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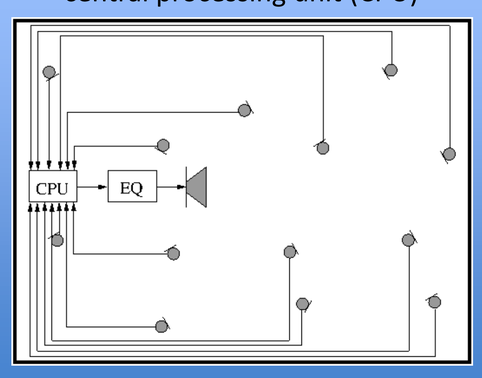
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Distributed Estimation and Equalization of Room Acoustics in a Wireless Acoustic Sensor Network

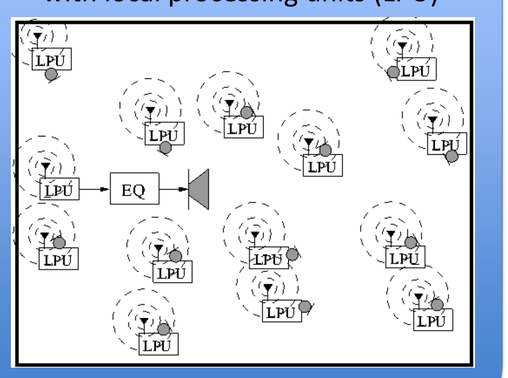
Room Equalization

- Multiple-point room equalization:
  - flattening of room response at large number of listening positions
  - prefilter design by estimation and inversion of acoustic room model

Traditional implementation:
wired microphones connected to central processing unit (CPU)



Proposed implementation:
wirelessly connected microphones with local processing units (LPU)



= wireless acoustic sensor network

Wireless Acoustic Sensor Network (WASN)

- **network** of automonous, battery-driven sensor nodes
- sensor node **capabilities**:
  - sensing: one/more microphones +ADC/DACs
  - processing: local processing unit (LPU)
  - communicating: wireless network connection
- **advantages** compared to wired EQ implementation:
  - flexibility: nodes can be easily added/(re)moved
  - ease of deployment

- **WASN topology**:
  - simple range-based communication model
  - symmetric *M* x *M* sensor connectivity matrix:

$$[\mathbf{C}]_{kl} = \begin{cases} 1, & \text{if } (\mathbf{r}_k - \mathbf{r}_l)^T(\mathbf{r}_k - \mathbf{r}_l) \leq \rho^2 \\ 0, & \text{if } (\mathbf{r}_k - \mathbf{r}_l)^T(\mathbf{r}_k - \mathbf{r}_l) > \rho^2 \end{cases}$$

  - neighborhood of equalization/loudspeaker node:

$$\mathcal{N}_s = \{m | (\mathbf{r}_m - \mathbf{r}_s)^T(\mathbf{r}_m - \mathbf{r}_s) \leq \rho^2\}$$

Room Model

- Measurement model (microphones *m*=1,…,*M*)

$$y_m(t) = H(q, \mathbf{r}_s, \mathbf{r}_m)\, x(t) + v_m(t)$$

Room impulse response (RIR)

- Common-acoustical-pole (CAP) room model

$$H(q, \mathbf{r}_s, \mathbf{r}_m) = \frac{1}{A(q)} \cdot \tilde{H}(q, \mathbf{r}_s, \mathbf{r}_m)$$

CAP model — Residual RIR

- CAP model parameter estimation
  1. estimation of *M* RIRs

$$\hat{H}(q, \mathbf{r}_s, \mathbf{r}_m) = H(q, \mathbf{r}_s, \mathbf{r}_m) + E(q, \mathbf{r}_s, \mathbf{r}_m)$$

RIR estimation error

  2. estimation of CAP model *A(q)*

- Equalization prefilter design:

$$F(q) = \hat{A}(q)$$

CAP Model Parameter Estimation

- Multi-channel least squares CAP model parameter estimation is closely approximated by computationally cheaper **averaging approach** [Haneda *et al.*, 1994]

$$\hat{\mathbf{a}}_{\text{LS}} = \left(\sum_{m=1}^{M} \hat{\mathbf{H}}_m^T \hat{\mathbf{H}}_m \right)^{-1} \left(\sum_{m=1}^{M} \hat{\mathbf{H}}_m^T \hat{\mathbf{h}}_m \right) \approx \sum_{m=1}^{M} \left[\left(\hat{\mathbf{H}}_m^T \hat{\mathbf{H}}_m \right)^{-1} \hat{\mathbf{H}}_m^T \hat{\mathbf{h}}_m \right] = \hat{\mathbf{a}}_{m,\text{LS}}$$

