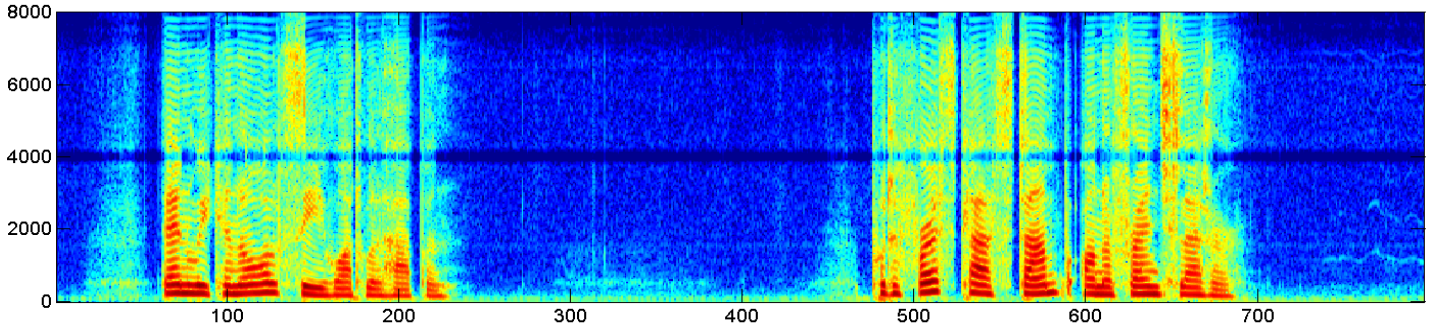
Summer School of Information Engineering
29 June – 3 July, Bressanone (BZ), Italy

Investigations about the optimization of artificial bandwidth extension



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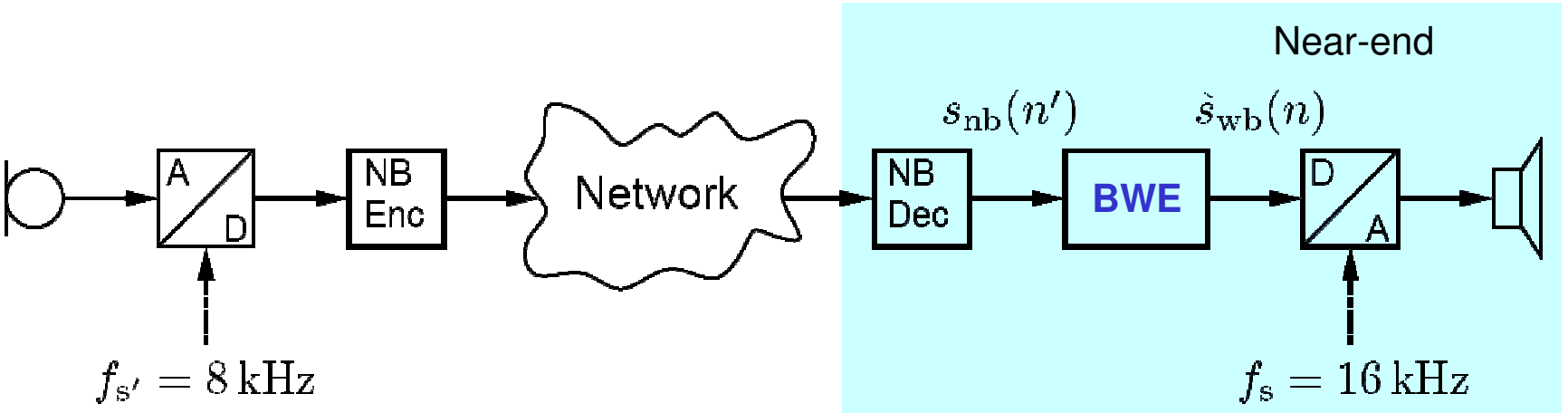
Motivation (1/2)

- ✓ **Problem**:
  - Telephone signals have a limited intelligibility
    - Similar voices (father – son)
    - Syllable confusion (spelling via NATO alphabet)
    - Misunderstanding
- ✓ **Cause**:
  - The acoustic bandwidth is reduced for the 8 kHz sampling:
    - Upper limit: 3.4 kHz → reduced intelligibility
    - Lower limit: 300 Hz → low subjective quality
- **Stress and distraction** during the conversation

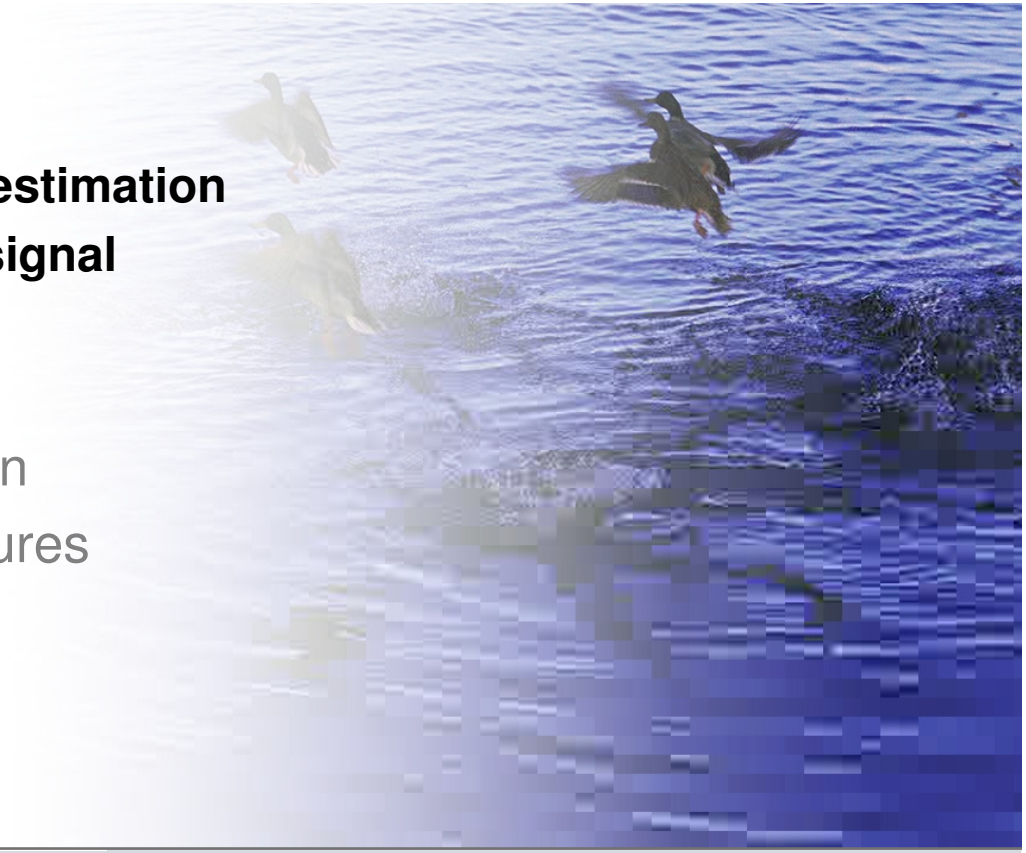
Motivation (2/2)



