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# Control Architecture of the Double-Cross-Correlation Processor (DXCP) for Sampling-Rate-Offset Estimation in Acoustic Sensor Networks

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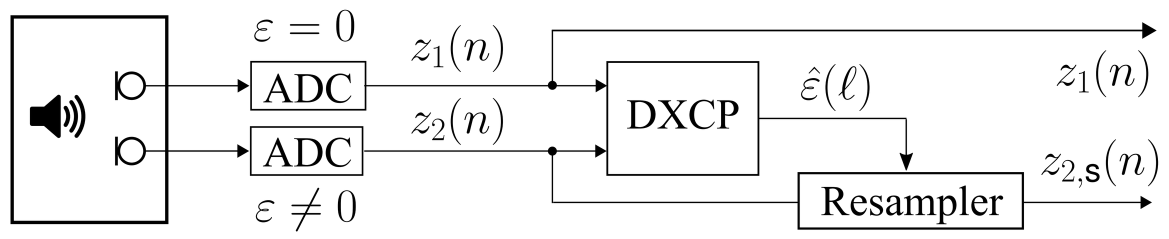
## 1. Preliminaries

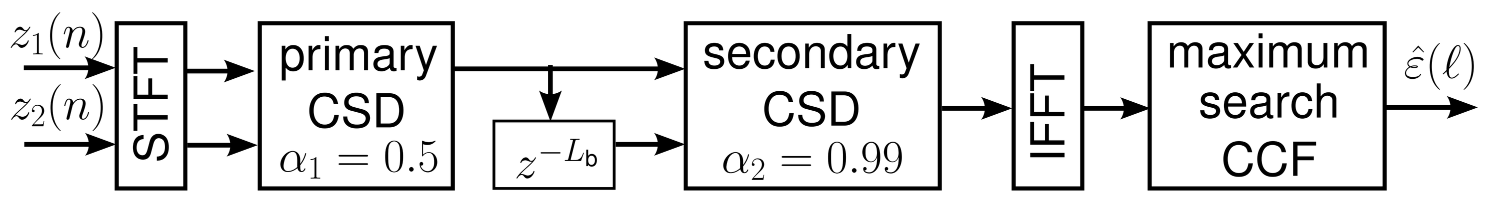
- **Ad-hoc acoustic sensor nodes** with independent clocks
  - Discrete-time signals damaged by **sampling rate offset (SRO)** $\varepsilon$
  - **Time-synchronization** controlled by **SRO assessment** is required
  - **Based on offline DXCP** for SRO estimation [Chinaev et al., 2019]
- Time-synchronization in an **open-loop architecture** using resampling




  - $z_2(n)$ sampled by ADC at a time interval $T_2 = (1+\varepsilon)\cdot T_1$ with SRO $\varepsilon \neq 0$

## 2. Novel online DXCP

- **Blind SRO estimator** in the STFT domain (frame shift of $N_s$ samples)

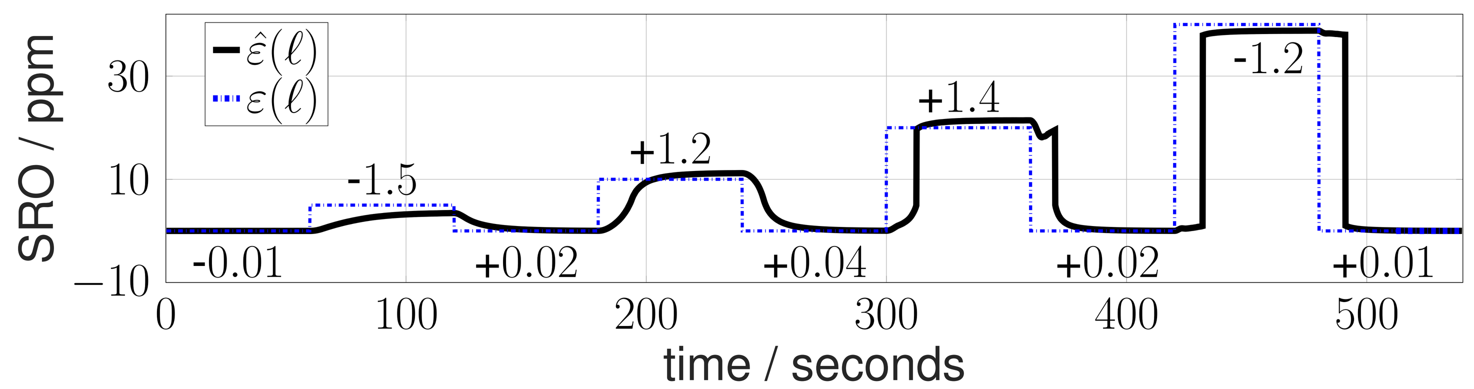



  - Calculation of **primary and secondary** cross spectral density (**CSD**) via **recursive averaging** with smoothing constants $\alpha_1$ and $\alpha_2$:

