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Audio inpainting: problem statement, relation with sparse representations and some experiments

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PROBLEM STATEMENT & APPLICATIONS: a unified scheme for existing tasks

Audio inpainting scheme: an inverse problem where

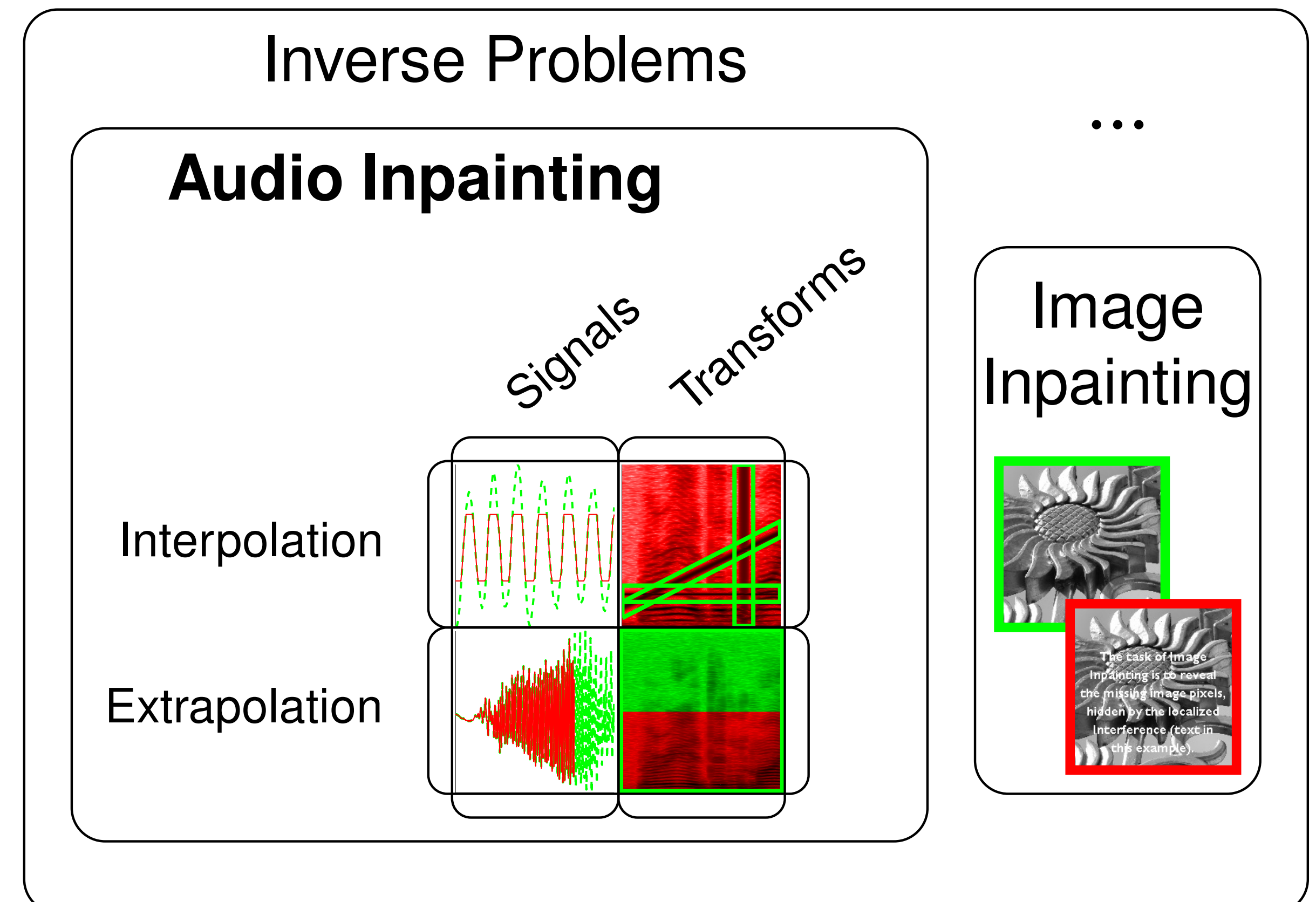
- a set of reliable audio data $\mathbf{y}$ is observed,
 - one must estimate the remaining missing or highly corrupted data.
- A unified scheme covering existing subproblems referred to as interpolation, extrapolation, imputation, (bandwidth) extension.

Formulation: estimate the original data $\mathbf{s}$ from $\mathbf{y}$ given $\mathbf{M}$

$$(1) \quad \mathbf{y} = \mathbf{M}\mathbf{s} \quad \text{with} \quad \begin{cases} \mathbf{s} & \in \mathbb{R}^N \\ \mathbf{y} & \in \mathbb{R}^{N-M} \\ \mathbf{M} & \in \mathbb{R}^{N-M \times N} \end{cases} \quad \text{and} \quad \begin{matrix} \text{M} \\ \text{[Diagram showing a matrix M with a dashed line indicating a missing block]} \end{matrix}$$

Several kinds of audio data: waveforms [1,2], transforms or mid-level representations [3].

