ECE ILLINOIS

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Application of the Turbo principle to Underwater Acoustic Communications: Receiver Architectures and Experimental Results

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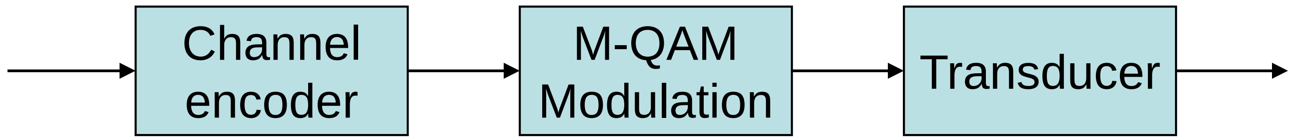
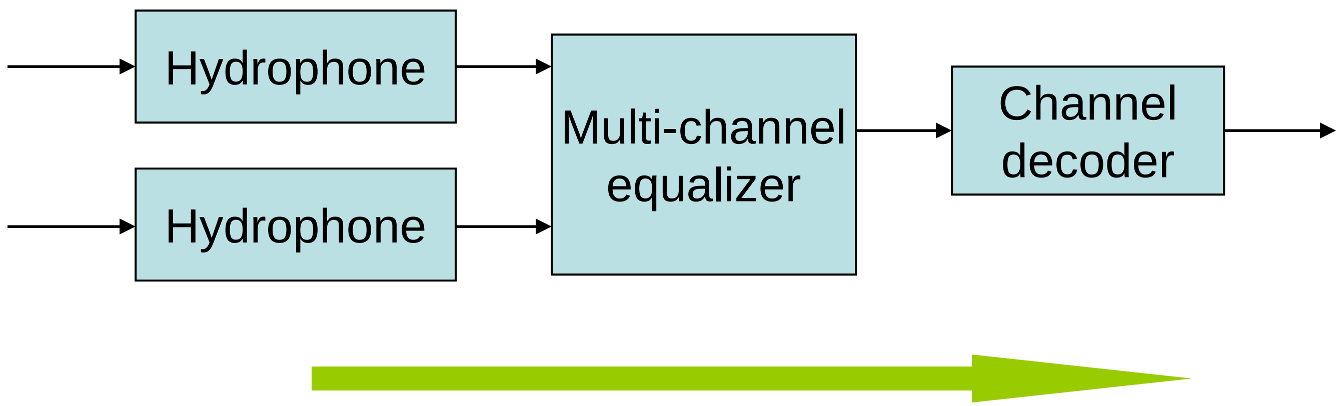
Equalization for underwater comm.