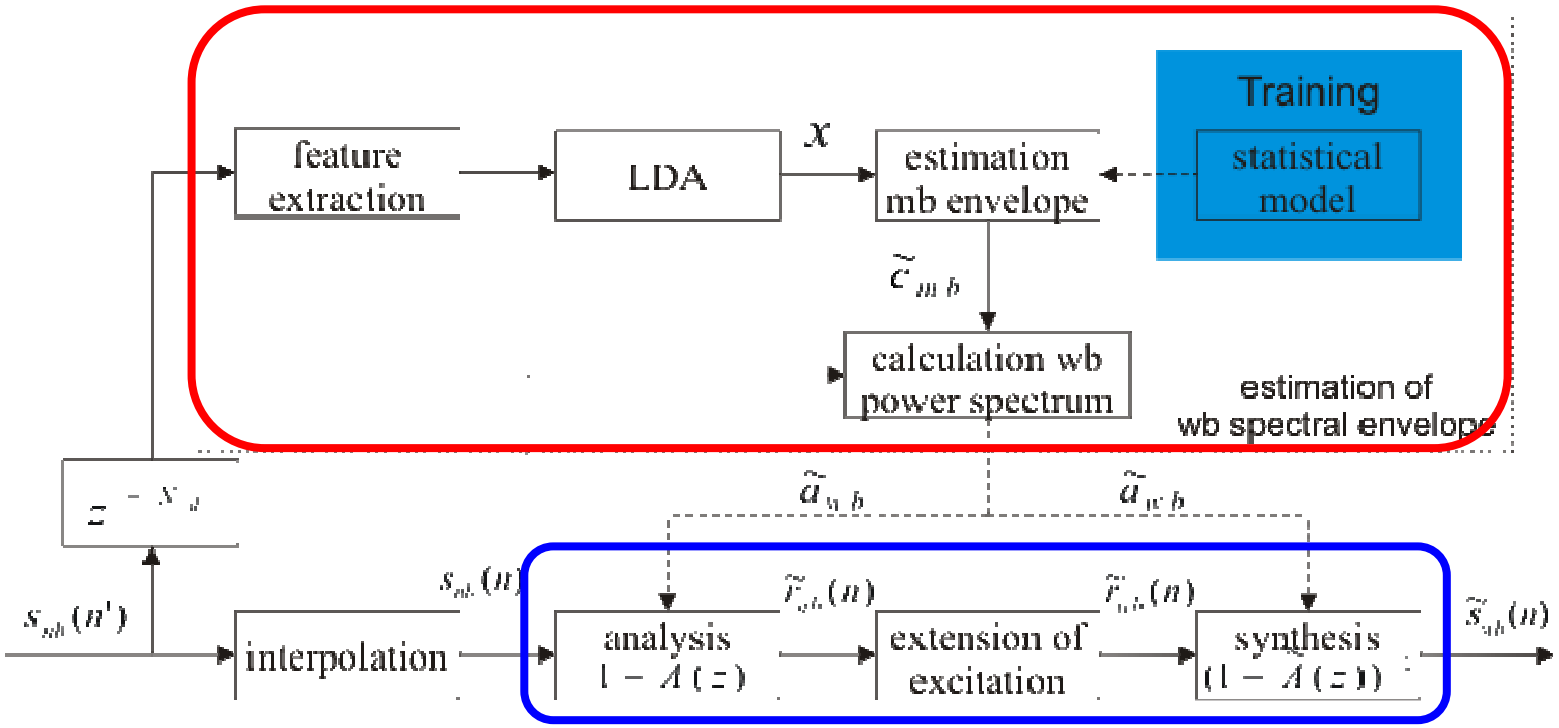
- ✓ Artificial Bandwidth Extension [ABWE]
  - Restoration of the wideband (7 kHz) without the need of additional information
  - Online processing: superior telephone quality, safer viva-voce
  - Offline processing: historical speech recordings
  - Fricative-oriented design (/s/, /z/, /f/)

Outline

1. **The ABWE algorithm**
   - **Block diagram**
   - **Statistical model: envelope estimation**
   - **Extension of the excitation signal**
   - **Result**
   - **Training**
2. Fricative-oriented optimization
3. Log-spectral distortion measures
4. Conclusions



