Estimation of Bandwidth Extension Parameters in ITU-T G.729.1

— An "Add-on" to the Standard Decoder —

Bernd Geiser and Peter Vary

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Institute of Communication Systems and Data Processing
Prof. Dr.-Ing. Peter Vary

RWTH AACHEN

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Outline

This work has been supported by Siemens AG, Munich, Germany.

- ITU-T G.729.1 — An Overview
- Proposed "Add-on":
  Estimation of TDBWE Parameters
- Results & Demonstration
- Discussion

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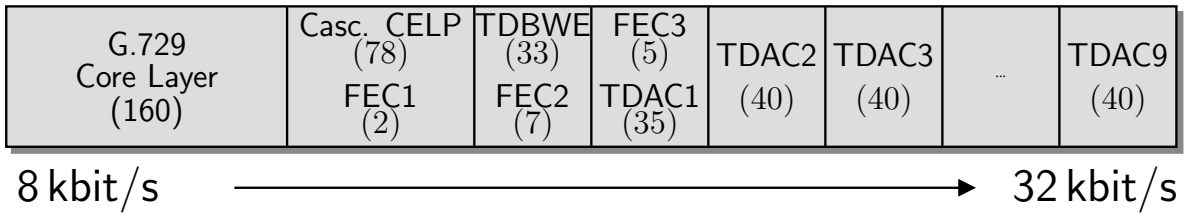
ITU-T G.729.1 — An Overview

▶ Embedded Codec with Hierarchical Bitstream



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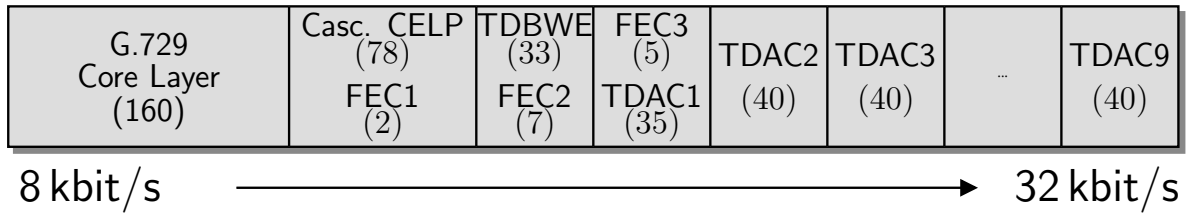

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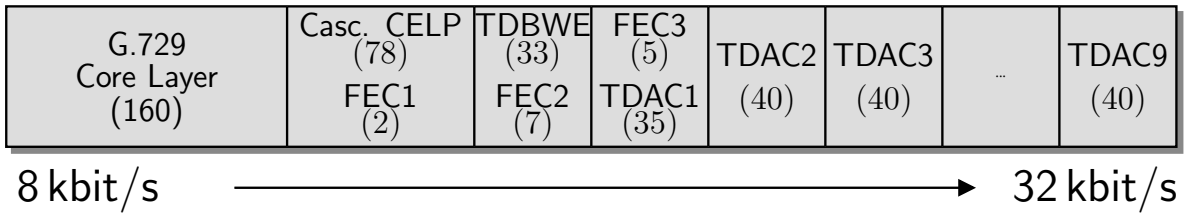

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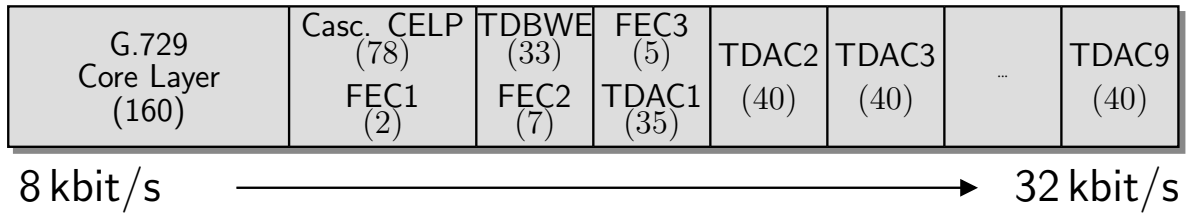

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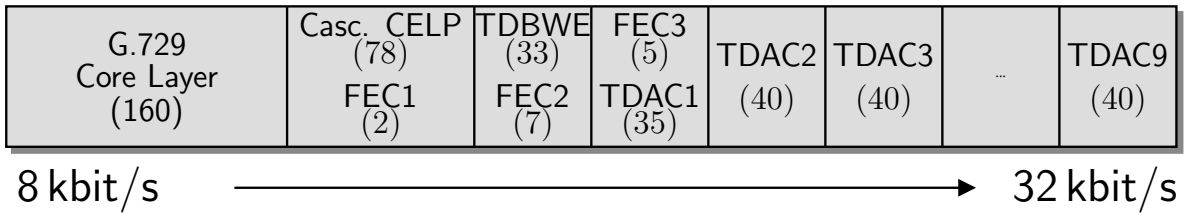

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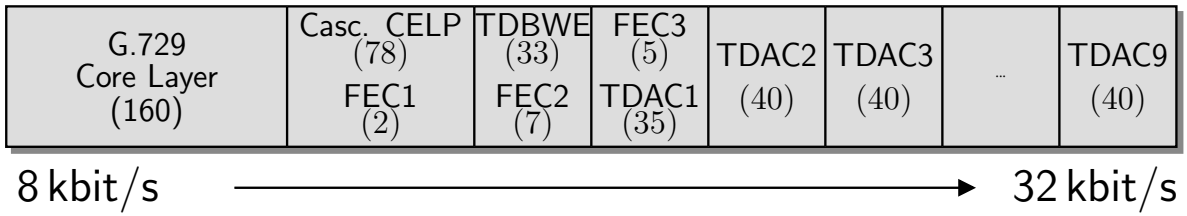