$$\widetilde{\Phi}_{12}(k,\ell) = \alpha_1 \cdot \widetilde{\Phi}_{12}(k,\ell-1) + (1-\alpha_1)\cdot Z_1(k,\ell)\cdot Z_2^*(k,\ell) \quad (1)$$

$$\widetilde{\Psi}_{12}(k,\ell) = \alpha_2 \cdot \widetilde{\Psi}_{12}(k,\ell-1) + (1-\alpha_2)\cdot \widetilde{\Phi}_{12}(k,\ell)\cdot \widetilde{\Phi}_{12}^*(k,\ell-L_b) \quad (2)$$

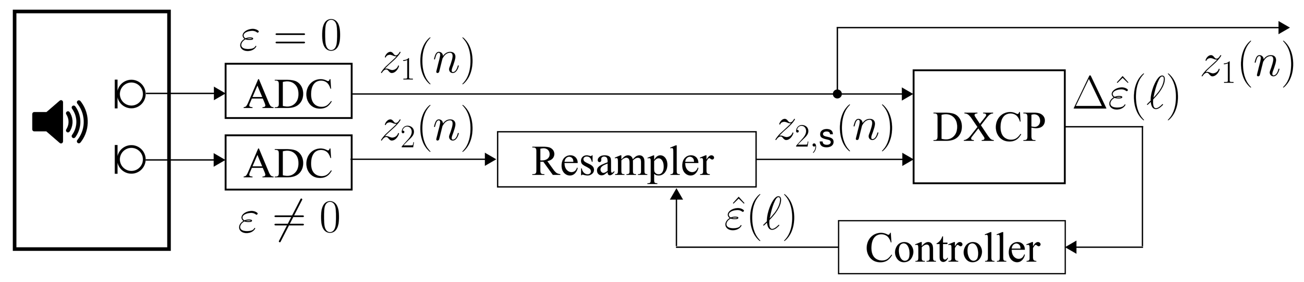
- **Dynamic response** of online DXCP to SRO $\varepsilon \in \{0, 5, 10, 20, 40\}$ ppm



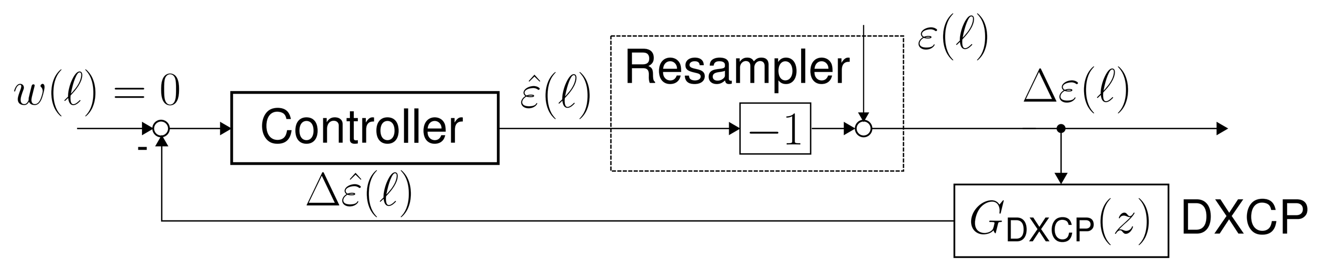

  - **Linear response** ($|\varepsilon| \leq \frac{1}{N_s \cdot L_b}$) and **dead-time behavior** ($|\varepsilon| > \frac{1}{N_s \cdot L_b}$)
  - **Diminishing estimation bias** for SRO $\varepsilon = 0$ ppm $\Rightarrow$ closed-loop

## 3. Closed-loop DXCP with IMC Controller

- Online **closed-loop** DXCP (**CL-DXCP**) with **controlled resampling**




  - **Residual SRO** $\Delta\hat{\varepsilon}(\ell)$ is estimated by DXCP and fed into **controller**
- Block diagram of **CL-DXCP** in the **domain of control signals**