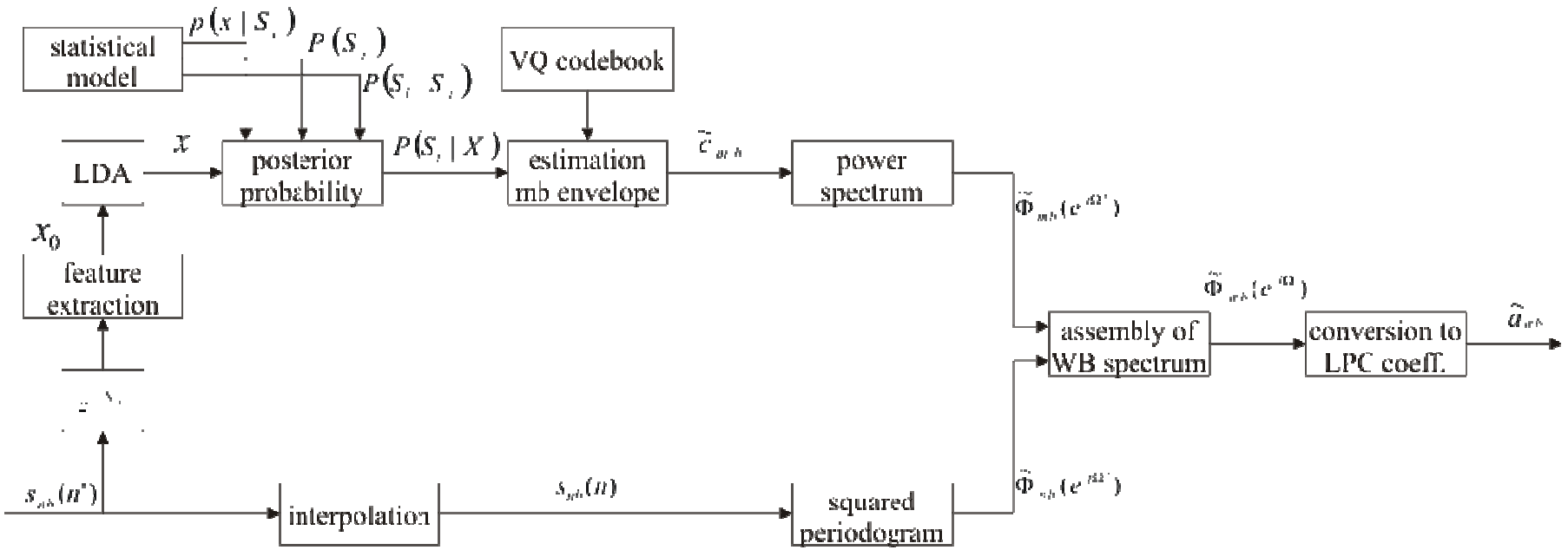
Block diagram



$s_{\mathrm{nb}}(n')$: narrowband signal
$\tilde{r}_{\mathrm{nb}}(n)$: narrowband residual
$\tilde{r}_{\mathrm{wb}}(n)$: wideband residual
$\tilde{s}_{\mathrm{wb}}(n)$: wideband speech

$z^{-N_{\mathrm{d}}}$: interpolation delay
$\mathbf{x}$: feature vector
$\tilde{\mathbf{c}}_{\mathrm{mb}}$: missing band cepstral vector
$\tilde{a}_{\mathrm{wb}}$: LPC filter coefficients

Statistical model: envelope estimation (1/3)



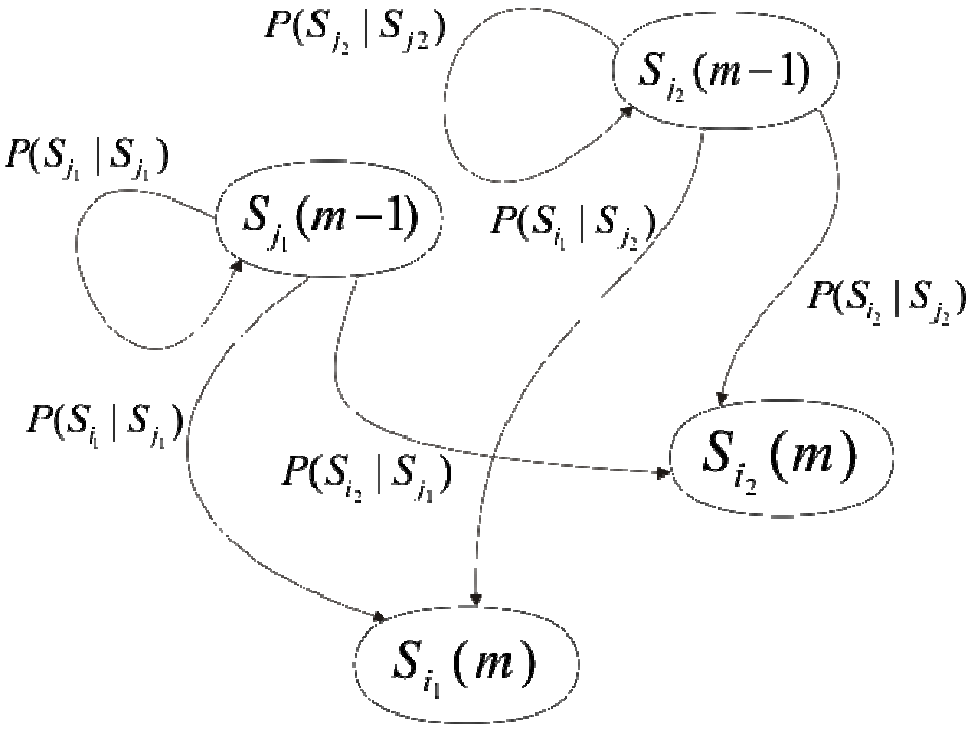
$p(\mathbf{x}|S_i)$: observation probability pdf
$P(S_i)$: state probability
$P(S_i|S_j)$: transition probability
$P(S_i|\mathbf{X})$: a posteriori probability

$\tilde{\Phi}_{\mathrm{bb}}(e^{j\Omega})$: baseband spectrum
$\tilde{\Phi}_{\mathrm{ub}}(e^{j\Omega''})$: estimated upper band spectrum
$\tilde{\Phi}_{\mathrm{wb}}(e^{j\Omega})$: assembled wideband spectrum

Statistical model: envelope estimation (2/3)

- ✓Hidden Markov Model (HMM)
  - ➢States → spectral envelopes
    $S_i \Longrightarrow \hat{\mathbf{y}}_{\mathrm{mb},i}$
  - ➢Input composite feature vector:
    $\mathbf{x}(m)$
  - ➢Transition probability:
    $P(S_i|S_j)$
  - ➢Observation pdfs
    $p(\mathbf{x}|S_i)$
  - ➢A posteriori probability:

$$P(S_i(m)|\mathbf{X}(m)) \Rightarrow \text{Bayes Eq.}$$



Statistical model: envelope estimation (3/3)

- ✓Soft-decision:
  - ➢Minimum mean square error (MMSE):

