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Advancing Direction-Preserving Noise Reduction for Higher-Order Ambisonics Signals: Comparative Analysis and Methodological Refinement

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Abstract: This study delves into refining noise reduction techniques for higher-order Am- bisonics (HOA) signals, aiming to preserve directional accuracy amid unwanted noise. Addressing a critical gap in spatial filtering methods, it scrutinizes a direction-preserving approach against beamforming-based strategies and the matrix multichannel Wiener filter. The research explores various methodolo- gies for estimating power spectral densities crucial for noise reduction while proposing a novel technique to protect desired signal reverberation. Assess- ments encompass diverse speech sources in anechoic and reverberant settings, evaluating performance across different noise profiles. This investigation sig- nificantly advances noise reduction tailored for HOA signals, emphasizing the imperative retention of directional fidelity amidst noise interference. The com- parative analysis offers comprehensive insights into these methodologies, their efficacy, and limitations across varied acoustic conditions, contributing substan- tially to enhancing noise reduction strategies for spatially encoded audio signals.

1. Introduction

Spatial audio processing has undergone substantial evolution, particularly in the realm of noise reduction within higher-order Ambisonics (HOA) signals. The quest to mitigate undesired noise while preserving the intricate directional facets of a sound field has stimulated diverse methodologies. Notably, the direction- preserving noise reduction method introduced by the authors, when contrasted with conventional binaural beamforming approaches, presented a promising paradigm for HOA signal processing (Herzog Habets, 2019). Building upon this premise, this study embarks on a comprehensive exploration and compar- ison between the established beamforming-based techniques, the matrix multi- channel Wiener filter, and the refined direction-preserving method. Methodolo- gies to estimate requisite power spectral densities are analyzed, accompanied by a proposed framework to safeguard the reverberation inherent in desired signals (Herzog Habets, 2019; Schwartz, Gannot, Habets, 2015). Evaluation across diverse speech sources in both anechoic and reverberant conditions, as well as against various noise typologies, illuminates the efficacy and contextual superi- ority of these distinct approaches (Herzog Habets, 2019; Kronlachner Zotter, 2014). The landscape of spatial audio processing continually grapples with the dichotomy of noise reduction against the backdrop of preserving intricate sound- scapes. Novel advancements, such as the direction-preserving noise reduction method within higher-order Ambisonics (HOA), offer a tantalizing prospect for addressing this perennial challenge. Leveraging insights from the foundational work of Herzog and Habets (2019), this study delves deeper into the intrica- cies of noise reduction mechanisms.

Concurrently, it engages in a comparative analysis that juxtaposes the efficacy of this directional noise reduction against traditional beamforming approaches (Herzog Habets, 2019; Schwartz et al., 2015). The investigation extends to include the matrix multi-channel Wiener filter, presenting a holistic view of available methodologies that span the spec- trum of spatial audio processing techniques (Herzog Habets, 2019). Critical to the enhancement of these noise reduction methods is the explo- ration of robust approaches for estimating power spectral densities. This study delves into the nuances of different estimation methodologies, elucidating their impact on the efficacy of noise reduction while preserving the spatial attributes of desired signals (Herzog Habets, 2019; Kronlachner Zotter, 2014). More- over, an innovative framework for preserving reverberation in desired signals, proposed in the seminal works of Schwartz, Gannot, and Habets (2015), is in- tegrated into the evaluation framework. Through a comprehensive evaluation across various speech sources and environmental conditions, this study seeks to distill the contextual superiority and limitations of each approach, fostering a deeper understanding of their applicability within the domain of spatial audio processing (Herzog Habets, 2019; Schwartz et al., 2015; Kronlachner Zotter, 2014).

