04 (DYSCO, 'Dynamical systems, control and optimization', 2007-2011), Research Project FWO nr. G.0600.08 ('Signal processing and network design for wireless acoustic sensor networks'), EC-FP6 project SIGNAL: 'Core Signal Processing Training Program'. The scientific responsibility is assumed by its authors.

³Katholieke Universiteit Leuven, Department of Neurosciences, ExpORL, O. & N2, Herestraat 49/721, 3000 Leuven, Belgium, E-mail: *Jan.Wouters@med.kuleuven.be*

⁴Aalborg University, Department of Electronic Systems, MISP, Niels Jernes Vej 12 A6-3, 9220 Aalborg, Denmark, E-mail: *shj@es.aau.dk*

Abstract

This paper presents a binaural approach to integrated active noise control and noise reduction in hearing aids and aims at demonstrating that a binaural setup indeed provides significant advantages in terms of the number of noise sources that can be compensated for and in terms of the causality margins.

Binaural Integrated Active Noise Control and Noise Reduction in Hearing Aids

Romain Serizel, Marc Moonen, Jan Wouters and Søren Holdt Jensen

Abstract—This paper presents a binaural approach to integrated active noise control and noise reduction in hearing aids and aims at demonstrating that a binaural setup indeed provides significant advantages in terms of the number of noise sources that can be compensated for and in terms of the causality margins.

Index Terms—Hearing aids, noise reduction, multichannel Wiener filter, active noise control, binaural processing

I. INTRODUCTION

Binaural hearing offers advantages over monaural hearing such as a better speech intelligibility, enhanced localisation, improved quality of listening [1], [2], [3]. If binaural information is really helpful for normal hearing persons, it may become tremendously important for persons with a hearing impairment.

State-of-the-art hearing aids perform noise reduction (NR) in order to improve their output signal-to-noise ratio (SNR) and hence to allow for a better speech understanding in background noise and to ease listening effort [4]. Conventional NR systems such as the generalised sidelobe canceller (GSC) [5] or techniques based on the multichannel Wiener filter (MWF) [6], [7] can be used.

When these processing schemes are applied in a monaural setup or a bilateral setup (*i.e.*, a setup with two hearing aids working independently), the SNR improvement can come with a degradation of binaural localisation cues, which can put the hearing aid user at a disadvantage. In a binaural setup, two hearing aids are worn, which can communicate each other, *e.g.*, via a wireless link. The NR schemes applied in hearing aids can be adapted to take advantage of this setup to deliver improved SNR [8] and to preserve binaural localisation cues [9].

Hearing aids with an open fitting (*i.e.*, where the earmold is replaced by a simple tube) can improve the physical comfort [10] and have become more common over the past years. Moreover, conventional NR techniques using monaural, bilateral or binaural processing do not take leakage effects into account, which can be significant whenever an open fitting is used. Combined with the attenuation in the secondary path, *i.e.*, the acoustic path from the hearing aid loudspeaker to the eardrum, the noise leaking through the open fitting directly to the eardrum can then override the action of the NR. One efficient way to tackle this problem is to use an active noise control (ANC) [10], [11] combined with the NR. In [12], an MWF-based monaural integrated ANC and NR has been introduced.

To be effective, the integrated ANC and NR scheme needs to be designed as a causal system. In a monaural setup, the causality margins depend on the distance between the hearing aid microphones

and the ear canal. These margins are therefore rather small and the causality may quickly become a limitation [12]. It has also been shown in [13] that in a single speech source scenario, the integrated ANC and NR scheme can compensate for noise sources only as long as the number of sources (speech source and noise sources) is less than or equal to the number of microphones. In a monaural setup the number of sources that can be compensated for is therefore limited by the number of microphones on one hearing aid (which is maximally three in the case of commercial hearing aids).

In this paper, the monaural integrated ANC and NR scheme presented in [12] is extended to a binaural setup. It is then investigated how a binaural integrated ANC and NR scheme can benefit from the causality margin increase owing to the (outpost) location of the contra-lateral microphones. The binaural integrated ANC and NR is also applied to a multiple noise sources scenario in order to confirm the analysis conducted in [13] on the number of sources that can be compensated for and to confirm the benefits from the increased number of available microphones.

The signal model, the binaural MWF-based NR and ANC, the secondary path and the signal leakage problem as well as the causality issues in ANC schemes are described in Section II. The binaural MWF-based integrated ANC and NR scheme is presented in Section III. Experimental results are presented in Section IV and finally conclusions are presented in Section V.

II. BACKGROUND AND PROBLEM STATEMENT

This section introduces the signal model and notation, the binaural MWF-based NR and ANC, the secondary path and signal leakage problems as well as the causality issues in ANC schemes.

A. Signal model

In an ideal binaural setup, microphone signals from both hearing aids are used to compute the hearing aid loudspeaker signals. Let M be the number of microphones (channels) on each hearing aid and N the NR and/or ANC filter length. The time-domain signal $x_{L,m}[k]$ for microphone m in the left hearing aid has a desired speech part $x_{L,m}^s[k]$ and an additive noise part $x_{L,m}^n[k]$:

$$x_{L,m}[k] = x_{L,m}^s[k] + x_{L,m}^n[k] \quad m \in \{1 \dots M\} \quad (1)$$

where k is the time index.