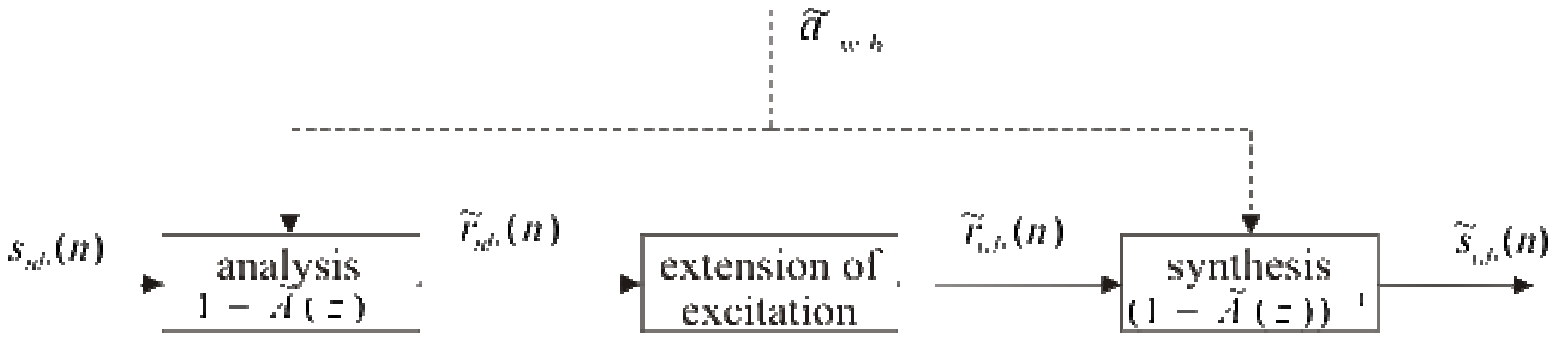
$$\tilde{\mathbf{y}}_{\mathrm{mb,MMSE}}(m) = \sum_{i=1}^{N_\mathrm{s}} \hat{\mathbf{y}}_{\mathrm{mb},i} P(S_i(m)|\mathbf{X}(m))$$

- ✓Assembly of the wideband spectrum
  - ➢Baseband periodogram (0 – 4 kHz)
  - ➢Upper band estimated (4 – 8 kHz)

- ✓LPC (Linear Predictive Coding) filter coefficients

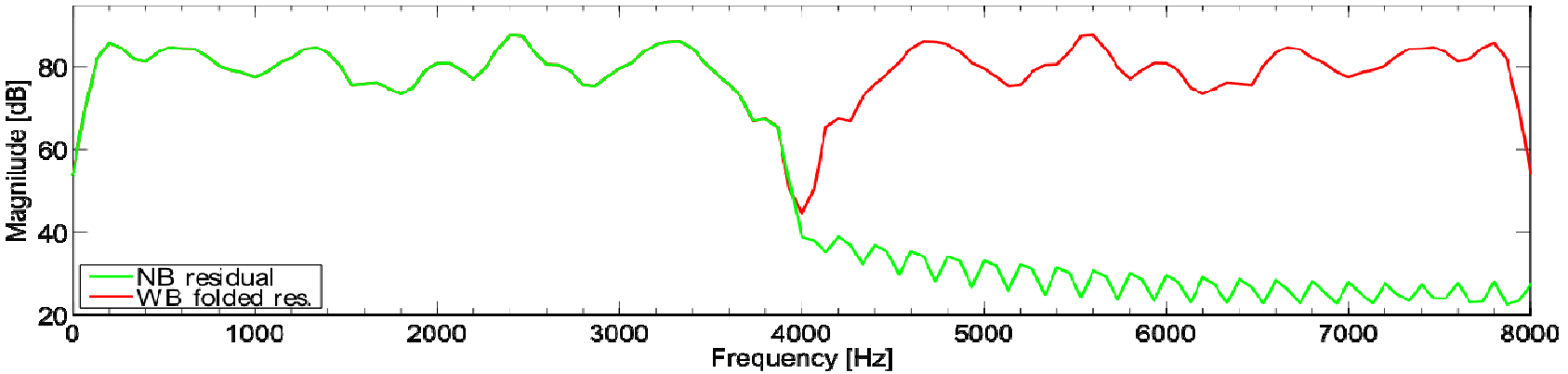
$$\tilde{\Phi}_{\mathrm{wb}}\left(e^{j\Omega}\right) \rightarrow \tilde{\mathbf{a}}_{\mathrm{wb}}$$

Extension of the excitation signal (1/2)



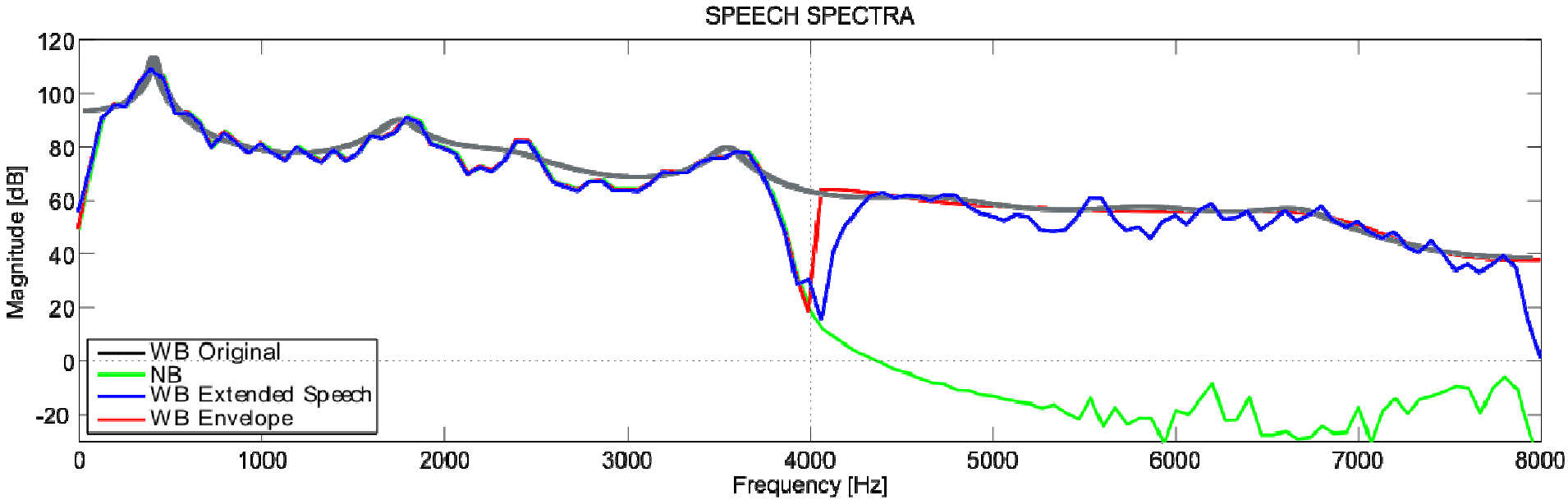
- ✓Analysis: Auto-regressive (AR) filter $1 - \tilde{A}(z) = 1 - \sum_{\nu=1}^{N_p} \tilde{a}_\nu z^{-\nu}$
  - ➢Residual signal $\tilde{r}_{wb}(n)$
- ✓Extension of the residual to 8 kHz
- ✓Synthesis: linear prediction (LP) filter $\left(1 - \tilde{A}(z)\right)^{-1}$
  - ➢Excitation signal $\tilde{r}_{wb}(n)$

Extension of the excitation signal (2/2)



- ✓Narrowband residual signal (white noise): $\tilde{r}_{\mathrm{nb}}(n)$
- ✓Folding around 4 kHz:
  - ➢0 – 4kHz ⟶ 0 – 8 kHz
- ✓Excitation of the synthesis filter: $\tilde{r}_{\mathrm{wb}}(n)$
  - ➢Wideband voice!