- Conventional equalization
  - Transmitter

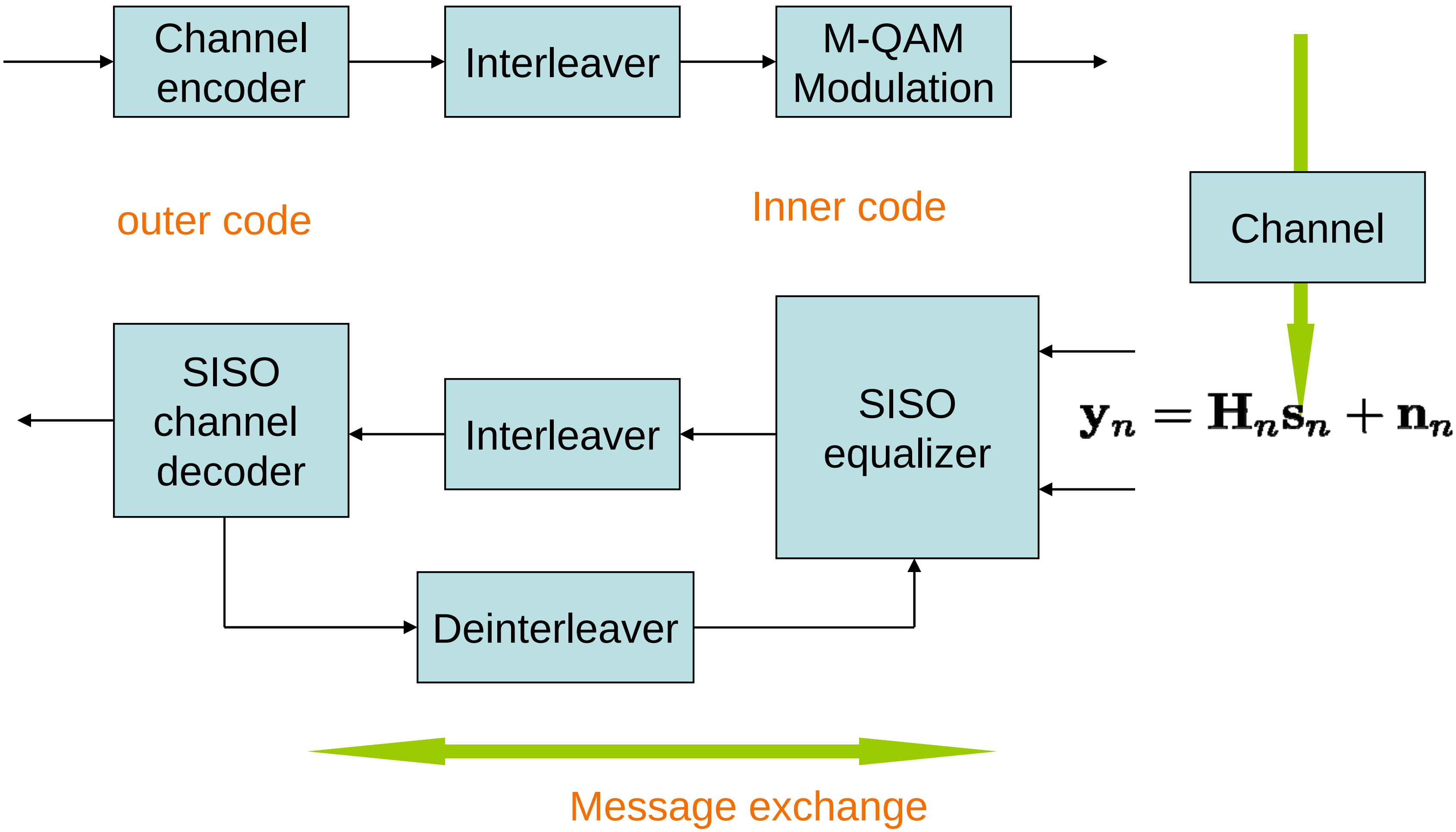


  - Receiver



Turbo principle

- Turbo equalization



Curse of dimensionality

- Consider time-domain equalization for tens of kbit/s transmission
  - Channel length: 50~100
  - Receiver array: 6~10
  - Transducer: 2
  - Processing window: 70~120

$$\mathbf{y}_n = \mathbf{H}_n \mathbf{s}_n + \mathbf{n}_n$$

1200×440 Size of channel matrix H

Even quadratic complexity might be expensive!

Turbo equalization algorithms

- Nonlinear Detectors
  - Exact a posteriori probability (APP) detection
  - List sphere decoding (Hochwald et al.)
  - Message passing algorithm
  - MCMC detection (Chen et al.)

Exponential and sometimes polynomial

- Detectors with linear structure
  - Direct-adaptive turbo equalizer (Laot et al.)
  - Linear MMSE turbo equalizer (Tuchler et al.)
  - Decision-feedback MMSE turbo equalizer (Tuchler et al.)

Polynomial complexity

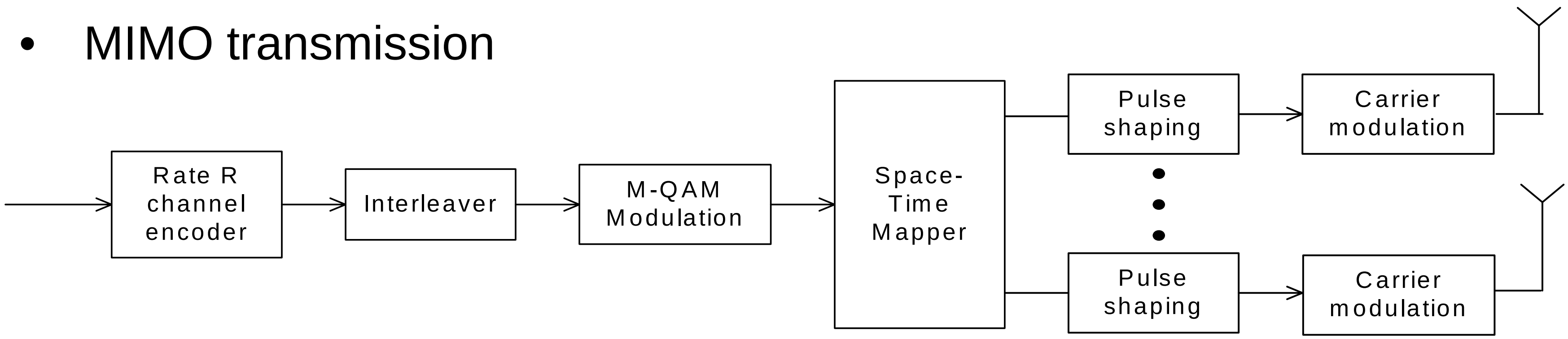
- Hybrid detection algorithms
  - Channel shortening prefilter + message passing equalizer (Roy et. al.)
- Frequency-domain approaches