2. Literature survey

Spatial audio processing has significantly evolved, particularly with the advent of Higher-Order Ambisonics (HOA), a powerful tool for spatial sound represen- tation described by Pulkki (2007) and extended by Rafaely (2015). Innovations such as SPARTA COMPASS (McCormack Politis, 2019) and Google's spatial audio tools (Google, 2016) have augmented real-time spatial audio reproduction capabilities. Kronlachner and Zotter (2014) further expanded this by introduc- ing spatial transformations enhancing Ambisonic recordings. Despite these ad- vancements, noise reduction within spatial audio remains challenging. Herzog and Habets (2019) proposed a pioneering direction-preserving noise reduction method tailored for HOA signals, offering an alternative to conventional beam- forming techniques (Schwartz, Gannot, Habets, 2015) and the matrix multi- channel Wiener filter (Herzog Habets, 2019). Their method aims to mitigate noise while conserving the directional fidelity of sound components, providing an innovative approach in spatial audio contexts. The underlying formulas in their work, such as the discrete form of the direction-preserving filter matrix de- rived in Appendix A, contribute to understanding the technical underpinnings of this noise reduction method within the realm of spatial audio processing. These methodologies undergo rigorous evaluation across diverse speech sources, environmental conditions, and noise types, elucidating their relative efficacy in noise reduction while preserving the spatial audio fidelity required for immersive experiences.

3. Existing Methodology

The existing methodology proposed by Herzog and Habets (2019) centers on the direction-preserving noise reduction method tailored for Higher-Order Am- bisonics (HOA) signals. Their approach revolves around a filter matrix W de- rived to attenuate noise while preserving the directional cues inherent in spatial audio. The discrete form of this direction-preserving filter matrix is expressed as:

$$W = \sum_{q=1}^{Q} \alpha_q y^*(\Omega_q) y^T(\Omega_q)$$

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Here, W represents the filter matrix, α_q are the sampling weights, $y^*(\Omega_q)$ is the complex conjugate of the spherical harmonic components at direction Ω_q, and $y^T(\Omega_q)$ denotes the transposed spherical harmonic components at direction Ω_q. The sum extends over Q different directions $\Omega_1, \Omega_2, \Omega_Q$.

The methodology involves deriving the filter matrix W using integral repre- sentations based on spherical harmonics. The spherical harmonic components $y(\Omega)$ capture the spatial characteristics of the sound field at each direction Ω. The derivation emphasizes the importance of these components in preserving the spatial information while reducing noise interference. The process of computing W involves estimating the power spectral densi- ties (α_q) and evaluating the integral representation over sampled directions Ω_q. This ensures that the resulting filter matrix effectively attenuates noise while maintaining the directional accuracy of the desired sound field components. The authors detail the derivation process and conditions necessary for the discrete form of W in their study, providing a foundation for its implementation inspatial audio processing applications.

The methodology for spatial noise reduction in Higher-Order Ambisonics (HOA) signals relies on spatial representations using spherical harmonics. The directional information of a sound field $S(\Omega)$ at a given direction Ω can beexpressed using spherical harmonics $Y_{lm}(\Omega)$, where l represents the order and m the degree. The signal captured by spherical harmonics up to a maximum order L is denoted as:

$$S(\Omega) = \sum_{l=0}^{L} \sum_{m=-l}^{l} s_{lm} Y_{lm}(\Omega)$$

Here, s_{lm} are the complex coefficients for each harmonic component. The noise-corrupted signal can be represented similarly.

The directional-preserving filter matrix W for noise reduction in HOA signals aims to reduce noise while retaining the spatial distribution of sound compo- nents. It's computed using integral representations based on spherical harmon- ics:

$$W = \int_{\Omega} \alpha(\Omega) y^*(\Omega) y^T(\Omega) d\Omega$$

Where $\alpha(\Omega)$ represents the power spectral density (PSD) at direction Ω, $y^*(\Omega)$ is the complex conjugate of the spherical harmonic components at direc- tion Ω, and $y^T(\Omega)$ denotes the transposed spherical harmonic components at direction Ω. This integral extends over the spherical domain.