Result



4. Synthesized wideband signal: **Baseband transparency!!**

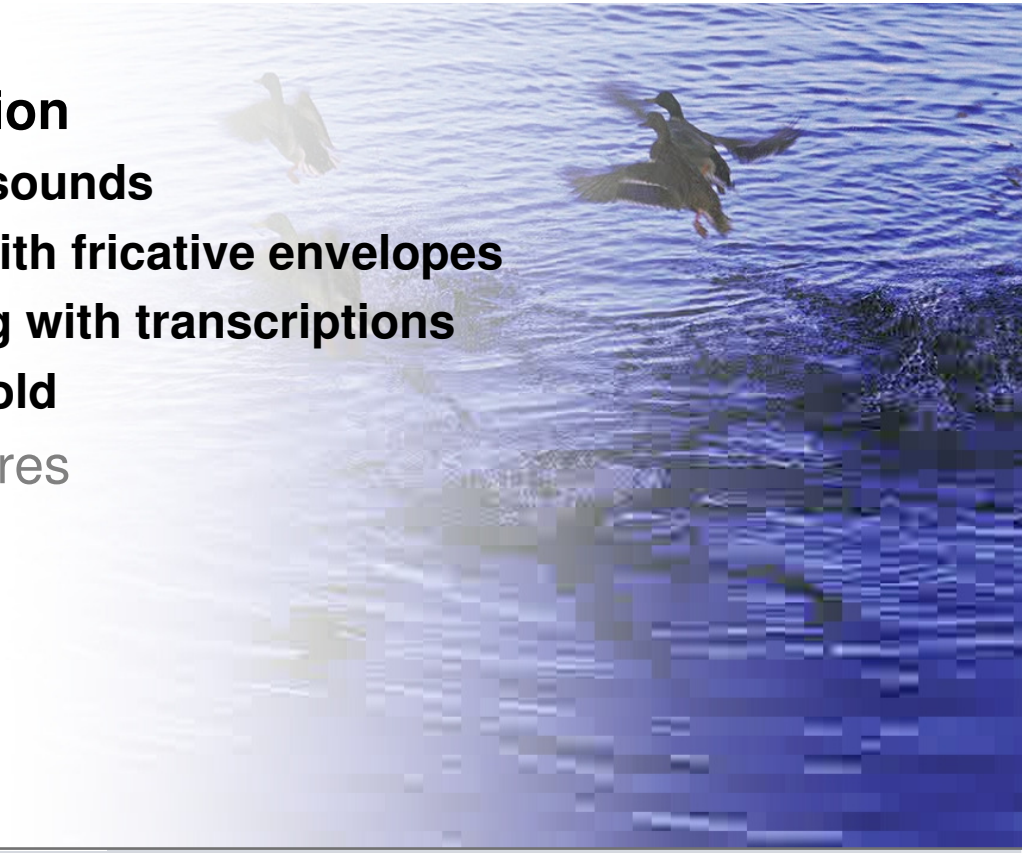
Training phase

- ✓Codebook Training
  - ➢Selective Linear Prediction (SLP) analysis, upper band
  - ➢LBG vector quantization (VQ)
    - ❖**Codebook (CB – 16 states S_i)**

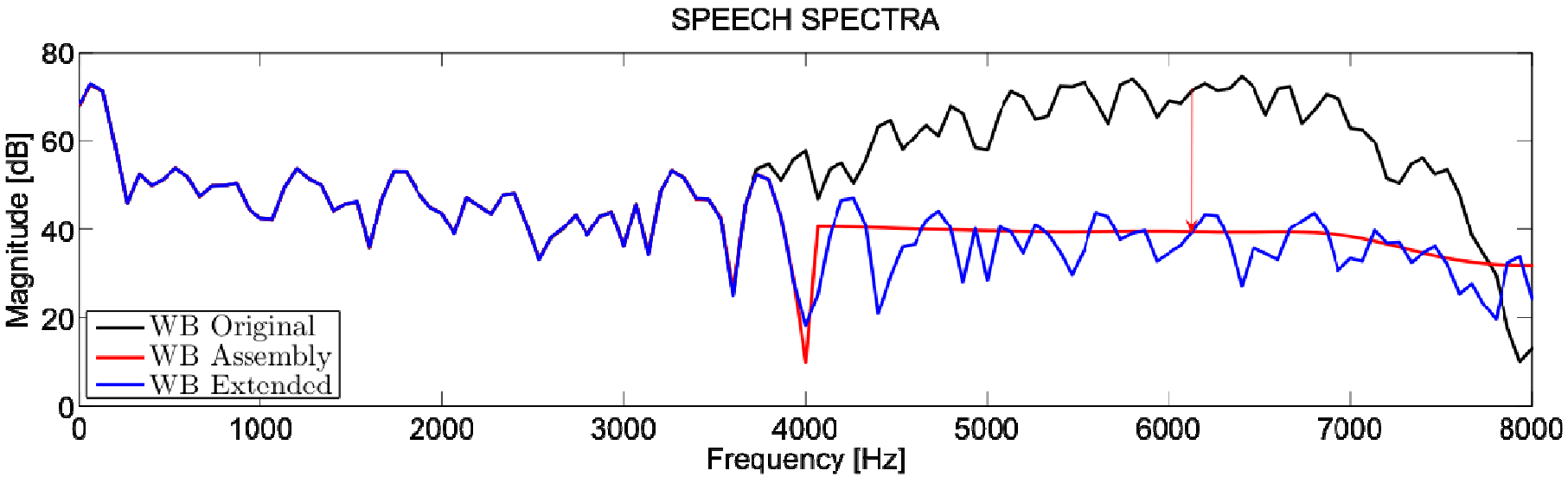
- ✓Training of the statistical model (HMM)
  - ➢State statistics:
    - ❖**State probabilities** $P(S_i)$
    - ❖**Transition probabilities** $P(S_i|S_j)$
  - ➢Likelihood statistics
    - ❖**Observation pdfs** $p(\mathbf{x}|S_i)$