In practice, in order to distinguish “speech plus noise periods” from “noise only periods” it is necessary to use a voice activity detector (VAD). The performance of the VAD can affect the performance of the filters. In this paper however, in order to exclude VAD error effects from the analysis, a perfect VAD is assumed.

The column vector $\mathbf{x}_{L,m}[k]$ contains the N most recent samples of the microphone signal m in the left hearing aid:

$$\mathbf{x}_{L,m}[k] = [x_{L,m}[k] \dots x_{L,m}[k - N + 1]]^T \quad m \in \{1 \dots M\} \quad (2)$$

The time-domain signal $x_{R,m}[k]$ and vector $\mathbf{x}_{R,m}[k]$ for microphone m in the right hearing aid can be specified similarly.

The MN -dimensional compound vectors $\mathbf{x}_L[k]$ and $\mathbf{x}_R[k]$ gathering all microphone signals from the left and the right hearing aid

respectively and the $2MN$ -dimensional compound signal vector $\mathbf{x}[k]$ are defined as follows:

$$\mathbf{x}_L[k] = [\mathbf{x}_{L,1}[k]^T \dots \mathbf{x}_{L,M}[k]^T]^T \quad (3)$$

$$\mathbf{x}_R[k] = [\mathbf{x}_{R,1}[k]^T \dots \mathbf{x}_{R,M}[k]^T]^T \quad (4)$$

$$\mathbf{x}[k] = [\mathbf{x}_L[k]^T \mathbf{x}_R[k]^T]^T \quad (5)$$

B. Binaural MWF-based NR, secondary path and signal leakage

In the subsequent sections, only the filter designed for the left hearing aid ($\mathbf{w}_L[k]$) will be considered. All the derivations, however, also hold for the filter in the right hearing aid ($\mathbf{w}_R[k]$). For conciseness, the filter $\mathbf{w}_L[k]$ will be denoted as $\mathbf{w}[k]$ in the remainder of the paper.

The binaural MWF-based NR filter $\mathbf{w}_{NR}[k]$ is designed to minimise the following mean squared error (MSE) criterion:

$$\begin{aligned} J_{NR}(\mathbf{w}[k]) &= \mathbb{E}\{|\mathbf{w}[k]^T \mathbf{x}[k] - G \cdot x_{L,1}^s[k - \Delta]|^2\} \\ &= \mathbb{E}\{|\mathbf{w}[k]^T \mathbf{x}[k] - d_{NR,L}[k]|^2\} \end{aligned} \quad (6)$$

where $\mathbb{E}\{\cdot\}$ is the expectation operator, G the desired gain and $d_{NR,L}[k]$ is the desired signal for the NR. The delay Δ is a design parameter. The speech part in the first microphone is used here as the desired signal for the Wiener filter.

The MWF minimising (6) is then:

$$\boxed{\mathbf{w}_{NR}[k] = \mathbf{R}_x[k]^{-1} \mathbf{r}_{x d_{NR}}[k]} \quad (7)$$

where $\mathbf{R}_x[k]$ is the correlation matrix of the microphone signals $\mathbf{x}[k]$ and $\mathbf{r}_{x d_{NR}}[k]$ is the cross-correlation vector between the input $\mathbf{x}[k]$ and the desired signal $d_{NR,L}[k]$. The correlation matrix $\mathbf{R}_x[k]$ is assumed to have full rank. The estimation of $\mathbf{r}_{x d_{NR}}[k]$ relies on a voice activity detection [7]

The NR output signal is then:

$$z[k] = \mathbf{w}_{NR}[k]^T \mathbf{x}[k] \quad (8)$$

The conventional NR filters are designed without taking the effect of the signal leakage and the secondary path effect into account. The secondary path represents the propagation from the loudspeaker to the eardrum and usually acts as an attenuation [12]. Assuming that the loudspeaker characteristic is approximately linear, the secondary path can be represented by a filter coefficient vector $\mathbf{c}[k]$ of length P . A hearing aid with an open fitting has no earmold to prevent ambient sound from leaking into the ear canal, which results in additional leakage signal $l[k]$ reaching the eardrum.

Taking both the signal leakage and the secondary path effect into account, leads to the following model for the eardrum signal:

$$\tilde{z}[k] = \mathbf{c}[k]^T [z[k] \dots z[k - P + 1]]^T + l[k] \quad (9)$$

It clearly appears that for small gains G the leakage SNR may affect the output SNR thus partly cancelling the improvement achieved with the NR. A feedforward ANC strategy can then be applied to compensate for the degradation introduced by the noise leakage.

C. Binaural MWF-based ANC and causality

The goal of the binaural ANC is to extend the monaural ANC based on existing work on binaural MWF-based NR [9], [14]. The binaural signal model from [9], [14] is applied to the ANC case to define a binaural ANC error criterion. In this paper, it is assumed that a microphone is present in the ear canal to provide the signal $\tilde{z}[k]$. Commercial hearing aids currently do not have an ear canal microphone, but it is technically possible to include a microphone at the end of the tube that is used to conduct the sound from the BTE to the ear canal, which is then sufficiently close to the eardrum.