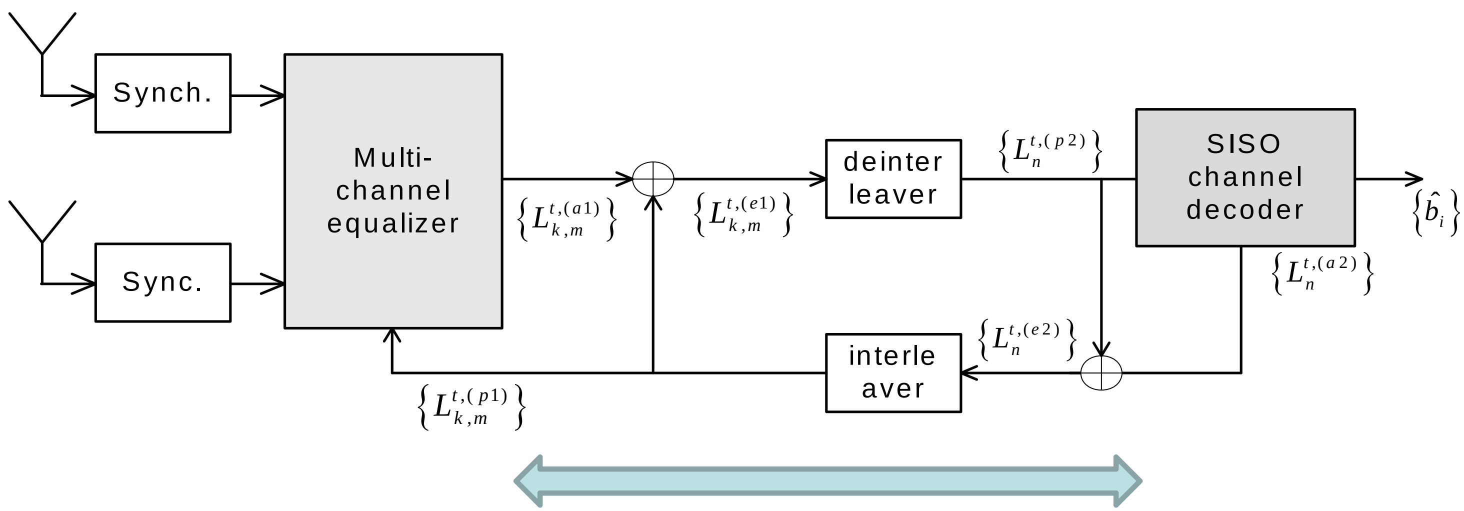
Contributions

- Intensive study on adaptive linear turbo equalizer (ALTEQ)
  - LMS adaptation - linear complexity
  - Compare it with optimal linear-MMSE TEQ
  - Modified ALTEQ to cope with underwater channels
    - Data-reusing adaptation
    - Sparse equalization
- Experimental results
  - SPACE 08
  - Include SIMO (10x1) and MIMO (10x2 ST-BICM) transmission
  - Intensive performance evaluation for ALTEQ

Turbo equalizer for underwater communications

- MIMO transmission





Soft information exchange

Problem description

- Received signal (linear-time-variant system)

$$\mathbf{r}_n = \sum_{k=-K_f}^{K_p} \mathbf{G}_{n,k}\mathbf{x}_{n-k} + \mathbf{w}_n, \qquad L \text{ hydrophones, } N \text{ transducers}$$

- Equivalent system (Observation window-$Nf+Np$)

$$\mathbf{y}_n = \mathbf{H}_n\mathbf{s}_n + \mathbf{n}_n$$

$$\begin{bmatrix} \mathbf{r}_{n+N_f} \\ \vdots \\ \mathbf{r}_{n-N_p} \end{bmatrix} = \begin{bmatrix} \mathbf{G}_{n+N_f,l-K_f} & \cdots & \mathbf{G}_{n+N_p,l+K_p} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \ddots & \cdots & \ddots & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{G}_{n-N_p,l-K_f} & \cdots & \mathbf{G}_{n-N_p,l+K_p} \end{bmatrix} \begin{bmatrix} \mathbf{x}_{n+K_f+N_f} \\ \vdots \\ \mathbf{x}_{n-K_p-N_p} \end{bmatrix} + \begin{bmatrix} \mathbf{w}_{n+N_f} \\ \vdots \\ \mathbf{w}_{n-N_p} \end{bmatrix}$$

- Turbo equalization
  - Estimate the kth symbol of $s_{n,k}$ based on the observation and a probabilistic information on $\mathbf{s}_n$ but except $s_{n,k}$

Adaptive linear turbo equalizer (ALTEQ)

Optimal linear MMSE TEQ

$$\hat{s}_{n,k}^{\text{MMSE}} = \mathbf{z}_n^H \left(\mathbf{y}_n - \mathbf{H}_n \bar{\mathbf{s}}_n + \mathbf{h}_{n,k} \bar{s}_{n,k} \right)$$

$$\mathbf{z}_n = \left(\mathbf{H}_n \boldsymbol{\Sigma}_n \mathbf{H}_n^H + \left(1 - \sigma_{n,k}^2\right) \mathbf{h}_{n,k} \mathbf{h}_{n,k}^H + \mathbf{R} \right)^{-1} \mathbf{h}_{n,k}$$

A priori mean vector $\bar{\mathbf{s}}_n = \left[\bar{s}_{n,1}, \cdots, \bar{s}_{n,K} \right]^T$

A priori covariance matrix

$$\boldsymbol{\Sigma}_n = \text{diag}\left(\sigma_{n,1}^2, \cdots, \sigma_{n,K}^2 \right)$$

$$\hat{s}_{n,k}^{\text{MMSE}} = \mathbf{z}_n^H \mathbf{y}_n - \mathbf{z}_n \left(\mathbf{H}_n \bar{\mathbf{s}}_n - \mathbf{h}_{n,k} \bar{s}_{n,k} \right)$$

Feedforward filter

Soft Feedback filter

CE-based Linear MMSE TEQ

Replace $\mathbf{H}_n$ by $\hat{\mathbf{H}}_n$

ALTEQ

$$\hat{s}_{n,k}^{\text{ALTEQ}} = \mathbf{f}^H \mathbf{y}_n + \mathbf{g}^H \begin{bmatrix} \bar{\mathbf{s}}_{n,1:k-1} \\ \bar{\mathbf{s}}_{n,k+1:K} \end{bmatrix}$$