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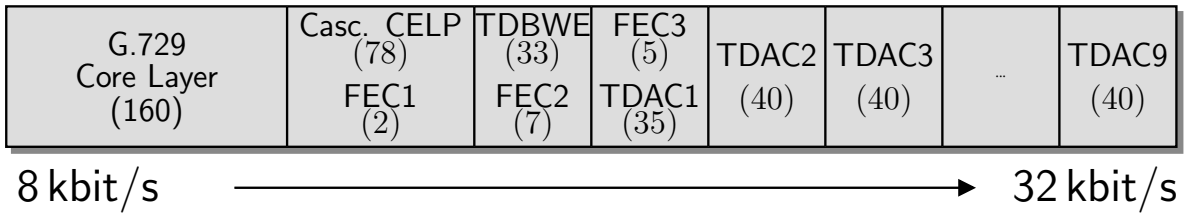

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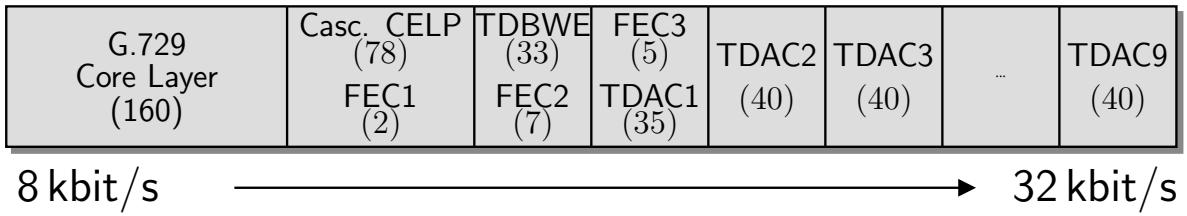

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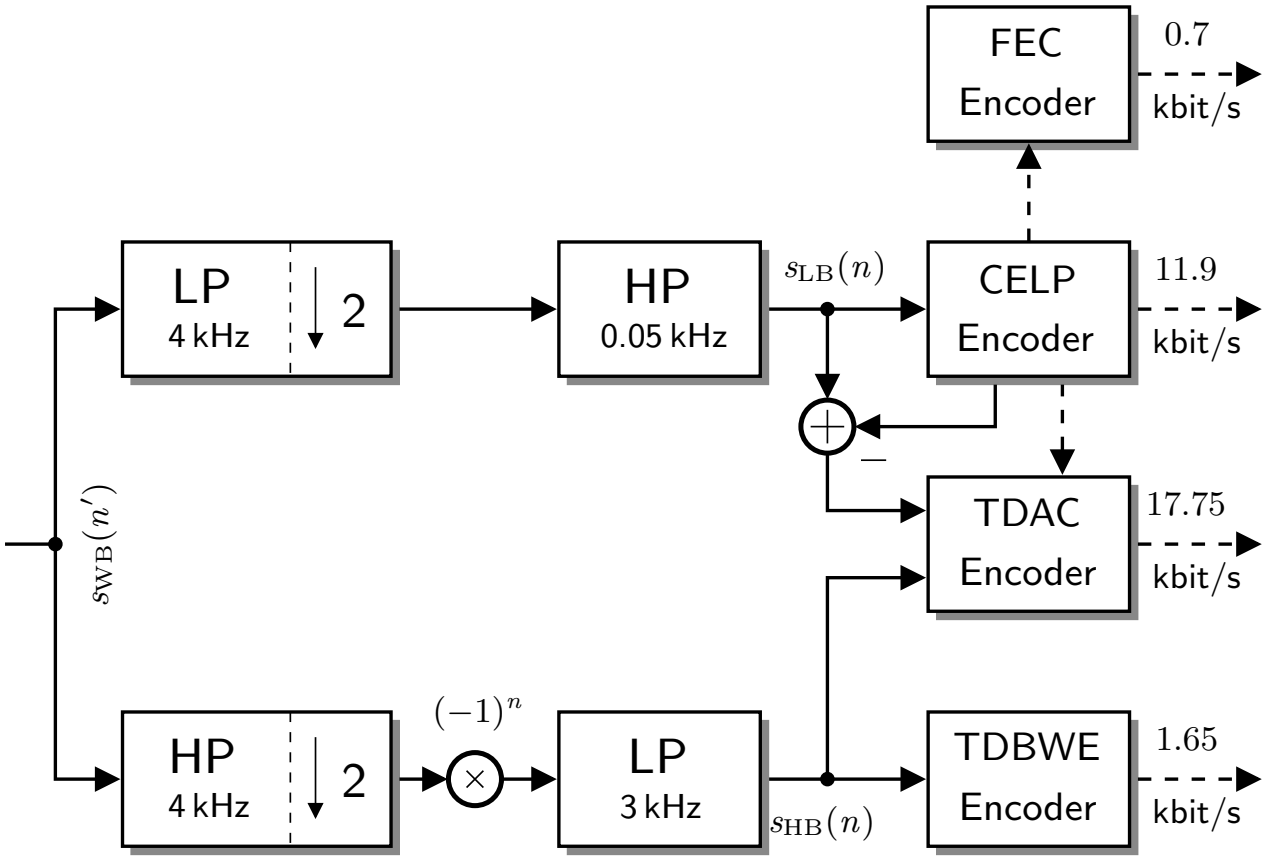