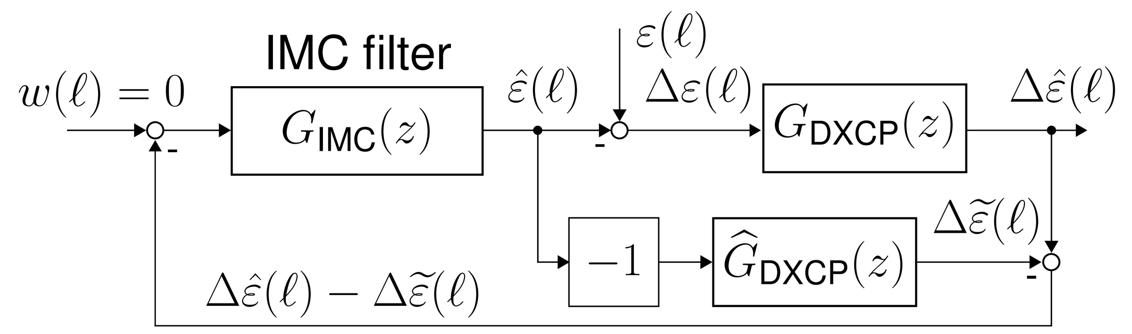

  - For **internal model control** (IMC) theory, DXCP model is required
- **Linear dynamic model** of online DXCP method **in the** $z$**-domain**

$$G_{\mathrm{DXCP}}(z) = \frac{N_s \cdot z}{z-1} \cdot \frac{(1-\alpha_1)\cdot z}{z-\alpha_1} \cdot \frac{z^{L_b}-1}{z^{L_b}} \cdot \frac{(1-\alpha_2)\cdot z}{z-\alpha_2} \cdot \frac{1}{N_s \cdot L_b} \quad (3)$$

  - **Model approximation** determined by the dominant time-constant

$$\widehat{G}_{\mathrm{DXCP}}(z) = \frac{1-\alpha_2}{z-\alpha_2} \quad (4)$$

- Online DXCP in a **IMC control-loop architecture**



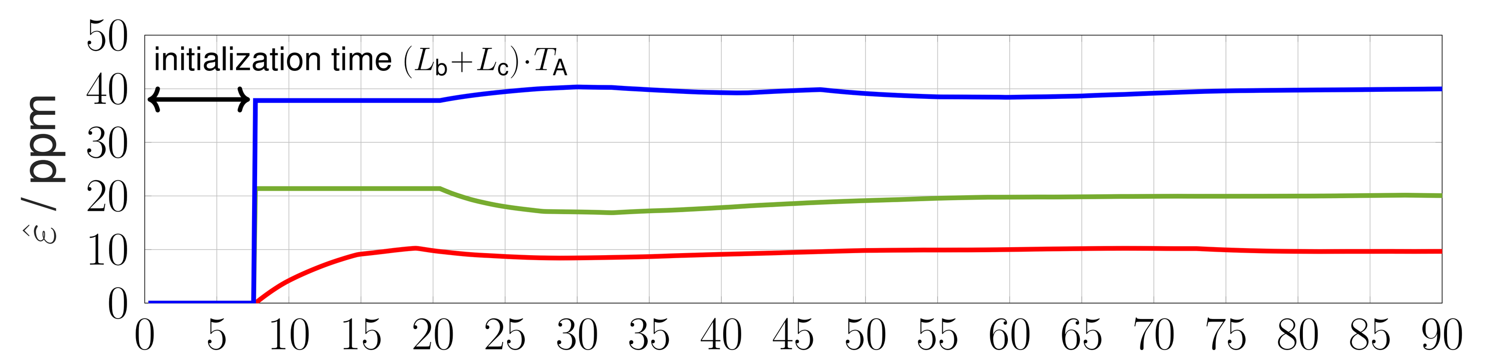

  - Quadratic **minimization** of $\Delta\varepsilon(\ell)$ and **feasibility** of control circuit