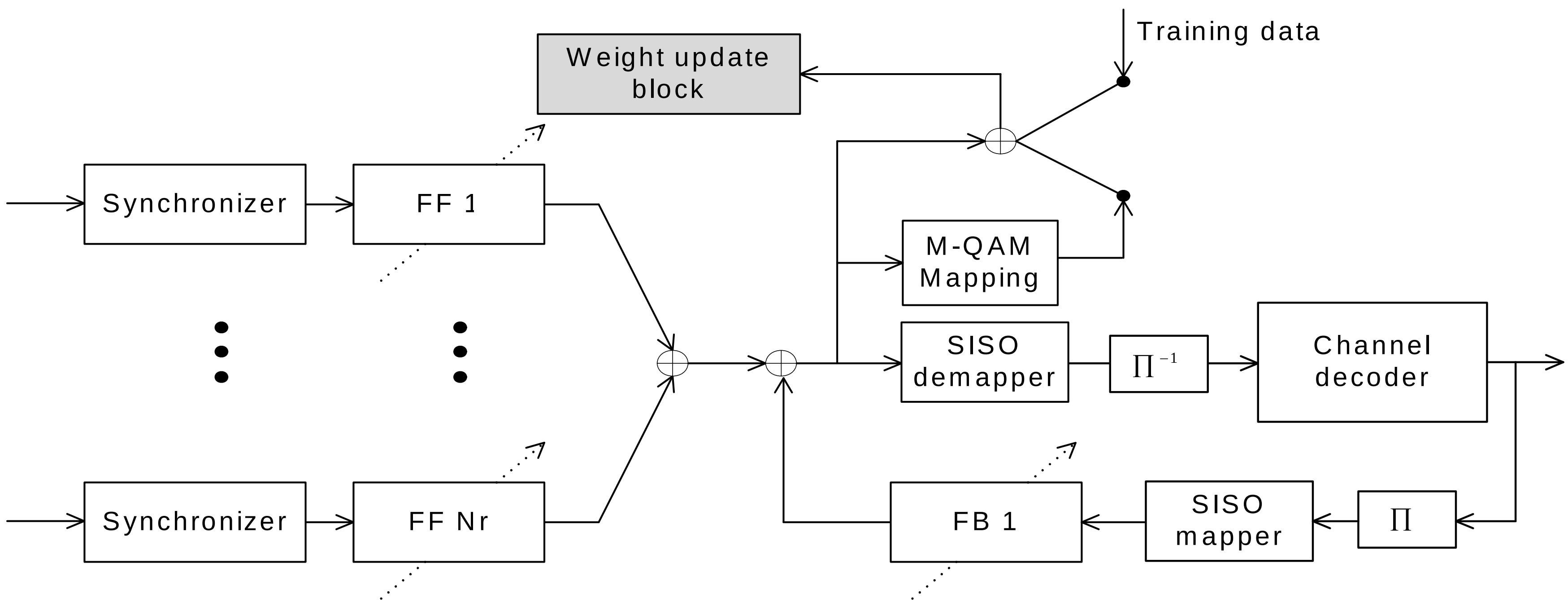
Minimize $E\left[\left| s_{n,k} - \hat{s}_{n,k}^{\text{ALTEQ}} \right|^2 \right]$

LMS update equation

$$\begin{bmatrix} \mathbf{f}^{(n+1)} \\ \mathbf{g}^{(n+1)} \end{bmatrix} = \begin{bmatrix} \mathbf{f}^{(n)} \\ \mathbf{g}^{(n)} \end{bmatrix} + \mu \left(s_{n,k} - \hat{s}_{n,k} \right) \begin{bmatrix} \mathbf{y}_n \\ \bar{\mathbf{s}}_{n,1:k-1} \\ \bar{\mathbf{s}}_{n,k+1:K} \end{bmatrix}$$

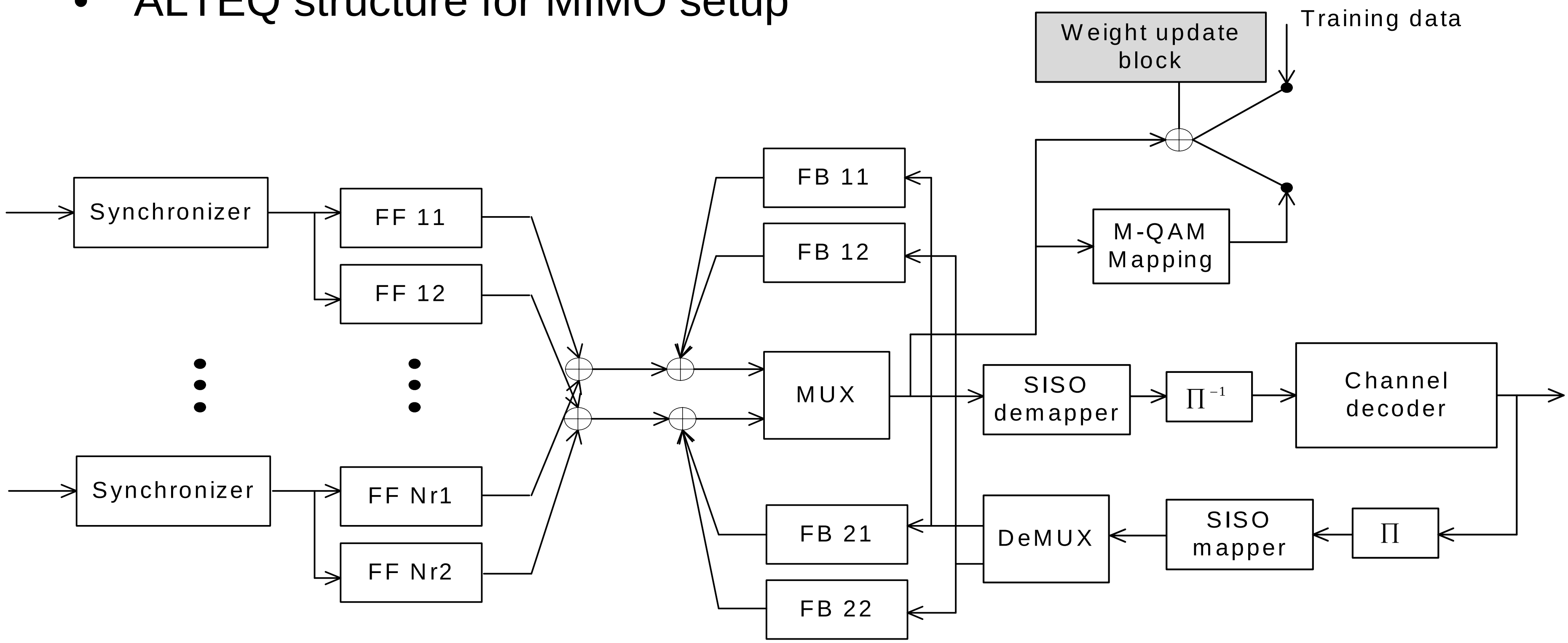
Adaptive linear turbo equalizer (ALTEQ)