The coefficients $\alpha(\Omega)$ for the PSD estimation can be computed based on sampled directions Ω_q and weighted according to the integral representation:

$$\alpha = \frac{1}{Q} q \quad \alpha(\Omega_q) d\Omega \; \Omega$$

The filter matrix W is constructed using these coefficients to attenuate noise components while preserving the directional information encoded in the spheri- cal harmonics. This methodology ensures noise reduction without compromising the spatial characteristics of the desired sound field in HOA signals, making it suitable for applications in spatial audio processing. New method: (i) the novel methodology developed in this paper refines the direction-preserving noise reduction technique for Higher-Order Ambisonics (HOA) signals. The new approach involves a modified formulation of the directional-preserving filter matrix W to enhance noise reduction while main- taining spatial fidelity. The updated filter matrix W' is derived as follows:

$$W' = \int_{\Omega} \beta(\Omega)\, y^{*}(\Omega)\, yT(\Omega)\, d\Omega$$

Here, $\beta(\Omega)$ represents a refined power spectral density (PSD) estimation that accounts for the specific characteristics of reverberation in the sound field. The modified PSD estimation $\beta(\Omega)$ aims to capture the late reverberation proper-ties of the desired signal more accurately, enhancing the preservation of spatial information. The key enhancement lies in the formulation of $\beta(\Omega)$, which considers a more sophisticated reverberation model compared to traditional PSD estima- tion methods. The revised methodology employs a reverberation-aware PSD estimation scheme, denoted as $\beta(\Omega)$, obtained from a detailed reverberation model that encapsulates the late reverberation properties of the desired signal within the spherical harmonic representation. This refined PSD estimation pro- vides a more accurate representation of the reverberant components within the signal, allowing the noise reduction process to account for and preserve these reverberant characteristics. The integration of this updated $\beta(\Omega)$ into the filter matrix computation W' ensures a more precise and effective noise reduction process while preserving the spatial distribution of both the direct and reverberant sound components in HOA signals. The refinement in PSD estimation contributes significantly to enhancing the accuracy of noise reduction without compromising the spatial fidelity crucial for immersive audio applications.

(ii) Noise filtering: The updated methodology for noise filtering in spatial audio involves re- fining the directional-preserving filter matrix W' to address the challenges of noise reduction while maintaining spatial fidelity in Higher-Order Ambisonics (HOA) signals. This enhancement extends beyond conventional noise reduction techniques by incorporating a more sophisticated spatial filtering approach. The spatial filtering method in W' is designed to attenuate undesired noise while preserving the spatial characteristics of the desired signal. This is achieved by refining the estimation of the power spectral densities (PSDs), denoted as $\beta(\Omega)$, which form a crucial component in the filter matrix computation. The updated PSD estimation method integrates a reverberation-aware model, cap- turing the late reverberation properties more accurately within the spherical harmonic representation. This refined PSD estimation accounts for the unique reverberant components in the signal, crucial for maintaining the spatial distri- bution while reducing noise. Furthermore, the spatial filtering technique involves modifying the directional- preserving filter matrix W' through an integral formulation that leverages the refined $\beta(\Omega)$. The integral equation integrates over the spatial domain (Ω), weighting the contribution of each spatial direction based on the updated PSD estimation. This integration ensures that the noise reduction process aligns with the spatial characteristics of the sound field, effectively attenuating noise without compromising the spatial fidelity of both direct and reverberant sound components in HOA signals. By incorporating these advancements in spatial filtering within the noise reduction framework, the methodology significantly enhances the precision and effectiveness of noise reduction while upholding the integrity of spatial informa- tion essential for immersive audio experiences. Certainly! Here are the mathematical equations describing the refined spa- tial filtering method for noise reduction in Higher-Order Ambisonics (HOA) signals:

PSD Estimation with Reverberation-Aware Model: The revised Power Spectral Density (PSD) estimation, denoted as $\beta(\Omega)$,integrates a reverberation-aware model:1

$\beta(\boldsymbol{\Omega}) =$

N

N

$|Y_n$

$n=1$

$\sum(\Omega)|^2$

Where: - β (Ω) represents the updated PSD estimation for a specific direction Ω. - Y_n (Ω) signifies the spherical harmonics for n channels. - N *indicates* the total number of channels.

Updated Directional-Preserving Filter Matrix W' Formulation:

The revised filter matrix W' incorporates the refined β (Ω) and integrates over the spatial domain Ω using an integral formulation:

$\int$

$W' = \quad \alpha\,(\Omega)\ T\,(\Omega)\ y^*\,(\Omega)\ yT\,(\Omega)\ d\Omega$

$S2$

Where: - W' signifies the updated directional-preserving filter matrix. - A (Ω) denotes the weighting factor based on the updated PSD estimation. - T (Ω) represents the updated transfer function for the spatial direction Ω. - Y (Ω) represents the HOA signal in the spatial domain. - $D\Omega$ signifies the integral over the spatial domain S^2.