The binaural ANC scheme relies on a Filtered-x structure. The filtered reference signal is defined as:

$$\mathbf{y}[k] = [\mathbf{y}_L[k]^T \mathbf{y}_R[k]^T]^T \quad (10)$$

where $\mathbf{y}_L[k]$ is the filtered reference signal derived from the microphone signals in the left hearing aid:

$$\begin{aligned} y_{L,m}[k] &= \hat{\mathbf{c}}[k]^T [x_{L,m}[k] \dots x_{L,m}[k - \hat{P} + 1]]^T \quad m \in \{1 \dots M\} \\ \mathbf{y}_{L,m}[k] &= [y_{L,m}[k] \dots y_{L,m}[k - N + 1]]^T \end{aligned} \quad (11)$$

$$\mathbf{y}_L[k] = [\mathbf{y}_{L,1}[k]^T \dots \mathbf{y}_{L,M}[k]^T]^T \quad (12)$$

with $\hat{\mathbf{c}}[k]$ a model of $\mathbf{c}[k]$ and where $\mathbf{y}_R[k]$, the filtered reference signal derived from the microphone signals in the right hearing aid, is similarly defined.

The binaural MWF-based ANC filter $\mathbf{w}_{ANC}[k]$ is designed to minimise the MSE:

$$J_{ANC}(\mathbf{w}[k]) = \mathbb{E}\{|\mathbf{c}[k]^T [z[k] \dots z[k - P + 1]]^T + l[k]|^2\} \quad (13)$$

where $z[k]$ is the output signal of the filter $\mathbf{w}[k]$. Assuming that the secondary path identification error is small ($\hat{\mathbf{c}}[k] \approx \mathbf{c}[k]$) and $y[k] \approx \mathbf{c}[k]^T [x_{L,m}[k] \dots x_{L,m}[k - P + 1]]^T$ and that the filter $\mathbf{w}[k]$ is adapting slowly (so that $\mathbf{w}[k]$ and $\mathbf{c}[k]$ can be interchanged), the MSE criterion (13) can be written as follows:

$$J_{ANC}(\mathbf{w}[k]) \approx \mathbb{E}\{|\mathbf{w}[k]^T \mathbf{y}[k] + l[k]|^2\} \quad (14)$$

The Filtered-x MWF (FxMWF) minimising (14) is then:

$$\boxed{\mathbf{w}_{ANC}[k] = -\mathbf{R}_y[k]^{-1} \mathbf{r}_{yl}[k]} \quad (15)$$

where $\mathbf{R}_y[k]$ is the correlation matrix of the filtered microphone signals $\mathbf{y}[k]$ and $\mathbf{r}_{yl}[k]$ is the cross-correlation vector between the filtered microphone signals $\mathbf{y}[k]$ and the leakage signal $l[k]$. The correlation matrix $\mathbf{R}_y[k]$ is assumed to have full rank. In practice, the leakage signal $l[k]$ can be estimated from the ear canal microphone signal $\tilde{z}[k]$ and the loudspeaker signal $z[k]$:

$$l[k] \approx \tilde{z}[k] - \hat{\mathbf{c}}[k]^T [z[k] \dots z[k - P + 1]]^T \quad (16)$$

The performance of a feedforward ANC scheme is highly dependent on the causality of the system [10]. The distance between the hearing aid microphones and the hearing aid loudspeaker must be sufficient to allow a causal design. In particular, the acoustic delay (*i.e.*, direct propagation) from the noise source to the ear canal microphone Δ_{pri} has to be larger than the sum of the acoustic delay from the noise source to one of the hearing aid microphones Δ_{ref} , the delay associated with the processing within the hearing aid δ (*i.e.*, Analogue-to-Digital (A/D) converter delays, Digital-to-Analogue (D/A) converter delays, wireless link delays...), and the acoustic delay of the secondary path Δ_{sec} (Figure 1).

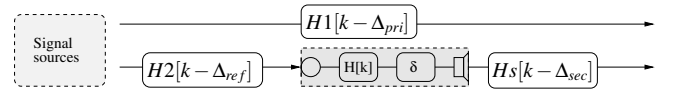


Fig. 1. Delays in hearing aid system

Here, δ is used as a parameter to determine how much delay the system can add in the signal path before the ANC performance starts to decrease. The limit value for δ will be referred to as the causality margin $\delta_0 = \Delta_{pri} - \Delta_{ref} - \Delta_{sec}$. When the causality margin δ_0 is positive, it is possible to have delays in the signal path, and so the system is said to be causal:

$$\Delta_{pri} \geq \Delta_{ref} + \Delta_{sec} \quad (17)$$

When the causality margin δ_0 is negative, the ANC has to act as a linear predictor. The system is then said to be non-causal:

$$\Delta_{\text{pri}} < \Delta_{\text{ref}} + \Delta_{\text{sec}} \quad (18)$$

In practice, this criterion does not define a hard limit but it gives an indication on the performance to be expected from an ANC scheme [15].

III. BINAURAL MWF-BASED INTEGRATED ANC AND NR

The goal of the binaural MWF-based integrated ANC and NR is to extend the MWF-based integrated ANC and NR scheme presented in [12]. The binaural integrated ANC and NR can then benefit from the extra contra-lateral hearing aid microphones in order to compensate for the effect of more noise sources. The ANC part of the integrated ANC and NR scheme can also benefit from the causality margin improvement owing to the contra-lateral hearing aid microphones location.