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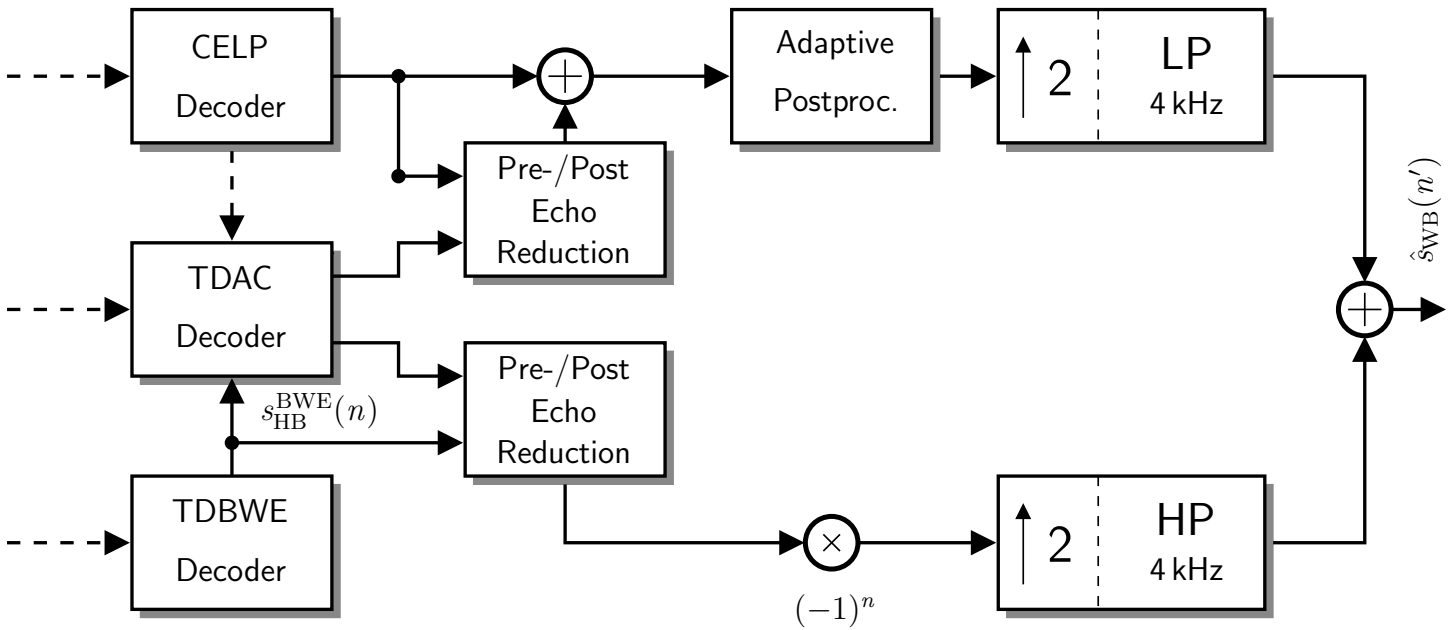

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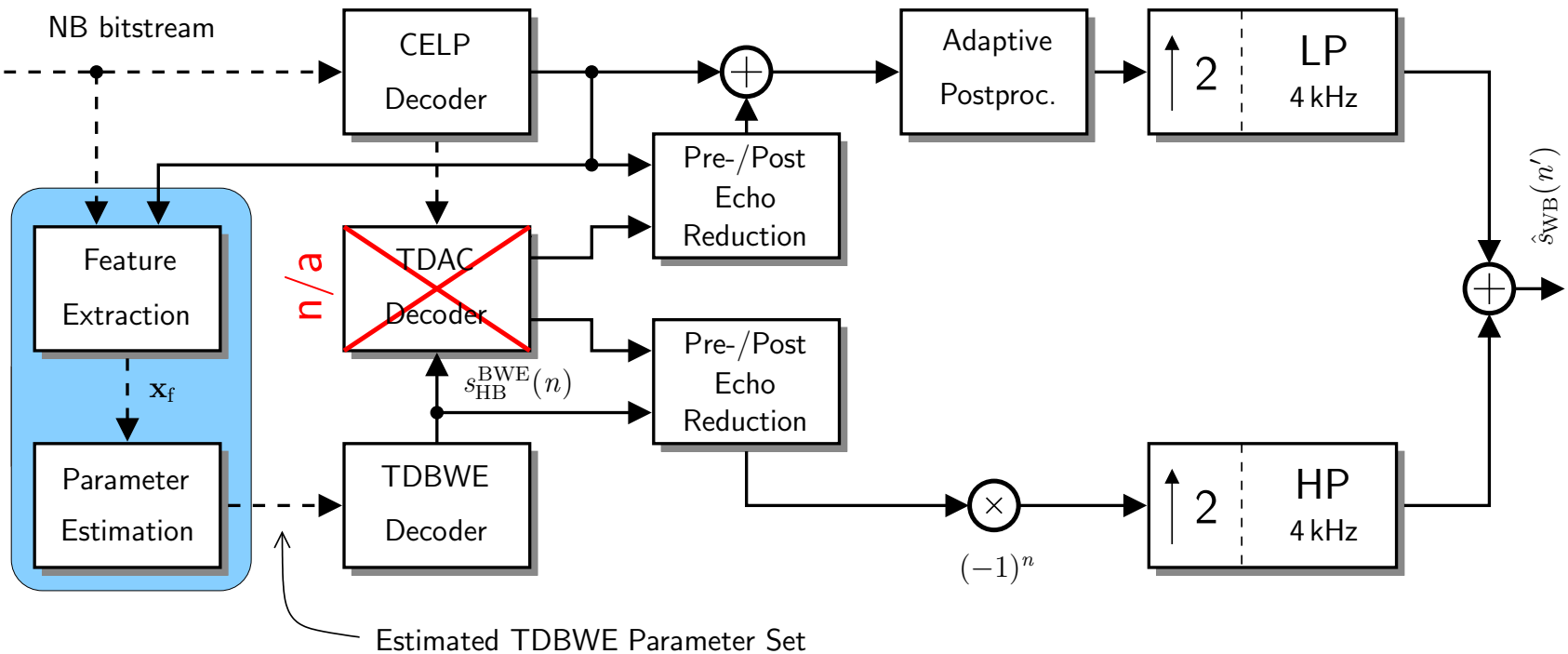
▶ Modified G.729.1 Decoder (8/12 kbit/s)