- ALTEQ structure for SIMO setup



Adaptive linear turbo equalizer (ALTEQ)

- ALTEQ structure for MIMO setup



Adaptive linear turbo equalizer (ALTEQ)

- Algorithm modifications for LMS ALTEQ
  - For a block of data, LMS weight update is repeated N times. A step size is reduced by a factor of 0.8 every time.
  - Applied sparse equalization algorithm (Stojanovic et al. 1995)

Experiment setups

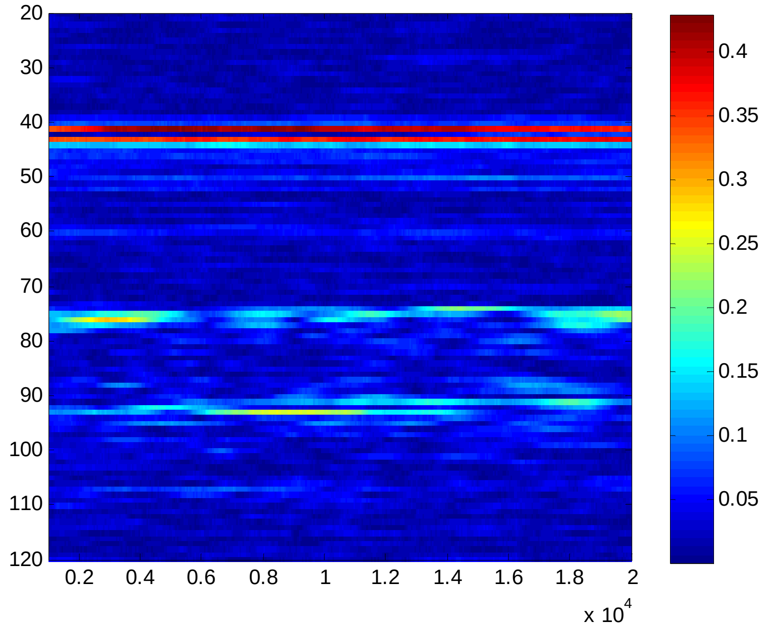
- “SPACE 08” (Martha’s Vinyard, MA, Oct. 14th – Nov. 2nd, 2008)
  - One minute data is transmitted every two hours: 149 epochs
  - Carrier frequency: 13k Hz

- Configurations
  - One frame = 0.2 sec. preambles + 6*(400 training symbols + 1600 data symbols)

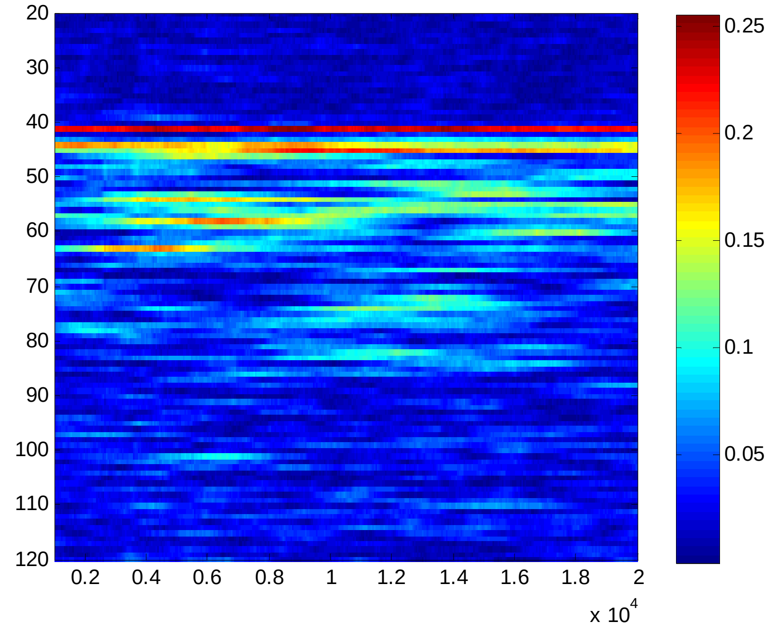
  - Turbo iteration is performed per frame (6400 data symbols)
  - Convolutional code with (23,35) and random interleaver
  - Normalized LMS is used with an initial step size of 0.1
  - LMS weight update is repeated 5 times (data-reuse adaptation)