A number of applications: removing clicks in old recordings, declipping, packet loss concealment in VoIP or P2P networks, bandwidth extension, recovery of TF coefficients masked by interfering sources/noise.



PROPOSED APPROACH: audio inpainting using sparse representations

Since the problem (1) is ill-posed, additional *a priori* is required.

Sparsity assumption on audio data

$$(2) \quad \mathbf{s} = \mathbf{D}\mathbf{x} \quad \text{with} \quad \begin{cases} \mathbf{D} \in \mathbb{R}^N \times \mathbb{R}^{K_D} \text{ (dictionary)} \\ \mathbf{x} \in \mathbb{R}^{K_D} \text{ (sparse coefficients)} \\ \|\mathbf{x}\|_0 \ll N \leq K_D \end{cases}$$

Noiseless ideal estimation

$$(3) \quad \hat{\mathbf{x}} \triangleq \arg \min_{\mathbf{x}} \|\mathbf{x}\|_0 \quad \text{s.t.} \quad \mathbf{y} = \mathbf{M}\mathbf{D}\mathbf{x}$$

Inpainting algorithms

Algorithm 1 Inpainting with l_1 -minimization (L_1)

Using convex minimization, do

$$\hat{\mathbf{x}} \leftarrow \arg \min_{\mathbf{x}} \|\mathbf{x}\|_1 \quad \text{s.t.} \quad \|\mathbf{y} - \mathbf{M}\mathbf{D}\mathbf{x}\|_2^2 \leq \theta^2$$

$$\hat{\mathbf{s}} \leftarrow \mathbf{D}\hat{\mathbf{x}}$$

Algorithm 2 OMP-based inpainting (OMP)

Dictionary $\tilde{\mathbf{D}} = [\tilde{\mathbf{d}}_1, \dots, \tilde{\mathbf{d}}_{K_D}] \leftarrow \mathbf{M} \times \mathbf{D} \times \mathbf{W}_{\mathbf{MD}}^{-1}$ ($\mathbf{W}_{\mathbf{MD}}$: diag. matrix of norms of $\mathbf{MD}$ columns)

Residual $\mathbf{r}_0 \leftarrow \mathbf{y}$

Iteration counter $k \leftarrow 1$, support set $\Omega_0 \leftarrow \emptyset$

while $k \leq K_{max}$ AND $\|\mathbf{r}_k\|_2 \geq \theta_{OMP}$ **do**

Select atom: $j \leftarrow \arg \max_j |\langle \mathbf{r}_k, \tilde{\mathbf{d}}_j \rangle|$

Update support $\Omega_k \leftarrow \Omega_{k-1} \cup j$

Update current solution $\mathbf{x}_k \leftarrow \arg \min_{\mathbf{x}} \|\mathbf{y} - \tilde{\mathbf{D}}_{\Omega_k} \mathbf{x}\|_2$

Update residual $\mathbf{r}_k \leftarrow \mathbf{y} - \tilde{\mathbf{D}}_{\Omega_k} \mathbf{x}_k$

Increment iteration counter $k \leftarrow k + 1$

end while

$$\hat{\mathbf{s}} \leftarrow \mathbf{D}\mathbf{W}_{\mathbf{MD}}\mathbf{x}_k$$

Specific inpainting algorithms for restoring clipped signals

→ Constrain the restored samples to be beyond the clipping threshold θ_{clip}

Algorithm 3 (L_1C)

Using convex minimization, do

$$\hat{\mathbf{x}} \leftarrow \arg \min_{\mathbf{x}} \|\mathbf{x}\|_1 \quad \text{s.t.} \quad \begin{cases} \|\mathbf{y} - \mathbf{M}\mathbf{D}\mathbf{x}\|_2^2 \leq \theta^2 \\ \mathbf{M}^+ \mathbf{D}\mathbf{x} \geq \theta_{clip} \\ \mathbf{M}^- \mathbf{D}\mathbf{x} \leq -\theta_{clip} \end{cases}$$

$$\hat{\mathbf{s}} \leftarrow \mathbf{D}\hat{\mathbf{x}}$$

Algorithm 4 (OMPc)

After the while loop in Alg. 1, refine $\mathbf{x}_k$ as

$$\mathbf{x}_k \leftarrow \arg \min_{\mathbf{x}} \|\mathbf{y} - \tilde{\mathbf{D}}_{\Omega_k} \mathbf{x}\|_2 \quad \text{s.t.} \quad \begin{cases} \mathbf{M}^+ \mathbf{D}\mathbf{x} \geq \theta_{clip} \\ \mathbf{M}^- \mathbf{D}\mathbf{x} \leq -\theta_{clip} \end{cases}$$