Outline

1. The ABWE Algorithm
2. **Fricative oriented optimization**
   - **Underestimation of fricative sounds**
   - **Extension of the codebook with fricative envelopes**
   - **Transition matrix and training with transcriptions**
   - **Transition probability threshold**
3. Log-spectral distortion measures
4. Conclusions



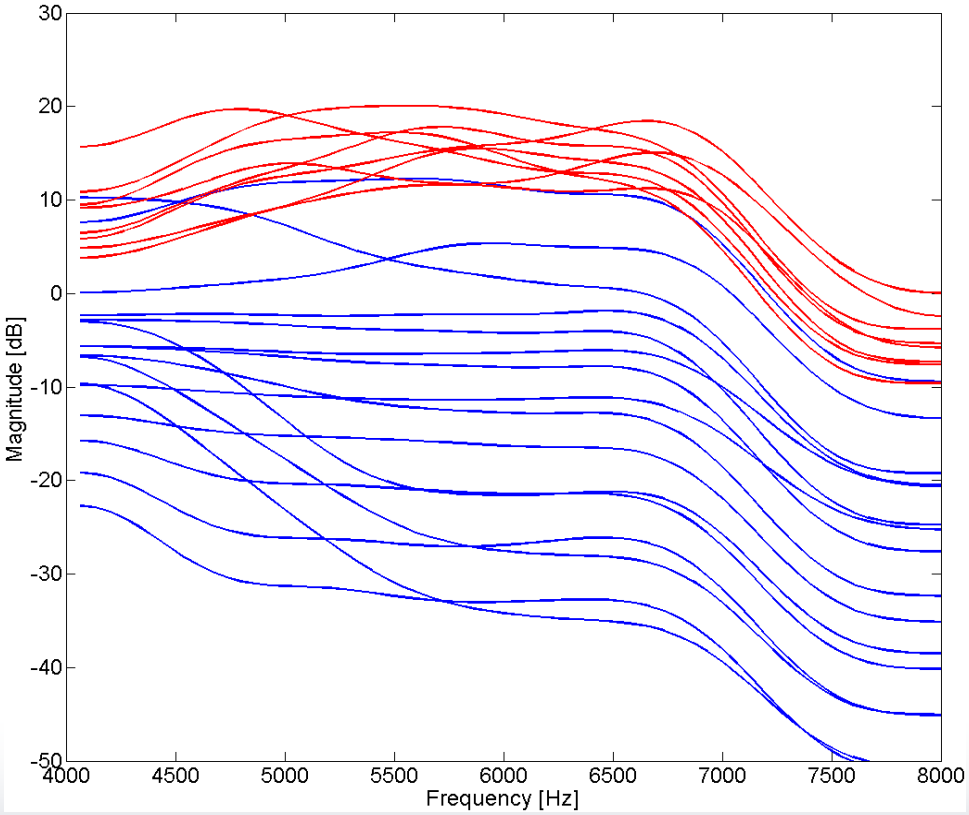
Underestimation of fricative sounds



✓High energy content in the upper band ⟶ difficult recognition

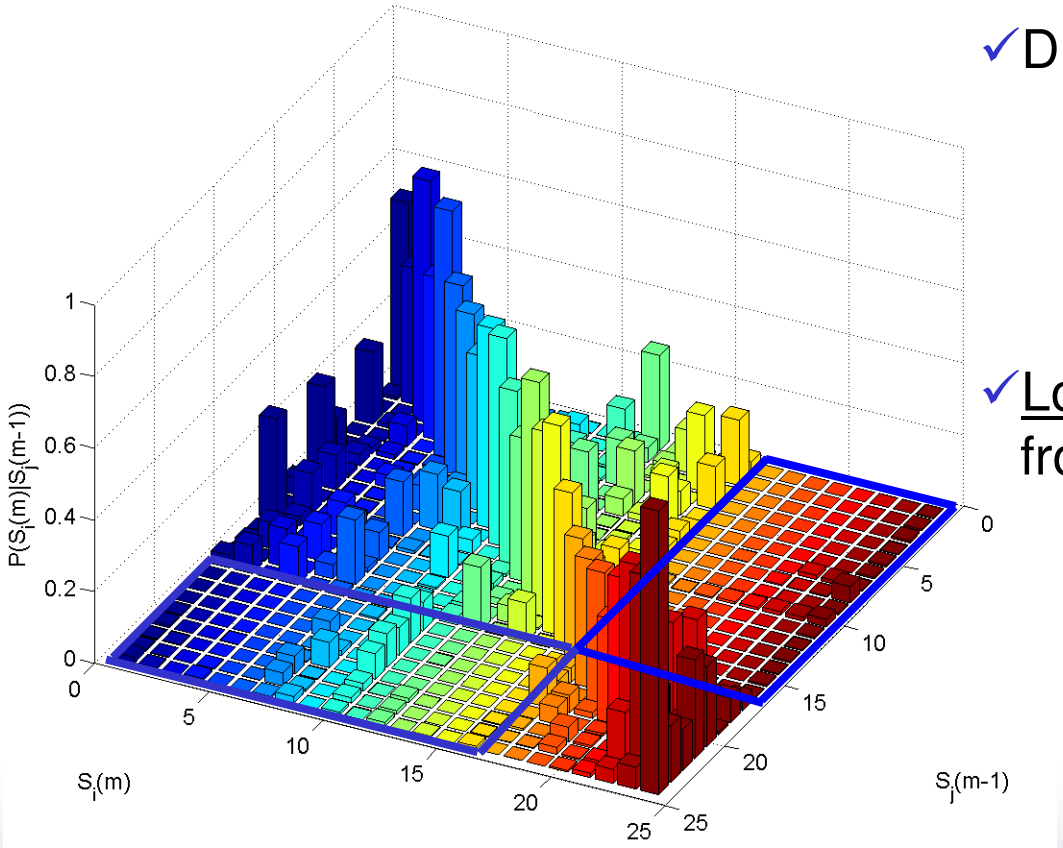
✓Inadequate envelope ⟶ energy underestimation ⟶ unfaithful sound

Extension of the codebook with fricative envelopes



- ✓ Increment of the statistical representation of the fricatives
  1. Material composed by /s/ and /z/
  2. Extraction of 8 representatives
  3. Assembly of the new states to the natural 16
  4. Extended codebook, 24 states
     - ❖ Training with transcriptions!