As speech component of the leakage can actually be helpful, *e.g.*, for localisation, it is chosen here to cancel only the noise component of the leakage. The overall desired signal (at the eardrum) to be used is then:

$$d_{\text{int},L}[k] = d_{\text{NR},L}[k] + l^s[k] \quad (19)$$

where $d_{\text{NR},L}[k]$ is defined in 6.

Hence the MSE criterion to be minimised is:

$$J_{\text{int}}(\mathbf{w}[k]) = \mathbb{E}\{|\mathbf{c}[k]^T [z[k] \dots z[k-P+1]]^T + \underbrace{l[k] - l^s[k]}_{l^n[k]} - d_{\text{NR},L}[k]|^2\} \quad (20)$$

where $z[k]$ is the output signal of the binaural filter $\mathbf{w}[k]$. The MSE criterion (20) is then the same as the MSE criterion introduced in [12] for the monaural integrated ANC and NR except that the filter $\mathbf{w}[k]$ is now applied to a binaural input.

Assuming that the secondary path identification error is small ($\hat{\mathbf{c}}[k] \approx \mathbf{c}[k]$) and that the filter $\mathbf{w}[k]$ is adapting slowly, the MSE criterion (20) can be written as follows:

$$J_{\text{int}}[k] \approx \mathbb{E}\{|\mathbf{w}[k]^T \mathbf{y}[k] + l^n[k] - d_{\text{NR},L}[k]|^2\} \quad (21)$$

Assuming that speech and noise are uncorrelated, the FxMWF minimising (20) is then:

$$\boxed{\mathbf{w}_{\text{int}}[k] = \mathbf{R}_y^{-1}[k](\mathbf{r}_{y^s d_{\text{NR},L}}[k] - \mathbf{r}_{y^n l^n}[k])} \quad (22)$$

Here $\mathbf{R}_y[k]$ is the correlation matrix of the filtered microphone signals $\mathbf{y}[k]$ and $\mathbf{r}_{y^s d_{\text{NR},L}}[k]$ is the cross-correlation vector between the speech component of the filtered microphone signals $\mathbf{y}^s[k]$ and the desired signal $d_{\text{NR},L}[k]$ which can again be estimated based on a voice activity detection. The correlation matrix $\mathbf{R}_y[k]$ is assumed to have full rank. Finally $\mathbf{r}_{y^n l^n}[k]$ is the cross-correlation vector between the noise component of the filtered microphone signals $\mathbf{y}^n[k]$ and the noise component of the leakage signal $l^n[k]$. The noise component of the leakage can be estimated similarly as in (16) during noise only periods. A description of how these statistics are computed in practice can be found in [12] (Section III-D).

IV. EXPERIMENTAL RESULTS

A. Experimental setup

The simulations were done with acoustic paths measured on a CORTEX MK2 manikin head and torso equipped with artificial ears and two-microphones behind-the-ear (BTE) hearing aids. The sound sources (FOSTEX 6301B loudspeakers) were positioned at 1 meter from the centre of the head. The speech source was located at 0°

and the noise sources at 90° , 270° and 330° (see Figure 2). The hearing aid considered here is the left hearing aid, facing the noise source at 270° . Commercial hearing aids currently do not have an ear canal microphone, therefore the artificial ear eardrum microphone is used here to generate the ear canal microphone signal. The tests were run on 22 seconds long signals. The speech was composed of three sentences from the HINT database [16] concatenated with silence periods. The noise was the multitalker babble from Auditec [17]. All signals were sampled at 16kHz.

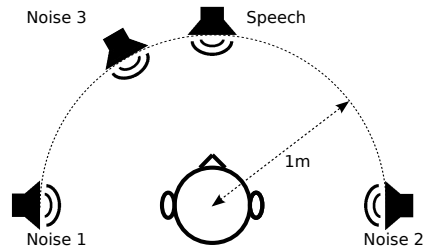


Fig. 2. Experimental setup

The filter length is set to $N = 128$, and the NR delay is set to half the NR filter length ($\Delta = 64$). If the speech component and the noise component of the microphone signals are assumed to be uncorrelated, it has been shown in [12] that the integrated ANC and NR can be decomposed into the sum of two sets of filters, one for NR and the other for the ANC. The NR delay (Δ) then does not affect the causality margin of the ANC part of the integrated ANC and NR scheme. The secondary path $\mathbf{c}[k]$ is estimated off-line using an identification technique based on the Normalised Least Mean Squares (NLMS) algorithm. The length of the estimated path $\hat{\mathbf{c}}[k]$ is set to $L = 32$.

The performance measure used for the ANC schemes is the residual noise power improvement at the eardrum:

$$\Delta \text{Pow}^n[k] = \text{Pow}_{\text{out}}^n[k] - \text{Pow}_{\text{leak}}^n[k] \quad (23)$$

where $\text{Pow}_{\text{out}}^n[k]$ and $\text{Pow}_{\text{leak}}^n[k]$ are the power (in dB) of the residual noise and the power of the noise component of the leakage signal at the eardrum.

The performance measure used for integrated ANC and NR schemes is the intelligibility-weighted SNR [18] improvement where the leakage signal SNR is taken as a reference:

$$\Delta \text{SNR}_{\text{intell}} = \sum_i I_i (\text{SNR}_{i,\text{Int}} - \text{SNR}_{i,\text{leak}}) \quad (24)$$

where I_i is the band importance function defined in [19] and $\text{SNR}_{i,\text{Int}}$ and $\text{SNR}_{i,\text{leak}}$ represent the output SNR of the integrated ANC and NR scheme and the leakage SNR (in dB) of the i th band, respectively.