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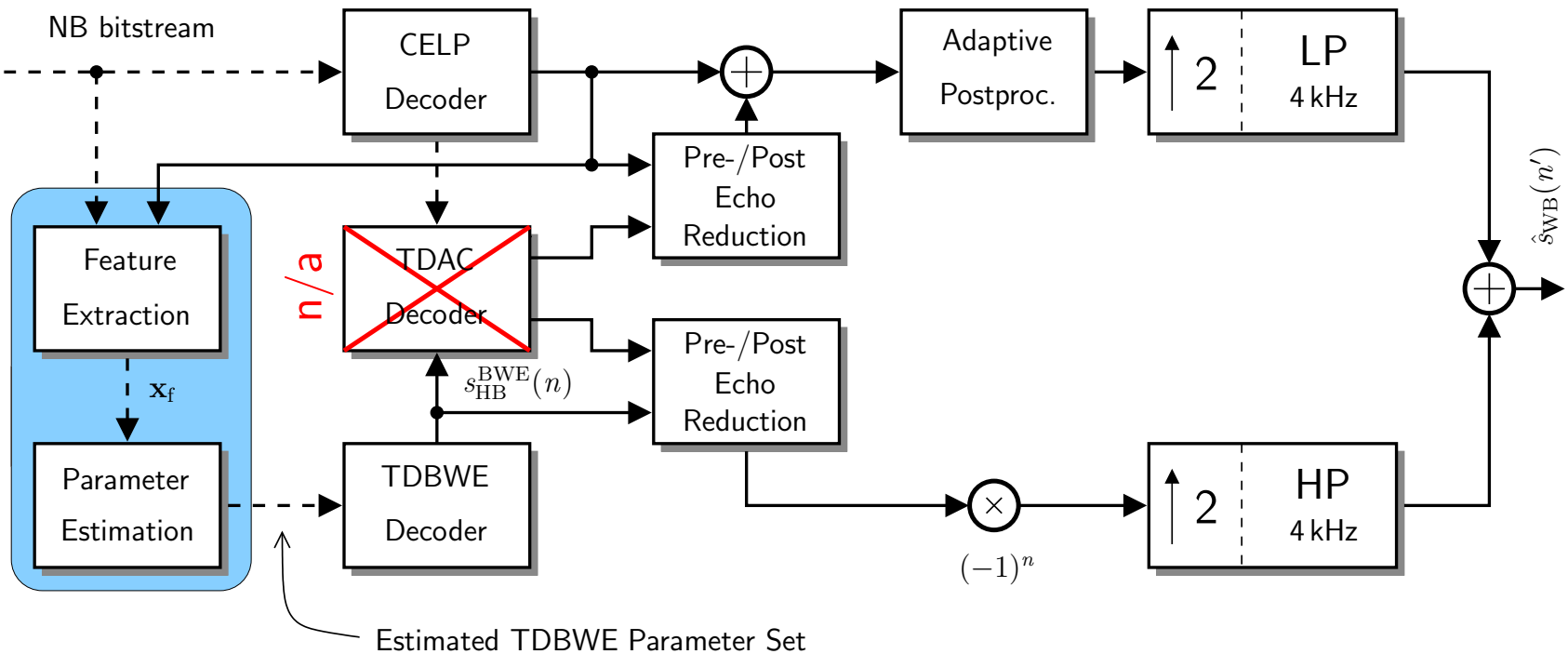