Local, node-specific CAP model estimates

Traditional implementation:
centralized averaging (CAV)

$$\hat{\mathbf{a}}_{\text{CAV}} = \sum_{m=1}^{M} \hat{\mathbf{a}}_{m,\text{LS}}$$

requires network-wide communicaiton

WASN-based implementation:

localized averaging (LAV)

$$\hat{\mathbf{a}}_{\text{LAV}} = \sum_{m \in \mathcal{N}_s} \hat{\mathbf{a}}_{m,\text{LS}}$$

requires local communication around loudspeaker node

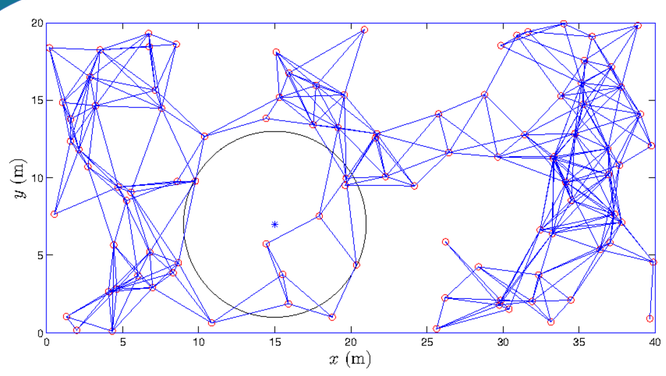
distributed averaging (DAV)

$$\hat{\mathbf{a}}_{\text{DAV}} = \sum_{m \in \mathcal{N}_s} \hat{\mathbf{a}}_{m,\text{FDLA}}^{(k_{\max})}$$

requires local communication around all WASN nodes

- Fast distributed linear averaging (FDLA) algorithm [Xiao & Boyd, 2004]:

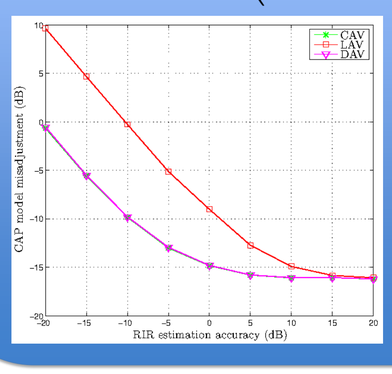
$$\hat{\mathbf{a}}_{m,\text{FDLA}}^{(0)} = \hat{\mathbf{a}}_{m,\text{LS}} \Rightarrow \left[\hat{\mathbf{a}}_{1,\text{FDLA}}^{(k)} \; \cdots \; \hat{\mathbf{a}}_{M,\text{FDLA}}^{(k)} \right] = \left[\hat{\mathbf{a}}_{1,\text{FDLA}}^{(k-1)} \; \cdots \; \hat{\mathbf{a}}_{M,\text{FDLA}}^{(k-1)} \right] \mathbf{W}_{\text{FDLA}}$$

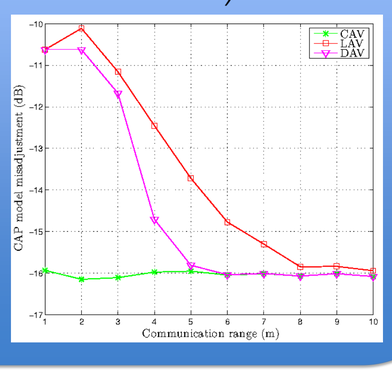


- **Simulated environment:**
  - simulated shoe-box shaped room with WASN comprising *M* = 100 sensor nodes
  - RIR simulation: numerator by image soure method, denominator by pole placement
  - *N* = 100 Monte Carlo trials for random realizations of sensor node positions
  - RIR estimation error simulated by 10 dB AGWN on denominator coefficients
  - WASN communication range = 6 m, FDLA maximum # iterations = 100

Estimation performance: CAP model parameter vector misadjustment

$$10 \log_{10} \left(\frac{1}{N} \sum_{n=1}^{N} \frac{\| \mathbf{a} - \hat{\mathbf{a}}_{\text{(C)(L)(D)AV}}^{(n)} \|_2^2}{\| \mathbf{a} \|_2^2} \right)$$





Equalization performance: Spectral flatness of residual RIR

$$\sum_{n=1}^{N} \sum_{m=1}^{M} \frac{10}{MN} \log_{10} \frac{\exp \left[\frac{1}{L} \sum_{k=0}^{L-1} \ln \left| \tilde{H}^{(n)} \left(e^{j \frac{2\pi k}{L}}, \mathbf{r}_s, \mathbf{r}_m \right) \right|^2 \right]}{\frac{1}{L} \sum_{k=0}^{L-1} \left| \tilde{H}^{(n)} \left(e^{j \frac{2\pi k}{L}}, \mathbf{r}_s, \mathbf{r}_m \right) \right|^2}$$