Results

- Channel estimates



60 meter

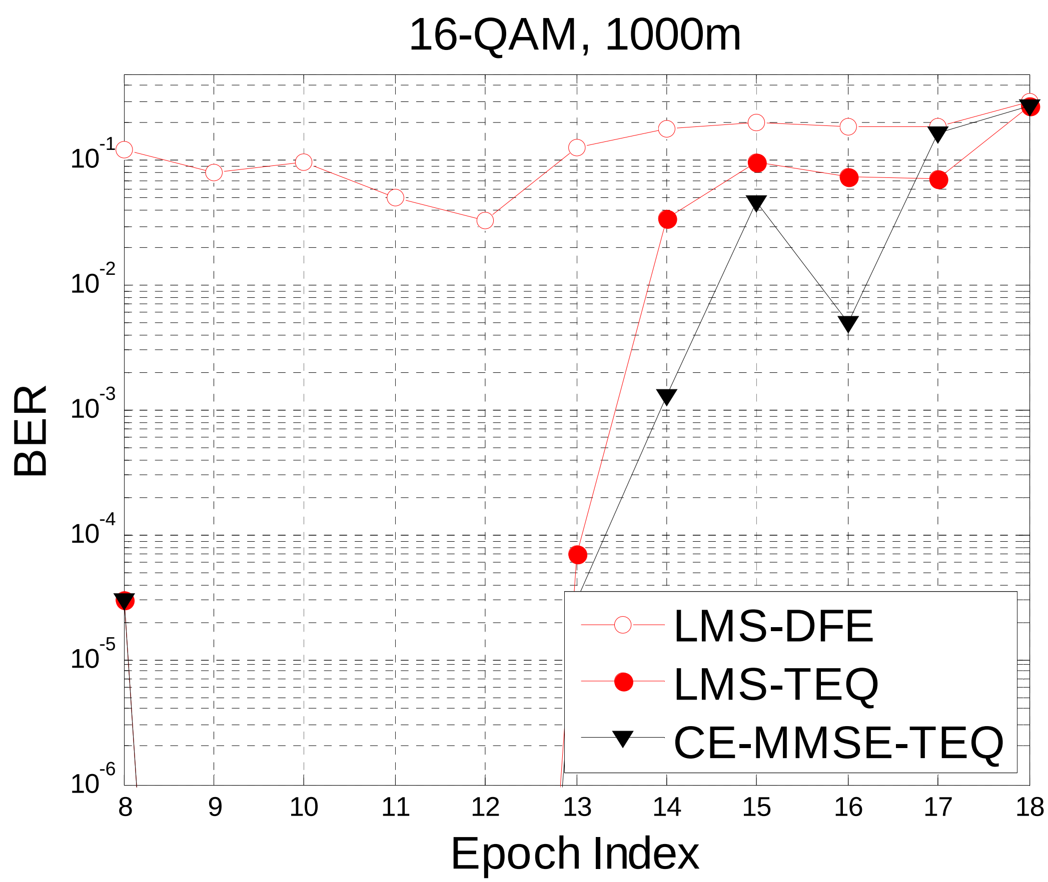


1000 meter

Maximum channel span = 80

Results

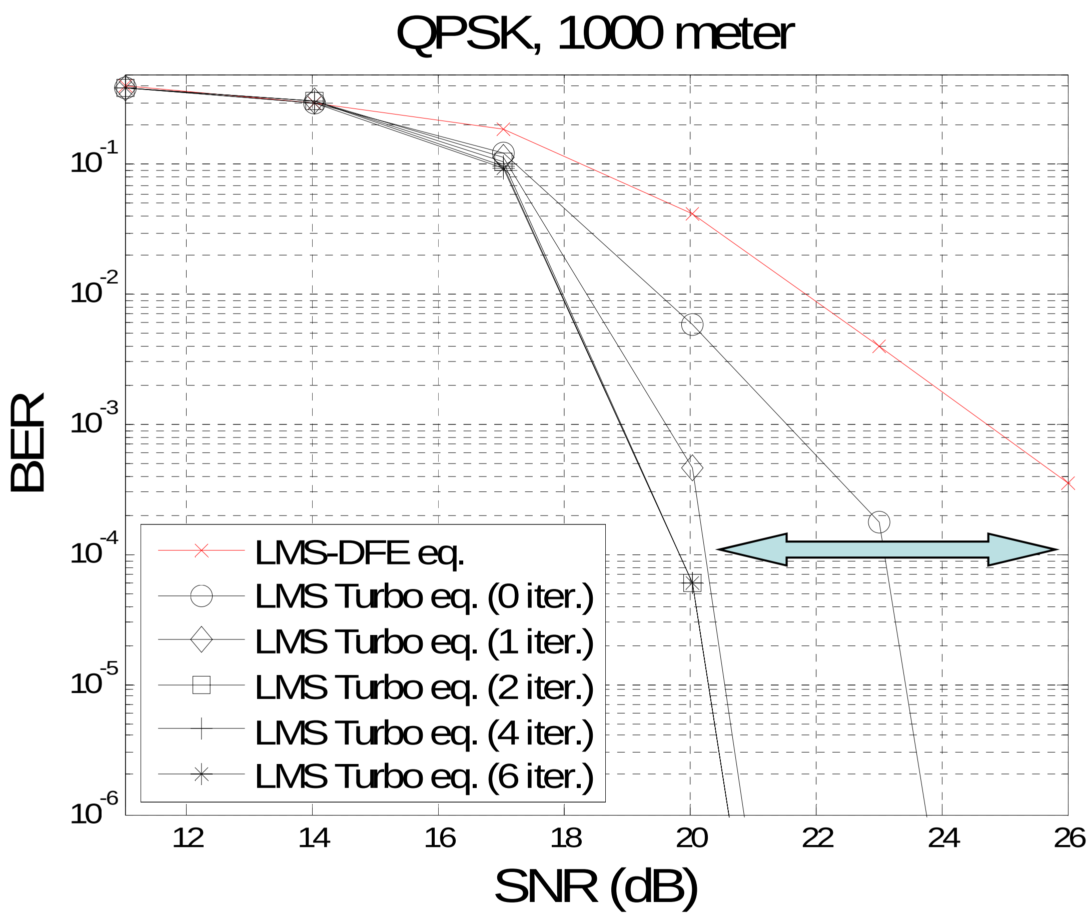
- SIMO case (10x1), 16-QAM
- Symbol rate: 9.77 k sym/s, Data rate: 19.53 kbit/s