B. Binaural ANC

Three different 2-channel ANC schemes are compared. Two monaural schemes are considered (one using the microphone signals from the left hearing aid, the other one using the microphone signals from the right hearing aid) and compared to a binaural scheme using one microphone signal from each hearing aid. The binaural scheme can also run with four microphone signals, but only two microphone signals are used here in order to have a fair comparison with the monaural schemes.

1) *Single noise source*: The first experiment is set up with only one noise source. The noise source can be located at 0° , 90° or at 270° . In each case the three different schemes are run for different delay δ and the residual noise power performance is evaluated. In practice, the microphone signals are artificially delayed by a delay δ .

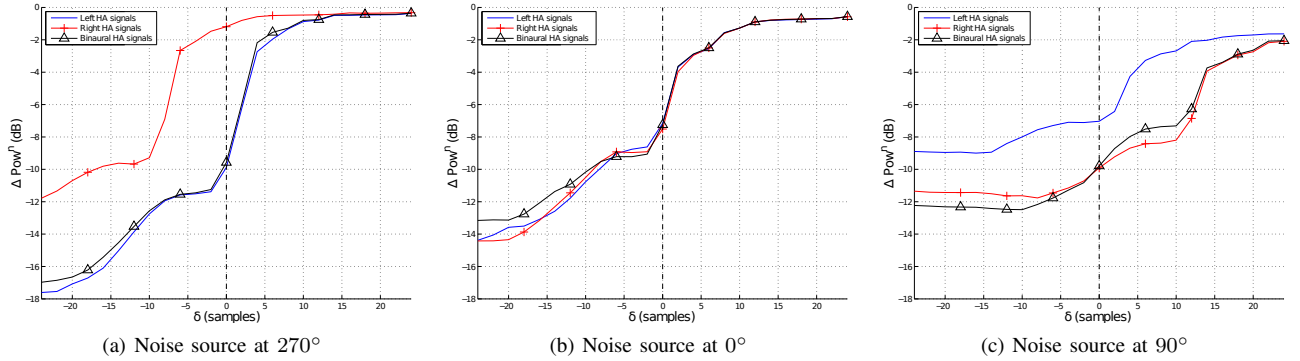


Fig. 3. Noise reduction for multichannel (monaural, binaural) ANC with a single noise source

Figure 3(a) presents the residual noise power improvement at the left eardrum for the three schemes when the source is facing the left hearing aid (270°). The noise signal then reaches the microphones of the left hearing aid before reaching the left eardrum. It is therefore possible to design a causal system based on the microphone signals from the left hearing aid, even if the causality margin is rather small ($\delta_0 \approx 2$). On the other hand, the noise signal reaches the microphones of the right hearing aid after reaching the left eardrum. The ANC scheme using the right hearing aid microphone signals is then non-causal ($\delta_0 \approx -8$). The binaural ANC scheme is based on a microphone signal from each hearing aid and matches the residual noise power performance of the monaural scheme using the microphone signals from the left hearing aid.

The residual noise power improvement at the left eardrum when the noise source is facing the listener (0°) is shown on Figure 3(b). The noise signal reaches the microphones of the left hearing aid at the same time as it reaches the microphones of the right hearing aid. The causality margins are then the same if the system is based on the microphone signals from the left hearing aid or from the right hearing aid ($\delta_0 \approx 1$). The binaural ANC scheme performance is, in this scenario, similar to the performance of the monaural schemes.

Figure 3(c) presents the residual noise power improvement at the left eardrum for the three schemes when the noise source is facing the right hearing aid (90°). The noise signal then reaches the left eardrum shortly after it reaches the microphones of the left hearing aid. The monaural ANC scheme using the microphone signals from the left hearing aid then has to be designed with low causality margin ($\delta_0 \approx 3$). In this scenario however, the noise signal reaches the microphones of the right hearing aid before reaching the left eardrum. Therefore, the ANC scheme using the microphone signals from the right hearing aid can be designed with a larger causality margin ($\delta_0 \approx 13$). Once again the binaural ANC scheme matches the residual noise power performance of the best of the two monaural schemes.

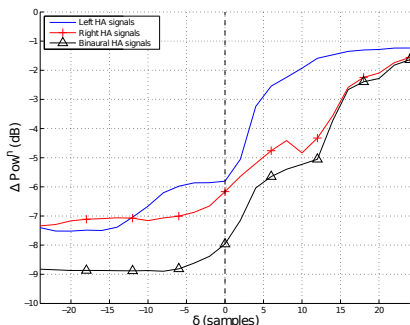


Fig. 4. Noise reduction for multichannel (monaural, binaural) active noise control with two noise sources (270° and 90°)

2) *Multiple noise sources*: The second experiment is set up with two noise sources, one on each side of the head, *i.e.*, one noise source at 270° and the other noise source at 90° . The residual noise power improvement at the left eardrum is presented in Figure 4. Each of the monaural ANC schemes is well suited to attenuate the noise signal from one of the sources but the attenuation of the other noise source can be problematic (see also above). The binaural ANC scheme on the other hand delivers a better performance than any of the monaural schemes in this particular case.