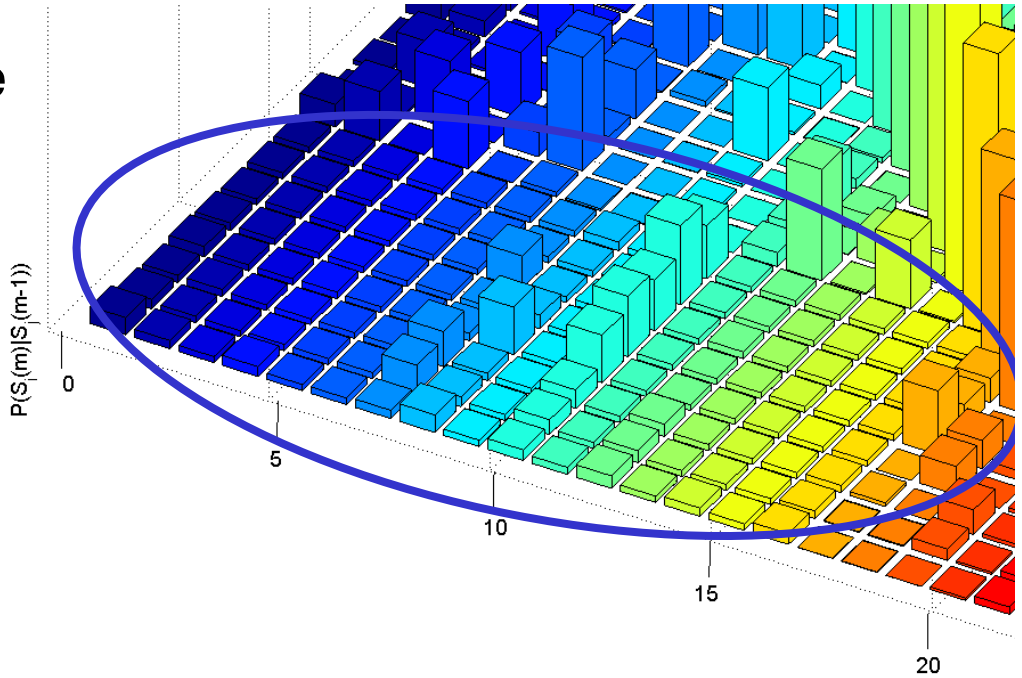
Transition matrix and training with transcriptions



- ✓During the training:
  - ➢Assignment of /s/ and /z/ to the new states
  - ➢Augmented statistics
- ✓Low transition probabilities to and from the new states
  - ➢Transitions delayed:
    - ❖Rise of the envelop (/s/ on-set)
    - ❖Decay of the envelope (/s/ off-set)
    - ❖Lisping effect and high frequency whistling

Transition probability threshold

- ✓Insufficient training material for the new states
- ✓Modification of the HMM transition probability matrix:
  - ➢Adding of 0.01 offset to both rectangles
  - ➢Renormalization
- ✓Enhancement of the transitions from and to the fricative group



Outline

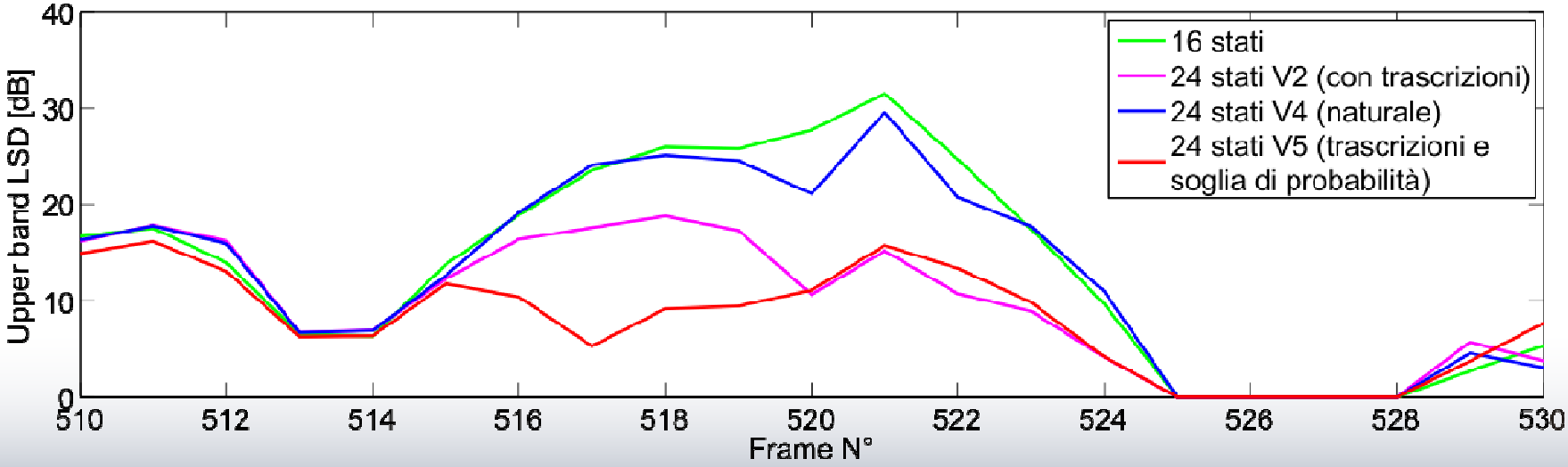
1. The ABWE algorithm
2. Fricative oriented optimization
3. **Log-spectral distortion measures**
   - **Log-spectral distance (LSD)**
   - **Mean distortion**
   - **Audio demo**
4. Conclusions

Log-spectral distance (LSD)

✓Logarithmic distance between the upper band cepstra:

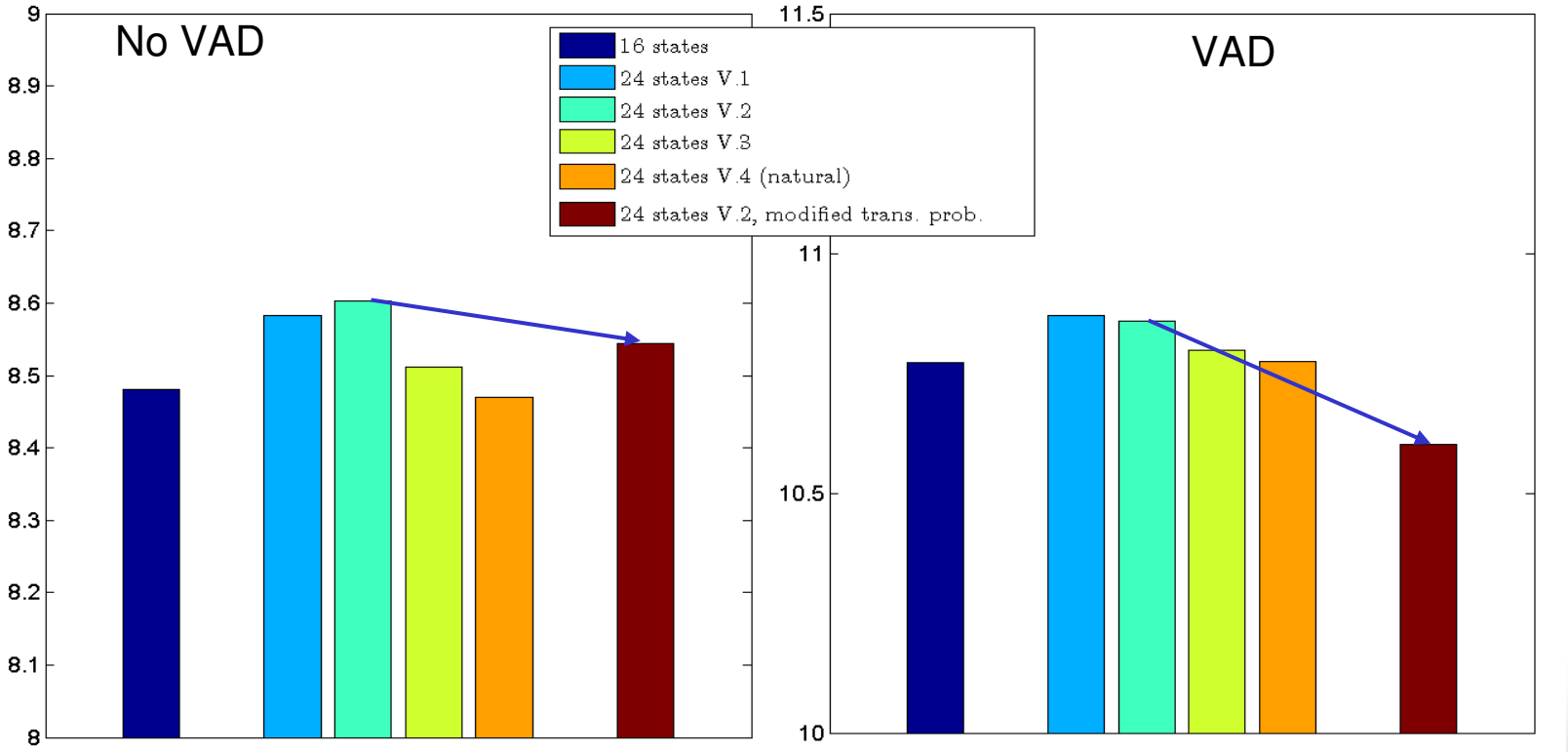
$$d_{\mathrm{lsd}} = \frac{10}{\ln 10} \cdot \sqrt{(c_0 - \tilde{c}_0)^2 + 2\sum_{d=1}^{\infty}(c_d - \tilde{c}_d)}$$

➢Example of distortion during an /s/ sound



Mean distortion

LSD measure on a database without transcriptions



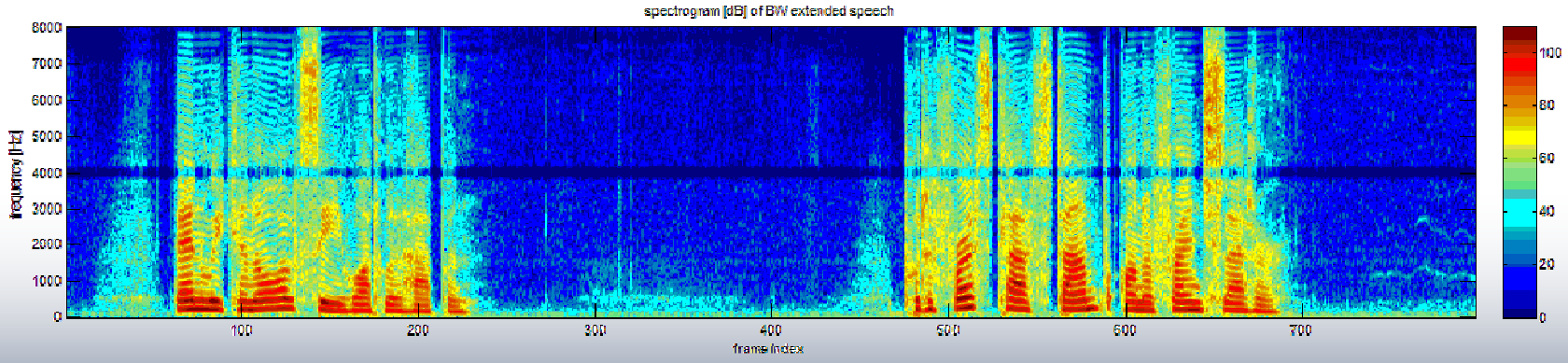
Audio demo

- "Then we can all see what will happen. Put a first class stamp on a French letter"

Narrowband speech

BWE speech - 16 states (no fricative states, natural training)

BWE speech – 24 states (8 fricative states, training with transcriptions and modified HMM transition matrix)



Summary

1. The ABWE algorithm
2. Fricative oriented optimization
3. Log-spectral distortion measures
4. **Conclusions**

Conclusions

- **Changes** to the basic implementation of the BWE:
  - Addition of fricative oriented states
  - Modifications to the training strategies
  - Modification of the HMM transition matrix

- **Result**:
  - HMM has a good reactivity
  - The reproduction of the fricatives is clearer

- **Outlook**:
  - Discriminative training using transcriptions
  - Extension under 300 kHz
  - Study of the offline processing

Thanks for the attention

Any question?

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