After 5 iterations

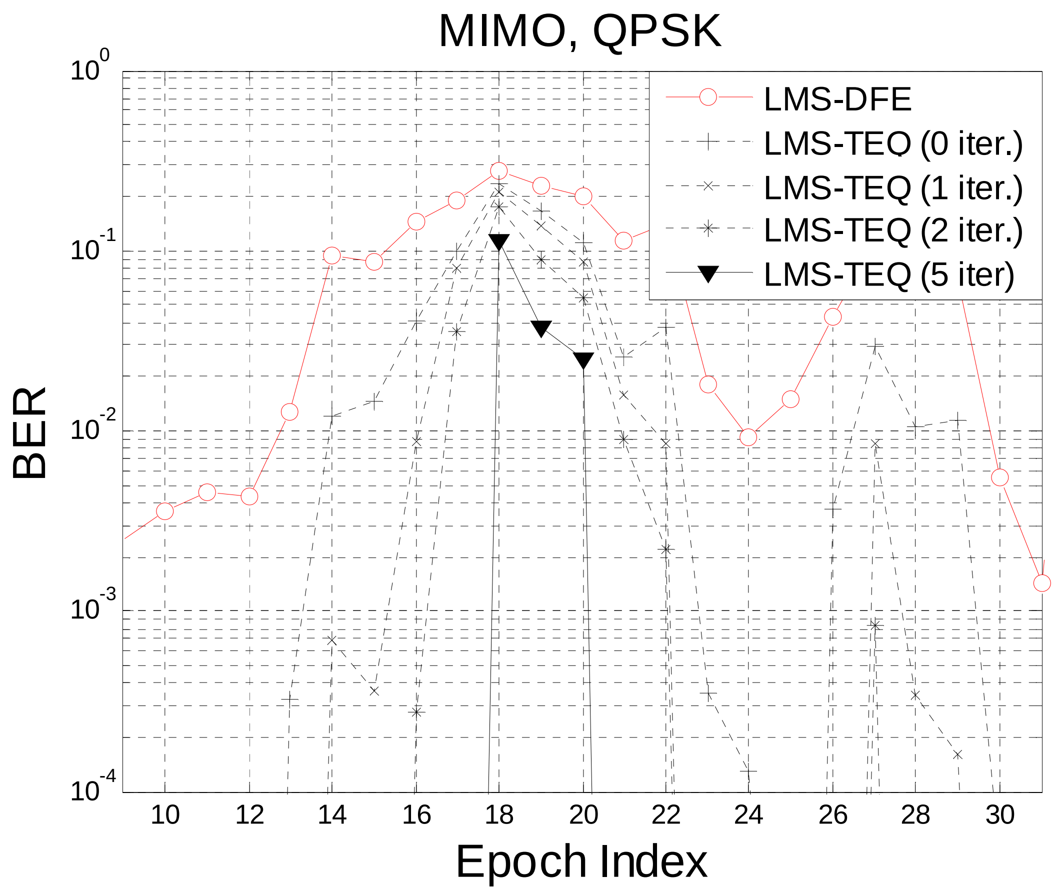
Results

- SIMO case (10x1), QPSK
- For epoch 12, ambient noise is added



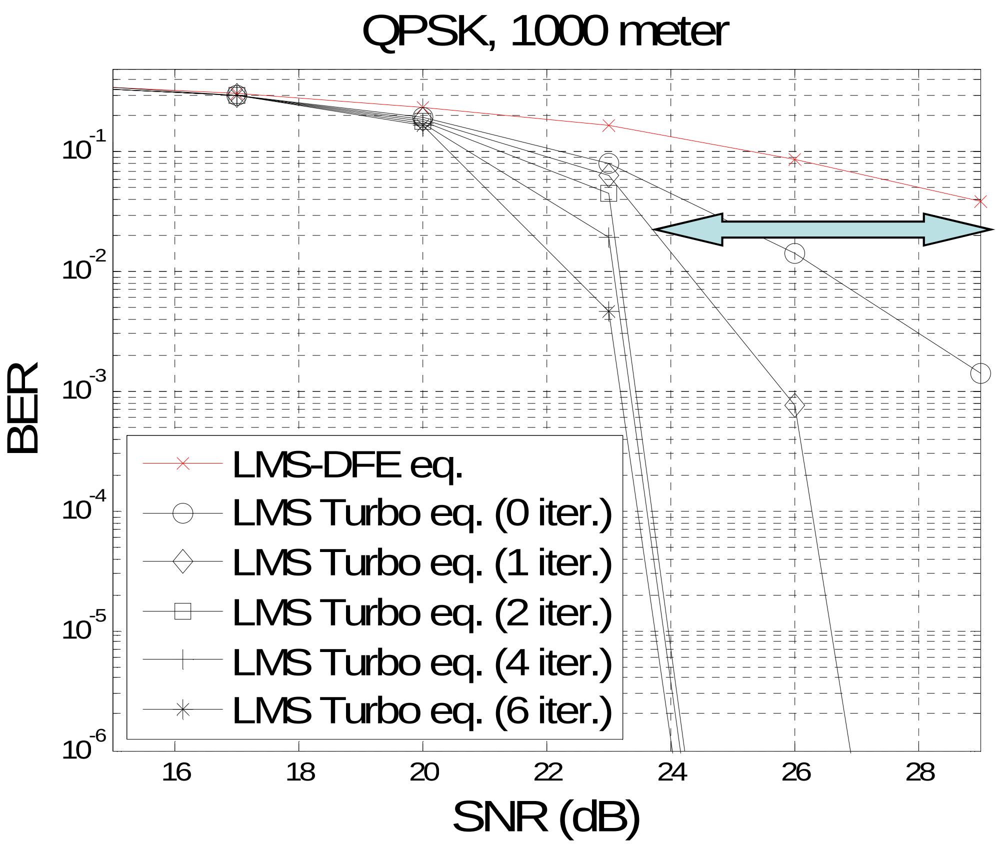
Results

- MIMO case (10x2), QPSK
- Epoch 8-32, data rate: 19.53 kbit/s



Results

- MIMO case (10x2), QPSK
- Epoch 12, ambient noise is added.



Thank you!

Results

– Increase symbol rate versus modulation order

- Results for 5 epochs are averaged.
- SIMO, 1000m

Table 1. The performance of the LMS-TEQ for different symbol rates and modulations.

Mod.	sym/s	No Iter.	Iter. 1	Iter. 2	Iter. 5
BPSK	6.51 k	0.0	0.0	0.0	0.0
	9.77 k	0.0	0.0	0.0	0.0
	19.53 k	0.0002	0.0	0.0	0.0
QPSK	6.51 k	0.0	0.0	0.0	0.0
	9.77 k	0.0	0.0	0.0	0.0
	19.53 k	0.310	0.004	0.002	0.0
16-QAM	6.51 k	0.01	0.0	0.0	0.0
	9.77 k	0.0211	0.0138	0.0108	0.0098
	19.53 k	0.48	0.49	0.51	0.55

Both cases achieve 19.53k bit/s

Comparison

$$\mathbf{\Phi} = \mathrm{diag}\left(E\left[|\bar{s}_{n,1}|^2\right], \cdots, E\left[|\bar{s}_{n,K}|^2\right]\right)$$

- CE-based Linear MMSE TEQ