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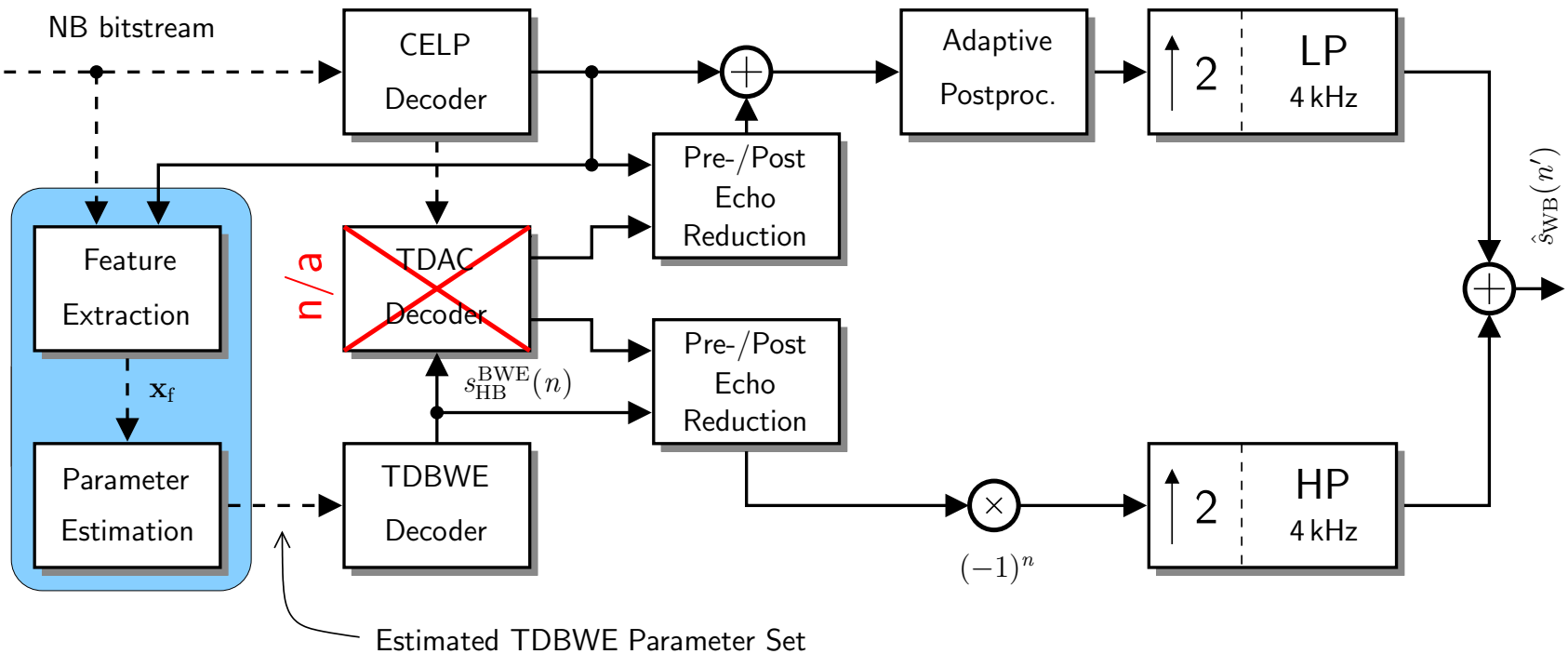

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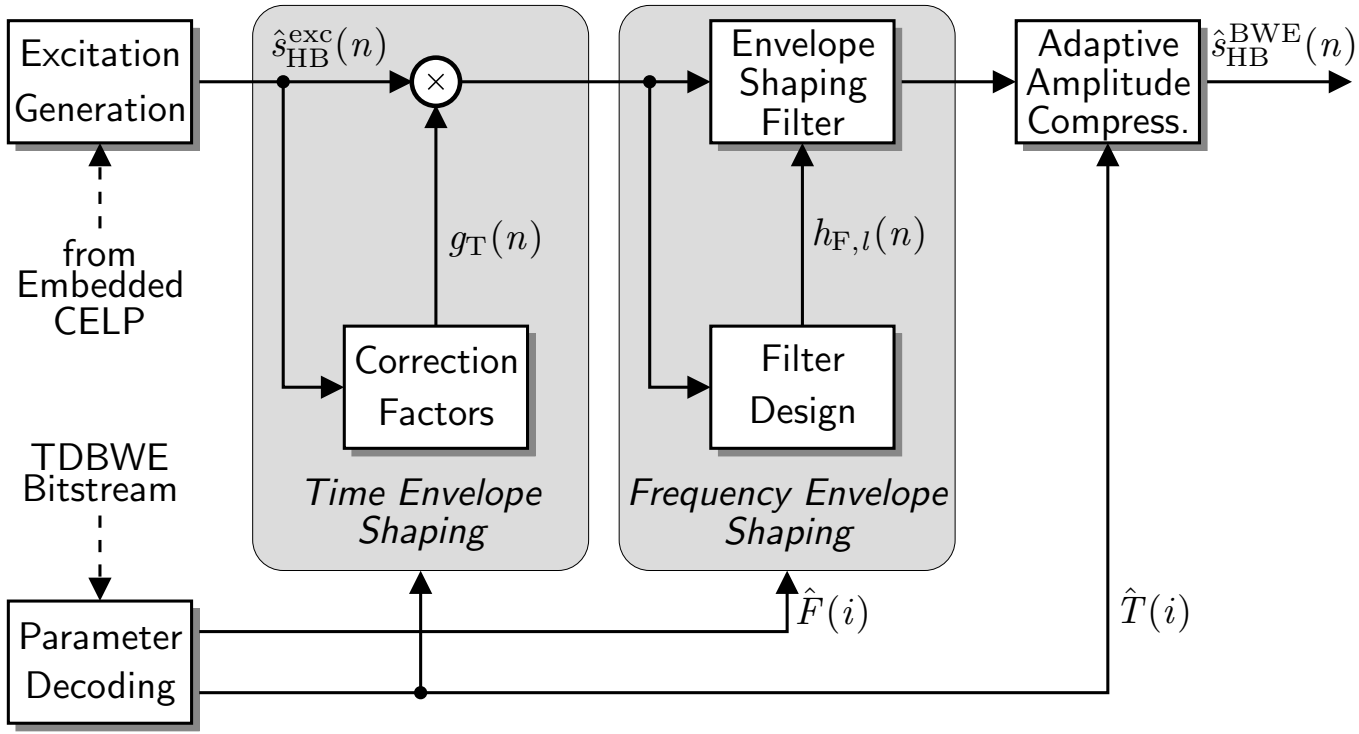