C. Binaural integrated ANC and NR

In this part, the performance of the integrated ANC and NR scheme is evaluated. The first experiment aims at showing the effect of causality on different integrated ANC and NR schemes while the second experiment focuses on the impact of the number of sources on the integrated ANC and NR schemes.

1) *Single noise source*: In the first experiment there is only one noise source which can be located at 90° or at 270° . The gain G is set to 10dB. For each scenario different schemes are run for different delay δ and their speech-intelligibility weighted SNR improvement is evaluated.

Three different 2-channel integrated ANC and NR schemes are compared here. As in the previous part, two monaural schemes are considered (one using the microphone signals from the left hearing aid, the other one using the microphone signals from the right hearing aid) and compared to a binaural scheme using one microphone signal from each hearing aid.

Figure 5(a) presents the SNR improvement at the left eardrum for the three schemes when the source is facing the left hearing aid (270°). In this scenario, a system based on the microphone signals from the left hearing aid would be causal and achieve an SNR improvement up to $\delta \approx 1$. A system based on the microphone signals from the right hearing aid on the other hand would be non-causal ($\delta_0 \approx -8$). The binaural scheme achieves a performance similar to the scheme based on the microphone signals from the left hearing aid and can achieve an SNR improvement up to $\delta \approx 1$.

The SNR power improvement at the left eardrum when the noise source is facing the right ear (90°) is shown in Figure 5(b). In this scenario the integrated ANC and NR scheme based on the microphone signals from the left hearing aid has a negative causality margin ($\delta_0 \approx -1$) whereas the schemes based on the microphone signals from the right hearing aid delivers SNR improvement up to $\delta \approx 8$. Once again, the binaural scheme matches the SNR improvement performance of the best of the two monaural schemes.

2) *Multiple noise sources*: The aim of the second experiment is to evaluate the effect of the number of sound sources (speech source plus noise sources) on the performance of the integrated ANC and

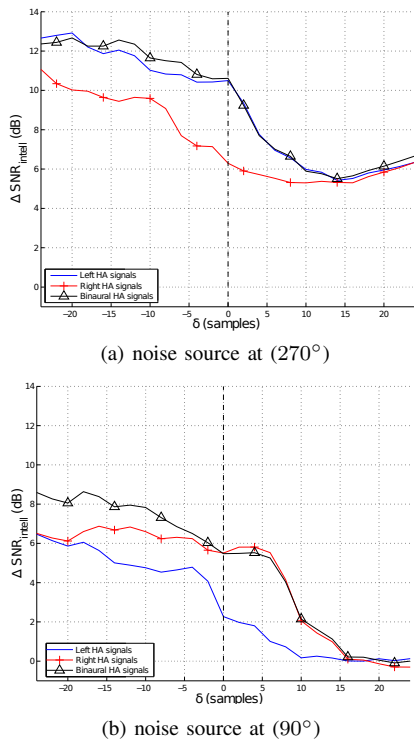


Fig. 5. Integrated active noise control and noise reduction for multichannel (monaural, binaural) active noise control with a single noise source

NR scheme. The causality margin of the system is (artificially) set to a positive value ($\delta_0 = 12$). This value is chosen to be larger than the causality margin resulting from the propagation from the contra-lateral ear to the error microphone (see also Figure 5). In this way, for any scenario, the binaural integrated ANC and NR scheme does not have any advantage in terms of causality compared to the monaural integrated ANC and NR scheme. Under a negative causality margin, the ANC would be ineffective and the SNR improvement would merely be due to the binaural NR [9], [14]. For the single noise source scenario, the noise source is at 270° . In the two noise sources scenario, the noise sources are at 270° and 90° . For the three noise sources scenario, the noise sources are at 270° , 90° and 330° .

The number of noise sources has an impact on the performance of MWF-based NR schemes when signal leakage effects and the effect of the secondary path are neglected, *i.e.*, the performance of the integrated ANC and NR scheme when the gain G is set to a high value [13]. In order to observe the effects of the number of sound sources (speech source plus noise sources) on the ANC part of the integrated ANC and NR schemes it is more convenient to look at the normalised output SNR improvement:

$$\overline{\Delta \text{SNR}_{\text{intellig}}} = \Delta \text{SNR}_{\text{intellig}} - \Delta \rho_{\text{intellig}} \quad (25)$$

Where $\Delta \rho_{\text{intellig}}$ is the intelligibility-weighted SNR improvement for the MWF-based NR scheme when no perturbation (signal leakage and secondary path) is taken into account.

Figure 6 presents the normalised output SNR improvement ($\overline{\Delta \text{SNR}_{\text{intellig}}}$) of two integrated ANC and NR schemes (2-channel monaural based on the microphone signals from the left hearing aid and 4-channel binaural), for a gain varying from 0dB to 25dB. For large gains, the integrated ANC and NR schemes deliver a normalised output SNR ($\overline{\Delta \text{SNR}_{\text{intell}}}$) of about 0dB.