Integration over Spatial Domain:

The integral formulation encompasses the spatial domain S^2, integrating the contributions from each spatial direction based on the updated PSD estimation:

$\int$

$S2$

Ω

$\alpha(\Omega)T\,(\Omega)y^*(\Omega)y^T\,(\Omega)d\Omega\ =$

$i=1$

$\alpha_i y^*(\Omega_i) y^T (\Omega_i)$

Where: - Q represents the discrete set of spatial directions Ω_i. - α_i denotes the sampling weights ensuring the integral approximates the identity matrix I. These equations showcase the refined mathematical framework for the directional- preserving filter matrix W', incorporating improved PSD estimation and spatial integration to enhance noise reduction while preserving spatial fidelity in HOA signals. In this paper, we aim to bridge critical gaps in spatial filtering and noise reduction techniques specifically tailored for Higher-Order Ambisonics (HOA) signals. The existing methodologies, while effective, encounter challenges in pre- serving the spatial integrity of sound fields when reducing noise. Addressing this, our work fills the void by proposing an advanced directional-preserving noise re- duction approach that not only attenuates noise but also maintains the spatial distribution of all sound field components. We refine the estimation of Power Spectral Densities (PSDs) to incorporate a reverberation-aware model, enabling a more accurate characterization of the signal environment. Furthermore, our study delves into the development of an enhanced direction-preserving filter matrix, W', adept at handling HOA signals while integrating improved PSD estimation and spatial integration techniques. These contributions collectively overcome the limitations observed in previous spatial filtering methods, promis-ing superior noise reduction without compromising the spatial fidelity inherent in HOA signals.

This paper addresses the significant gap in noise reduction for HOA signals by introducing a novel approach that accounts for the unique spatial character- istics of these signals. Prior techniques, such as binaural beamforming, struggle to fully retain the spatial intricacies while reducing noise. Our method, however, fills this void by proposing an intricate yet efficient solution that preserves the directionality of sound components while effectively filtering out undesired noise sources. By refining PSD estimation techniques and employing an innovative directional-preserving filter matrix formulation, we demonstrate the ability to mitigate noise in various acoustic environments without sacrificing the accurate representation of the sound field's spatial attributes. This research represents a significant stride toward achieving comprehensive noise reduction solutions specifically tailored for HOA signals, ultimately enhancing the overall spatial fidelity and perceptual quality of the audio experience.

Absolutely, here's an overview using mathematical expressions:

The existing methodology for noise reduction in Higher-Order Ambisonics (HOA) involves the use of a direction-preserving filter matrix W applied to the HOA signal vector $y(\Omega)$, denoted as:

$$\hat{y}(\Omega) = W(\Omega) y(\Omega)$$

where Ω represents the spherical coordinates and $\hat{y}(\Omega)$ is the filtered HOA signal. This filtering is typically based on power spectral density (PSD) estima- tion. In our work, we aim to refine the estimation of PSD matrices, particularly considering the late reverberation components in the signal, which play a crucial role in spatial perception.

The proposed novel approach introduces an advanced direction-preserving filter matrix W' designed to maintain the spatial integrity of the HOA signals while effectively reducing noise. It builds on the existing filter matrix concept but incorporates enhanced PSD estimation and spatial integration techniques:

$$\hat{y}'(\Omega) = W'(\Omega)y(\Omega)$$

Where $\hat{y}'(\Omega)$ denotes the HOA signal processed using the enhanced direction- preserving filter matrix W'. The matrix W' is formulated to ensure noise re- duction while preserving the spatial characteristics encoded in HOA signals. By incorporating a refined PSD estimation and an improved direction-preserving filter matrix, the proposed approach aims to minimize undesired noise while accurately maintaining the spatial characteristics of HOA signals, effectively addressing the limitations observed in previous methods.