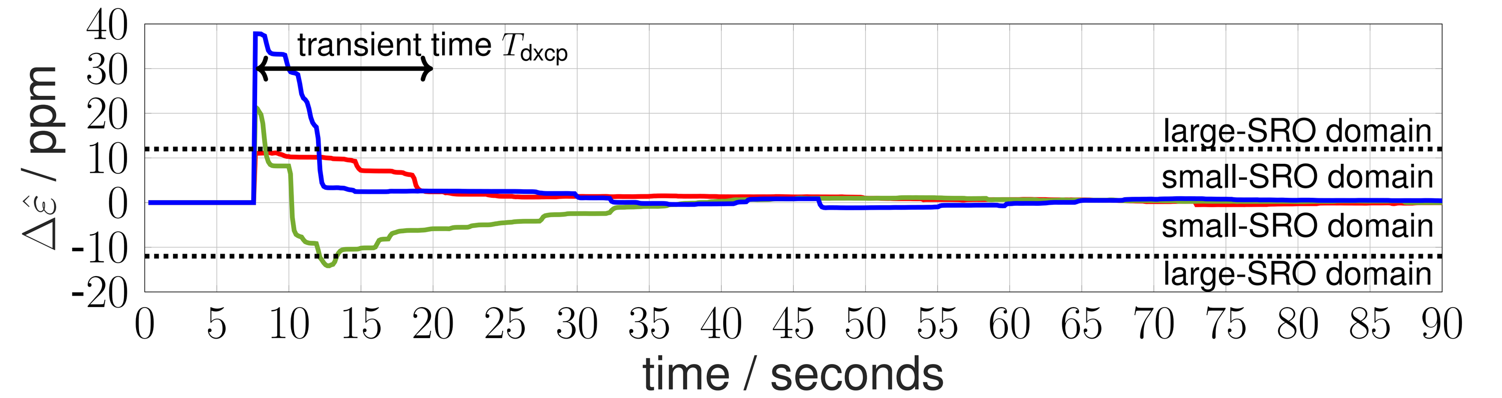
$$G_{\mathrm{IMC}}(z) = -\frac{F(z)}{\widehat{G}_{\mathrm{DXCP}}(z)} \quad \text{with a filter function} \quad F(z) = \left(\frac{1-\beta}{z-\beta}\right)^{n_f} \quad (5)$$

- Online DXCP with **IMC-based feedback-control** is further extended by **detection-based large-SRO feedforward-control path** (see paper)

## 4. Evaluation and Conclusions

- **CL-DXCP:** Convergence of signals $\widehat{\varepsilon}(\ell)$ and $\Delta\widehat{\varepsilon}(\ell)$ for $\varepsilon \in \{10, 20, 40\}$ ppm




  - Both small ($|\Delta\varepsilon| \leq \frac{1}{N_s L_b}$) and large ($|\Delta\varepsilon| > \frac{1}{N_s L_b}$) SRO are **well estimated**
- **Different SRO estimators** $\hat{\varepsilon}$ implemented **in various architectures**

| | architecture and method | online ability | RMSE$_\varepsilon$ / ppm noise | RMSE$_\varepsilon$ / ppm speech | RTF$\times 10^{-3}$ w/ sinc | RTF$\times 10^{-3}$ w/o |
|---|---|---|---|---|---|---|
| open-loop | LCD [Bahari, 2017] | (✓) | 0.86 | 19.86 | 129.7 | 5.3 |
| open-loop | WLCD [Bahari, 2017] | (✓) | 1.41 | 17.50 | 129.7 | 5.4 |
| open-loop | DXCP [Chinaev, 2019] | - | 0.52 | 1.10 | 131.4 | 7.0 |
| open-loop | **prop. online DXCP** | ✓ | 0.94 | **0.59** | 127.1 | **2.7** |
| multi-stage | LCD [Bahari, 2017] | - | $< 0.1$ | 0.32 | 1936.8 | - |
| multi-stage | WLCD [Bahari, 2017] | - | $< 0.1$ | 0.20 | 1292.9 | - |
| multi-stage | WACD [Schmalen., 2017] | - | $< 0.1$ | 0.25 | 1032.6 | - |
| multi-stage | DXCP [Chinaev, 2019] | - | $< 0.1$ | $< 0.1$ | 394.2 | - |
| | **prop. online CL-DXCP** | ✓ | $< 0.1$ | **0.30** | 130.1 | **3.8** |

  - **Low** values of **RMSE** and real-time factor (**RTF**) for proposed DXCP

- **CONCLUSIONS:**
  - Translation of offline DXCP [Chinaev, 2019] to **online DXCP form**
  - Embedding into a **closed-loop internal-model control** architecture **unbiased** as the multi-stage and **efficient** as online processors

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