  - Performance degradation is due to channel estimation error
- ALTEQ
  - Performance degradation is due to excessive MSE and …
  - For locally time-invariant channels $\mathbf{H}_n = \mathbf{H}$, ALTEQ converges to

$$\hat{s}_k^{\mathrm{ALTEQ,SS}} = \mathbf{f}_0^H \left(\mathbf{y}_n - \mathbf{H}\bar{\mathbf{s}}_n + \mathbf{h}_k \bar{s}_{n,k}\right)$$

$$\mathbf{f}_0 = \left(\mathbf{H}\left(\mathbf{I} - \mathbf{\Phi}\right)\mathbf{H}^H + E\left[|\bar{s}_{n,k}|^2\right]\mathbf{h}_k\mathbf{h}_k^H + \mathbf{R}\right)^{-1}\mathbf{h}_k$$

Time-invariant filter

- On the other hand, the optimal linear MMSE-TEQ is

$$\hat{s}_{n,k}^{\mathrm{MMSE}} = \mathbf{z}_n^H \left(\mathbf{y}_n - \mathbf{H}_n\bar{\mathbf{s}}_n + \mathbf{h}_{n,k}\bar{s}_{n,k}\right)$$

$$\mathbf{z}_n = \left(\mathbf{H}\mathbf{\Sigma}_n\mathbf{H}^H + \left(1 - \sigma_{n,k}^2\right)\mathbf{h}_k\mathbf{h}_k^H + \mathbf{R}\right)^{-1}\mathbf{h}_k$$

Time-variant filter

  - With iterations, the gap decreases

$$\mathbf{\Sigma}_n \to \mathbf{0}, \quad \mathbf{\Phi} \to \mathbf{I}$$

Exit-chart analysis