High band (4 kHz – 7 kHz) parameter set (per 20 ms frame):

- "Time envelope" $\mathbf{T}$: 16 sub-frame energies (1.25 ms)
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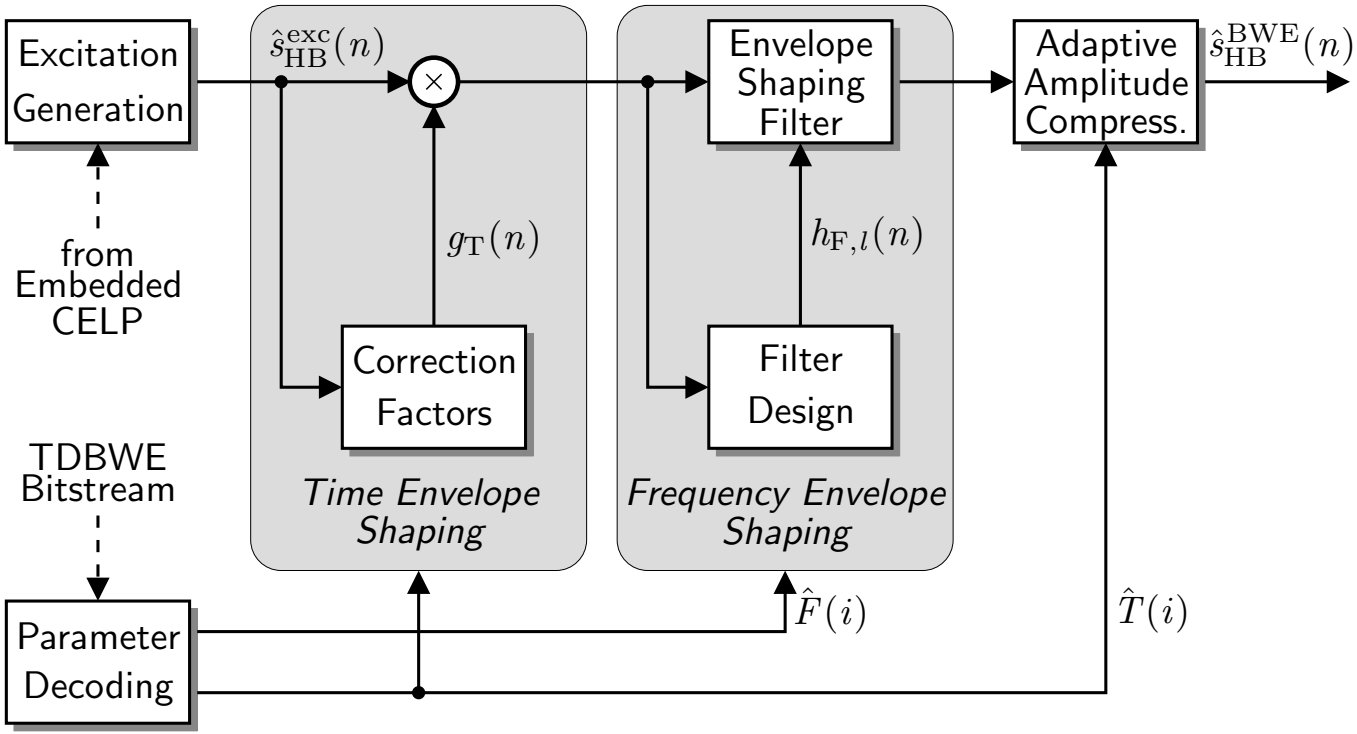

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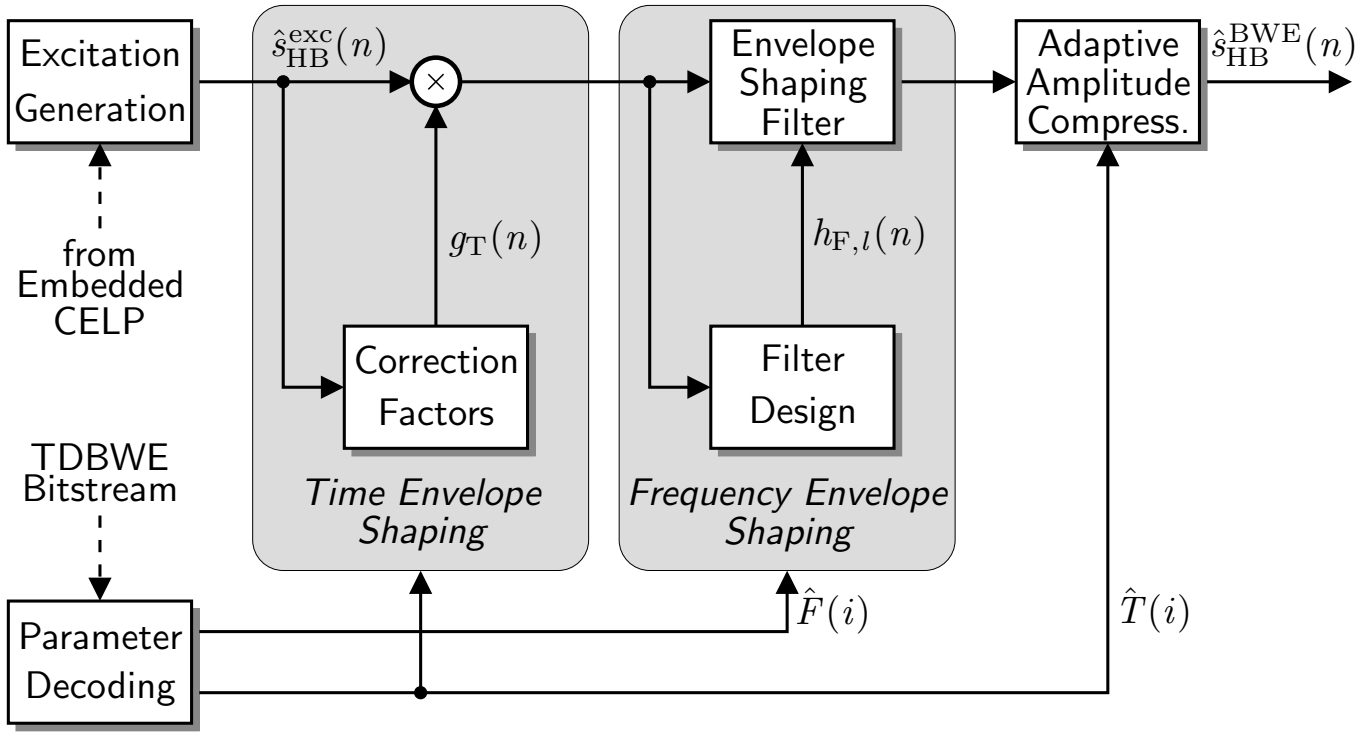