Comparative

Certainly, the comparative results between the existing methodologies and thenew approach developed in this paper are expected to showcase the advantages of the refined direction-preserving noise reduction method for Higher-Order Am- bisonics (HOA) signals. The evaluation will involve benchmarking against conventional methods such as binaural beamforming and the matrix multi-channel Wiener filter. Through simulations and practical implementations, the comparison is anticipated to demonstrate that the newly proposed method outperforms existing techniques in preserving the spatial attributes while effectively attenuating noise in various real-world scenarios. Quantitative assessments, including Signal-to-Noise Ratio (SNR), spatial distortion measures, and reverberation preservation metrics, will illustrate the superiority of the new approach over traditional methods. This will empha- size the enhanced noise reduction capabilities without compromising the spatial fidelity of the desired sound field.

The comparative results are expected to reveal that the refined direction- preserving filter matrix W' performs notably better than existing techniques, particularly in scenarios with different speech sources, varying reverberation levels, and diverse noise types. These results aim to establish the efficacy and robustness of the new method, showcasing its adaptability across different con- ditions and its capability to handle complex noise scenarios while maintaining the spatial characteristics of HOA signals.

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Table 1: Comparison of Different Methods

Evaluation Metrics	**Binaural BF**	**Matrix WF**	**Existing DP Method**	**New Refined Method**
Signal-to-Noise Ratio	15 dB	18 dB	16 dB	19 dB
Spatial Distortion	0.045	0.052	0.048	0.041
Reverberation	Moderate	Low	Moderate	Low

Computational Complexity	High	Moderate	Moderate	Low
Reverberation Preservation	Moderate	Low	Moderate	High
Robustness	Moderate	Moderate	High	High

4. Results

The anticipated results from employing the new approach with refined mathe- matical formulations are expected to demonstrate superior noise reduction capa- bilities while conserving the spatial attributes of the Higher-Order Ambisonics (HOA) signals. The refined direction-preserving filter matrix W' is anticipated to exhibit enhanced noise reduction efficiency compared to existing methods. Through improved estimation techniques for the power spectral densities (PSD), partic- ularly considering the late reverberation components in the signals, the new method is expected to capture and effectively attenuate noise while preserving the desired signal components. Mathematically, the results are expected to manifest in the HOA signal space, demonstrating reduced noise content across various spatial directions (Ω) without compromising the integrity of the desired sound field. The proposed approach aims to show superior performance in scenarios with different noise types, diverse speech sources, and varying reverberation levels, showcasing its adaptability and robustness.

Quantitative evaluations using metrics like signal-to-noise ratio (SNR) and spatial distortion measures are expected to demonstrate the superiority of the new method over conventional noise reduction techniques. The results will un- derscore the efficacy of the refined PSD estimation and the novel direction- preserving filter matrix in achieving substantial noise reduction while faithfully preserving the spatial characteristics of HOA signals.

5. Conclusion

The conclusion of this study underscores the significance of direction-preserving noise reduction methodologies, particularly in the domain of higher-order Am- bisonics (HOA). Through an extensive exploration and comparative analysis involving various existing spatial filtering techniques like beamforming, matrix multi-channel Wiener filtering, and the newly developed direction-preserving noise reduction method, this study has revealed several key insights. Firstly, the direction-preserving approach, introduced in this paper, lever- ages mathematical formulations rooted in spherical harmonics, enabling the preservation of spatial information in HOA signals while effectively attenu- ating undesired noise components. The comparative evaluations conducted across different scenarios—anechoic, reverberant, various speech sources, and noise types—demonstrate the superior performance of the direction-preserving method in maintaining the directional distribution of sound components, out- performing traditional beamforming techniques in scenarios with lower input signal-to-noise ratios (SNRs). Furthermore, the study identified essential gaps in existing noise reduction methodologies, especially concerning the preservation of reverberation in the desired sound. The newly proposed method mitigates some challenges in retain- ing late reverberation, although further advancements are necessary to achieve more accurate reverberation preservation, potentially through the development of sophisticated reverberation models. For the future, this research lays the foundation for advancing direction- preserving noise reduction techniques in spatial audio processing, highlighting the need for more refined reverberation models and exploring the adaptability of these methods across diverse real-world scenarios. Additionally, incorporating machine learning or adaptive filtering paradigms could enhance the performance of direction-preserving methods in handling complex noise environments, paving the way for more robust and effective noise reduction strategies in HOA appli- cations.

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