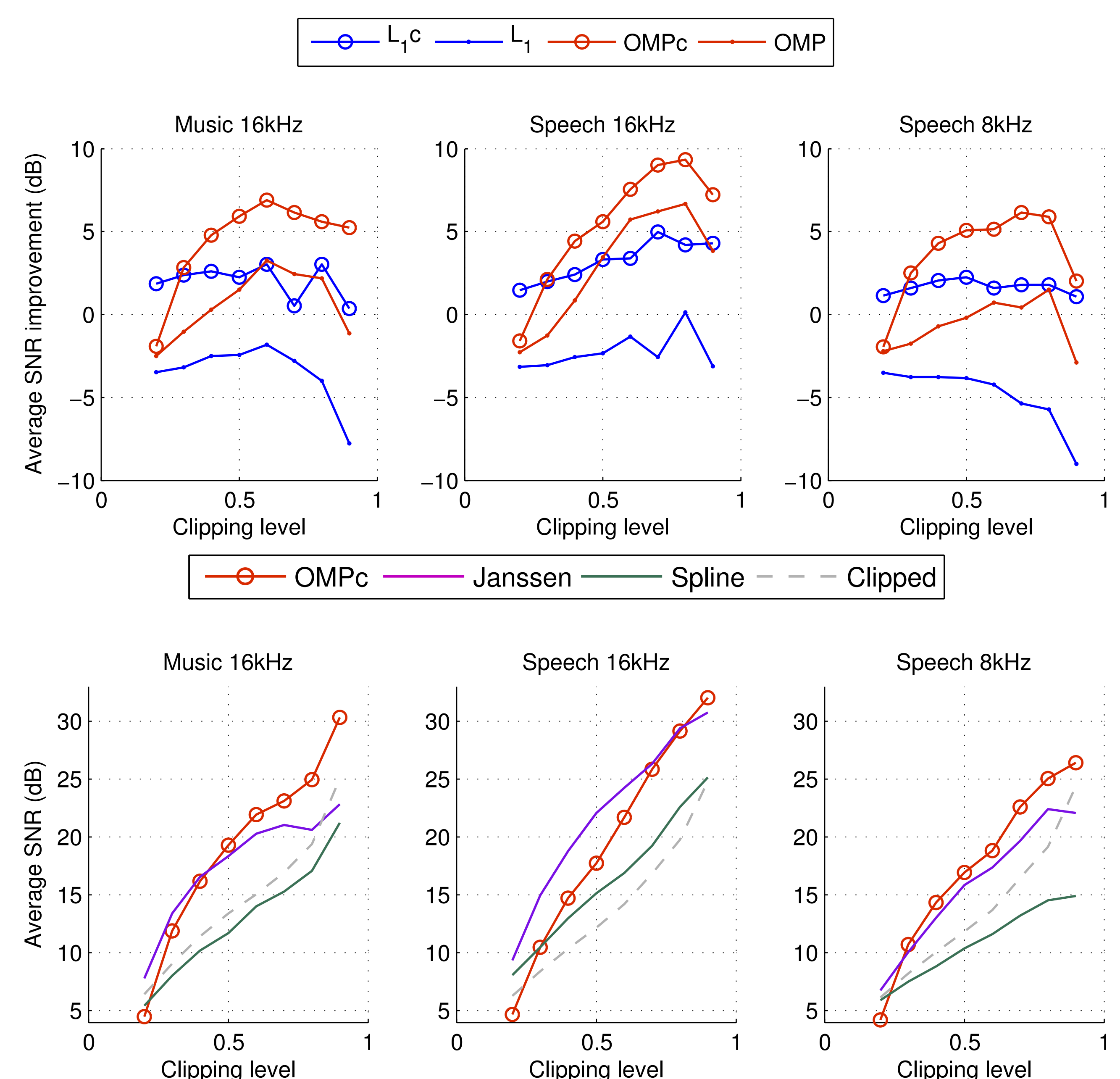
$$\hat{\mathbf{s}} \leftarrow \mathbf{D}\mathbf{W}_{\mathbf{MD}}\mathbf{x}_k$$

where $\mathbf{M}^+$ and $\mathbf{M}^-$ are the projectors onto the subspace of positive and negative clipped samples respectively.

EXPERIMENTS: declipping audio signals

Experimental settings

- 3 datasets with 10 5-seconds signals
- Frame-by-frame processing with OLA reconstruction: 75% overlap, 64ms frames, sine weighting windows
- Algorithms OMP, OMPc, L_1 , L_1C are applied in each frame
- OMPc is compared to spline interpolation and Janssen's algorithm [1] based on autoregressive models.
- Algorithm parameters are fixed (tuned on a separate database)
- Dictionary $\mathbf{D}$: redundant sine-windowed DCT
- SNR is computed on the corrupted samples only



[1] A. Janssen, R. Veldhuis, L. Vries, *Adaptive interpolation of discrete-time signals that can be modeled as autoregressive processes*, in IEEE Trans. on Acoustics, Speech and Signal Proc., 34 (2), 1986.

[2] S. J. Godsill, P. J. W. Rayner, *Digital audio restoration - A statistical model-based approach*, Springer-Verlag London, 1998.

[3] J. Le Roux, H. Kameoka, N. Ono, A. de Cheveigné, S. Sagayama, *Computational auditory induction by missing-data non-negative matrix factorization*, Proc. of SAPA, 2008.