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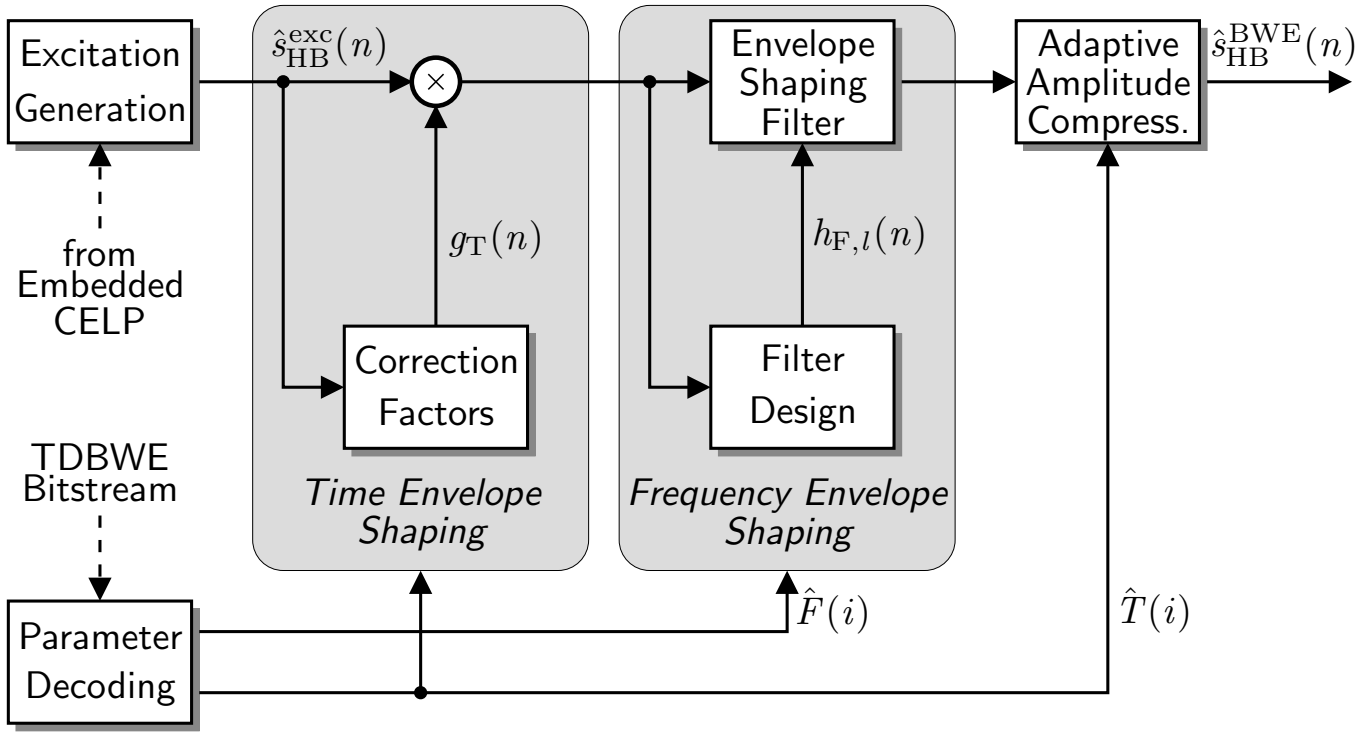

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  - Quantized spectral envelope (LSP vector) of the G.729 core codec
  - Temporal envelope of the low band signal:
    16 sub-frame energies (1.25 ms)
- **Parameter Estimation**
  - MMSE estimation using *a priori* knowledge of 1st order [Jax, Vary 2003]

$$\tilde{\mathbf{y}}_\mathrm{MMSE} = \sum_{\hat{\mathbf{y}}_i \in \mathcal{C}} \hat{\mathbf{y}}_i \cdot P(\hat{\mathbf{y}}_i | \mathbf{X}_\mathrm{f})$$