The two integrated ANC and NR schemes are able to deliver an almost constant SNR improvement for any gain when only one noise source is present. When two or more noise sources are present, the

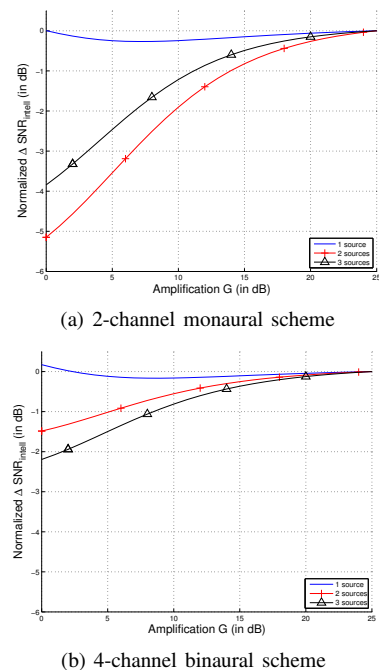


Fig. 6. Normalised SNR performance of integrated ANC and NR schemes

normalised SNR performance of the 2-channel integrated NC and NR drops to -4dB to -5dB for low gains. The 4-channel integrated ANC and NR scheme on the other hand allows to maintain a normalised SNR performance above -2dB for up to three noise sources.

V. CONCLUSION

It has been shown in previous work that an MWF-based integrated ANC and NR provides an efficient solution to the signal leakage problem in hearing aids with an open fitting. Hearing aids, however, have small dimensions. Therefore, the integrated ANC and NR scheme is subject to strong constraints on causality and on the number of noise sources that can be compensated for.

The binaural MWF-based integrated ANC and NR scheme presented in this paper is based on the microphone signals from both ears. Here, the contra-lateral microphones are distant from the ear canal microphone where the noise is to be cancelled. The propagation time from these microphones to the ear canal microphone is therefore larger and allows, in some scenarios, to design a scheme with a larger causality margin. Therefore, this approach allows to attenuate the noise from a larger number of sources than the monaural integrated ANC and NR scheme.

REFERENCES

- [1] W. Koenig, "Subjective effects in binaural hearing," *The Journal of the Acoustical Society of America*, vol. 22, no. 1, pp. 61–62, 1950.
- [2] N. W. MacKeith and R. R. A. Coles, "Binaural advantages in hearing of speech," *The Journal of Laryngology and Otology*, vol. 85, no. 03, pp. 213–232, 1971.
- [3] A. Markides, *Binaural hearing aids*. Academic Press London, 1977.
- [4] P. C. Loizou, *Speech Enhancement: Theory and Practice*. Boca Raton, FL: CRC Press, 2007.
- [5] L. J. Griffiths and C. W. Jim, "An alternative approach to linearly constrained adaptive beamforming," *IEEE Transactions on Antennas and Propagation*, vol. 30, pp. 27–34, 1982.
- [6] J. Chen, J. Benesty, Y. Huang, and S. Doclo, "New insights into the noise reduction Wiener filter," *IEEE Transactions on Audio, Speech, and Language Processing*, vol. 14, no. 4, pp. 1218–1234, 2006.
- [7] S. Doclo, A. Spriet, J. Wouters, and M. Moonen, "Frequency-domain criterion for the speech distortion weighted multichannel wiener filter for robust noise reduction," *Elsevier Speech Communication*, vol. 49, no. 7-8, pp. 636–656, 2007.

- [8] D. P. Welker, J. E. Greenberg, J. G. Desloge, and P. M. Zurek, "Microphone-array hearing aids with binaural output. II. A two-microphone adaptive system," *IEEE Transactions on Speech and Audio Processing*, vol. 5, no. 6, pp. 543–551, 2002.
- [9] T. J. Klaseen, T. Van den Bogaert, M. Moonen, and J. Wouters, "Binaural noise reduction algorithms for hearing aids that preserve interaural time delay cues," *IEEE Transactions on Signal Processing*, vol. 55, no. 4, pp. 1579–1585, 2007.
- [10] S. J. Elliott and P. A. Nelson, *Active control of sound*. Cambridge: Academic press, 1993.
- [11] S. M. Kuo and D. R. Morgan, "Active noise control: a tutorial review," *Proceedings of the IEEE*, vol. 87, Issue: 6, no. 0018-9219, pp. 943–973, June 1999.
- [12] R. Serizel, M. Moonen, J. Wouters, and S. H. Jensen, "Integrated active noise control and noise reduction in hearing aids," *IEEE Transactions on Speech Audio and Language*, vol. 18, no. 6, pp. 1137–1146, August 2010.
- [13] —, "Output snr analysis of integrated active noise control and noise reduction in hearing aids under a single speech source," *EURASIP Signal Processing*, vol. 91, no. 8, pp. 1719–1729, August 2011.
- [14] B. Cornelis, S. Doclo, T. Van den Bogaert, M. Moonen, and J. Wouters, "Theoretical analysis of binaural multi-microphone noise reduction techniques," *IEEE Transactions on audio, speech and language processing*, vol. 18, no. 2, pp. 342–355, February 2010.
- [15] X. Kong and S. M. Kuo, "Study of causality constraint on feedforward active noise control systems," *IEEE Transactions on Circuits and Systems II: Analog and Digital Signal Processing*, vol. 46, no. 2, pp. 183–186, February 1999.
- [16] M. Nilsson, S. D. Soli, and A. Sullivan, "Development of the Hearing in Noise Test for the measurement of speech reception thresholds in quiet and in noise," *The Journal of the Acoustical Society of America*, vol. 95, no. 2, pp. 1085–1099, Feb. 1994.
- [17] Auditec, "Auditory Tests (Revised), Compact Disc, Auditec, St. Louis," St. Louis, 1997.
- [18] J. E. Greenberg, P. M. Peterson, and P. M. Zurek, "Intelligibility-weighted measures of speech-to-interference ratio and speech system performance," *The Journal of the Acoustical Society of America*, vol. 94, no. 5, pp. 3009–3010, Nov. 1993.
- [19] A.-S. (1997), "ANSI S3.5-1997 American National Standard Methods for calculation of the speech intelligibility index," *Acoustical Society of America*, June 1997.