$\mathbf{y}$: "estimation quantity" ($\mathbf{T}$ or $\mathbf{F}$)
$P(\hat{\mathbf{y}}_i|\mathbf{X}_\mathrm{f})$: "a posteriori" probabilites
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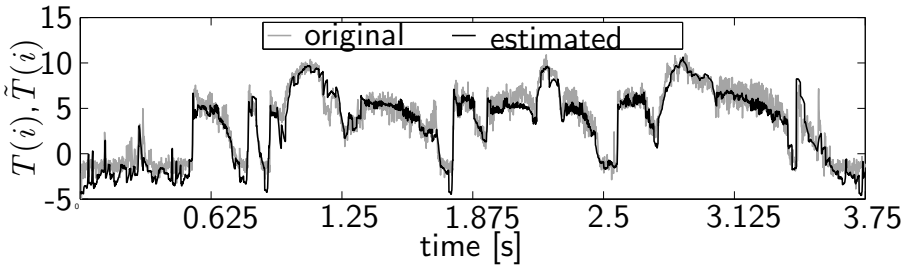

▶ High Band Spectral Distortion (obtained with 8th order AR model)

- **Proposed solution:** *estimated* TDBWE parameters,
  BWE *without* side information $\rightarrow \bar{d}_{\mathrm{LSD}} \approx 5.05\,\mathrm{dB}$
- **Standardized solution:** *quantized* TDBWE parameters,
  BWE with 1.65 kbit/s side information $\rightarrow \bar{d}_{\mathrm{LSD,quant.}} \approx 3.55\,\mathrm{dB}$

▶ Demonstration

G.729.1 bit rate	12 kbit/s	**12 kbit/s with BWE**	14 kbit/s
Speaker 1	🔊	🔊	🔊
Speaker 2	🔊	🔊	🔊

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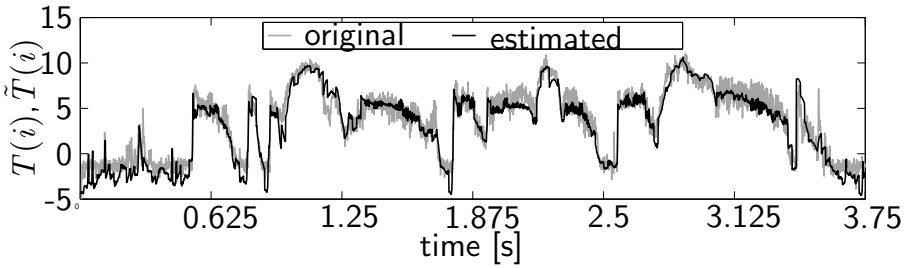

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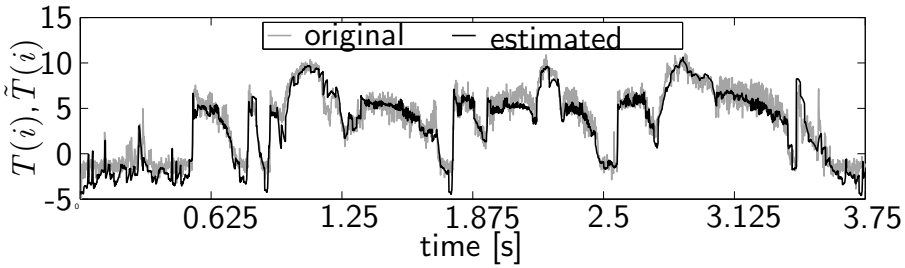

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- Proposal: New *wideband* modes for G.729.1 at 8 and 12 kbit/s
- Estimation of TDBWE parameters based on the narrowband bitstream/signal → Encoder *not modified* (backwards compatible!)
- Band split frequency of 4 kHz leads to improved estimation performance (e.g. identification of fricative sounds)
- Satisfactory wideband speech quality is possible
- Efficient implementation through reuse of G.729.1 components

Application Scenarios:

- Increased speech quality and intelligibility at 8 and 12 kbit/s
- Heterogeneous conference scenario: constant acoustic bandwidth can be provided
- Treatment of bit rate switchings between 12 and 14 kbit/s

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- Proposal: New *wideband* modes for G.729.1 at 8 and 12 kbit/s
- Estimation of TDBWE parameters based on the narrowband bitstream/signal → Encoder *not modified* (backwards compatible!)
- Band split frequency of 4 kHz leads to improved estimation performance (e.g. identification of fricative sounds)
- Satisfactory wideband speech quality is possible
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Application Scenarios:

- Increased speech quality and intelligibility at 8 and 12 kbit/s
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References

ITU-T Rec. G.729.1, "*G.729 based embedded variable bit-rate coder: An 8-32 kbit/s scalable wideband coder bitstream interoperable with G.729*."

S. Ragot et al., "*ITU-T G.729.1: An 8-32 kbit/s scalable coder interoperable with G.729 for wideband telephony and Voice over IP*," in Proc. of IEEE ICASSP, Honolulu, Hawai'i, USA, Apr. 2007.

D. Massaloux et al., "*An 8-12 kbit/s embedded CELP coder interoperable with ITU-T G.729 coder: First stage of the new G.729.1 standard*", in Proc. of IEEE ICASSP, Honolulu, Hawai'i, USA, Apr. 2007.

P. Jax, B. Geiser, S. Schandl, H. Taddei, and P. Vary, "*An embedded scalable wideband codec based on the GSM EFR codec*," in Proc. of IEEE ICASSP, vol. 1, Toulouse, France, May 2006, pp. 5–8.

P. Jax and P. Vary, "*On artificial bandwidth extension of telephone speech*," Signal Processing, vol. 83, no. 8, pp. 1707–1719, Aug. 2003.