Marc Moonen Marc Moonen (M'94, SM'06, F'07) received the electrical engineering degree and the PhD degree in applied sciences from Katholieke Universiteit Leuven, Belgium, in 1986 and 1990 respectively.

Since 2004 he is a Full Professor at the Electrical Engineering Department of Katholieke Universiteit Leuven, where he is heading a research team working in the area of numerical algorithms and signal processing for digital communications, wireless communications, DSL and audio signal processing.

He received the 1994 K.U.Leuven Research Council Award, the 1997 Alcatel Bell (Belgium) Award (with Piet Vandaele), the 2004 Alcatel Bell (Belgium) Award (with Raphael Cendrillon), and was a 1997 "Laureate of the Belgium Royal Academy of Science". He received a journal best paper award from the IEEE Transactions on Signal Processing (with Geert Leus) and from Elsevier Signal Processing (with Simon Doclo).

He was chairman of the IEEE Benelux Signal Processing Chapter (1998-2002), and is currently Past-President of EURASIP (European Association for Signal Processing) and a member of the IEEE Signal Processing Society Technical Committee on Signal Processing for Communications.

He has served as Editor-in-Chief for the "EURASIP Journal on Applied Signal Processing" (2003-2005), and has been a member of the editorial board of "IEEE Transactions on Circuits and Systems II" (2002-2003) and "IEEE Signal Processing Magazine" (2003-2005) and "Integration, the VLSI Journal". He is currently a member of the editorial board of "EURASIP Journal on Applied Signal Processing", "EURASIP Journal on Wireless Communications and Networking", and "Signal Processing".



Romain Serizel Romain Serizel received the M.Eng. degree in Automatic System Engineering from ENSEM (Nancy, France) in 2005 and the M.Sc. degree in Signal Processing from Universit Rennes 1 (Rennes, France) in 2006. He received the Ph.D. degree in Engineering Sciences from the Katholieke Universiteit Leuven (KUL), Belgium in June 2011.

Since 2011 he is a research assistant with Prof. Marc Moonen research group at the Electrical Engineering Department (ESAT-SCD) of the KUL. His research interests include hearing aids systems, cochlear implants and digital signal processing for audio.



Jan Wouters Jan Wouters was born in Leuven, Belgium, in 1960. He received the physics degree and the Ph.D. degree in sciences / physics from the Katholieke Universiteit Leuven, Leuven, Belgium, in 1982 and 1989, respectively. From 1989 till 1992 he was a Research Fellow with the Belgian National Fund for Scientific Research (FWO) at the Institute of Nuclear Physics (UCL Louvain-la-Neuve and K.U.Leuven) and at NASA Goddard Space Flight Center (USA). Since 1993 he is a Professor at the Neurosciences Department of the K.U.Leuven (Full

Professor since 2001). His research activities center around audiology and the auditory system, signal processing for cochlear implants and hearing aids. He is author of about 145 articles in international peer-reviewed journals and is a reviewer for several international journals.

Dr. Wouters received an Award of the Flemish Ministry in 1989, a Fullbright Award and a NATO Research Fellowship in 1992, and the Flemish VVL Speech therapy - Audiology Award in 1996. He is member of the International Collegium for ORL (CORLAS), a Board Member of the International Collegium for Rehabilitative Audiology (ICRA) and is responsible for the Laboratory for Experimental ORL and the audiology program at K.U.Leuven.



Søren Holdt Jensen Søren Holdt Jensen (S87M88SM00) received the M.Sc. degree in electrical engineering from Aalborg University, Aalborg, Denmark, in 1988, and the Ph.D. degree in signal processing from the Technical University of Denmark, Lyngby, Denmark, in 1995. Before joining the Department of Electronic Systems of Aalborg University, he was with the Telecommunications Laboratory of Telecom Denmark, Ltd, Copenhagen, Denmark; the Electronics Institute of the Technical University of Denmark; the Scientific Computing

Group of Danish Computing Center for Research and Education (UNI•C), Lyngby; the Electrical Engineering Department of Katholieke Universiteit Leuven, Leuven, Belgium; and the Center for PersonKommunikation (CPK) of Aalborg University.

He is Full Professor and is currently heading a research team working in the area of numerical algorithms and signal processing for speech and audio processing, image and video processing, multimedia technologies, and digital communications.

Prof. Jensen was an Associate Editor for the IEEE Transactions on Signal Processing and Elsevier Signal Processing, and is currently Member of the Editorial Board of IEEE Transactions on Audio, Speech and Language Processing and EURASIP Journal on Advances in Signal Processing. He is a recipient of an European Community Marie Curie Fellowship, former Chairman of the IEEE Denmark Section, and Founder and Chairman of the IEEE Denmark Sections Signal Processing Chapter. He is member of the Danish Academy of Technical Sciences and was in January 2011 appointed as member of the Danish Council for Independent Research—Technology and Production Sciences by the Danish Minister for Science, Technology and Innovation.