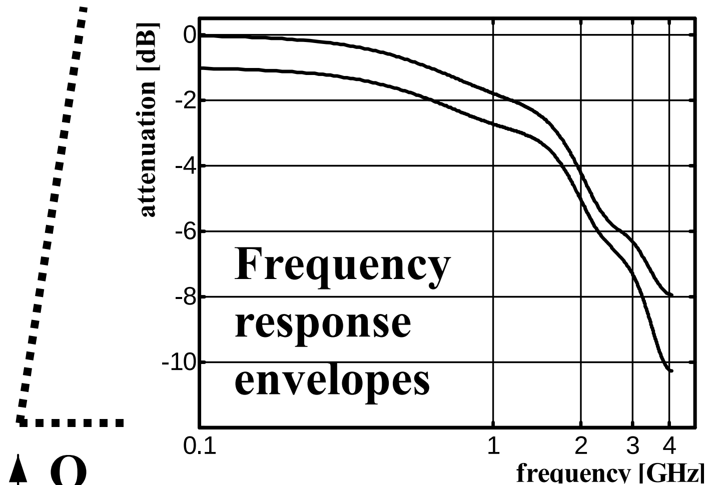
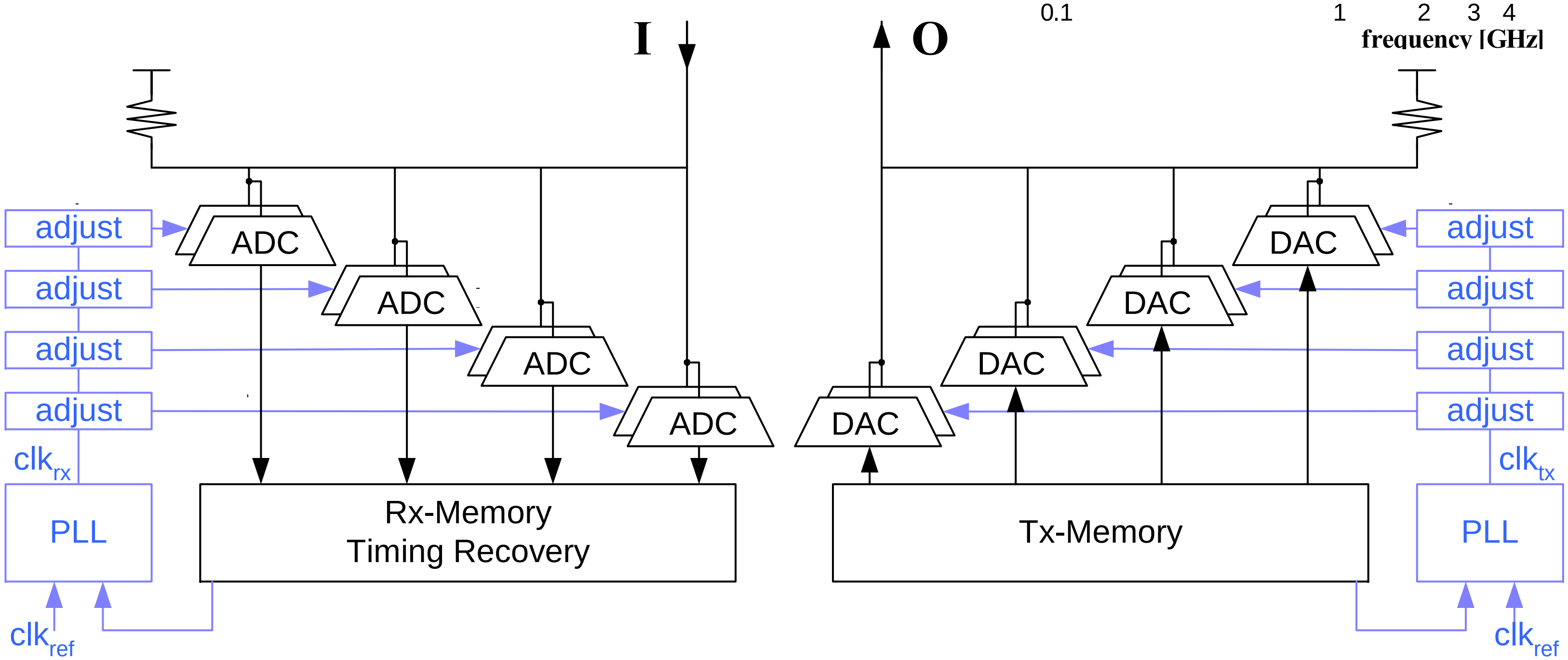
# Transmit Pre-emphasis for High-Speed Time-Division-Multiplexed Serial Link Transceiver

Vladimir Stojanović, George Ginis, Mark A. Horowitz
Stanford University

# High-speed Link Transceiver

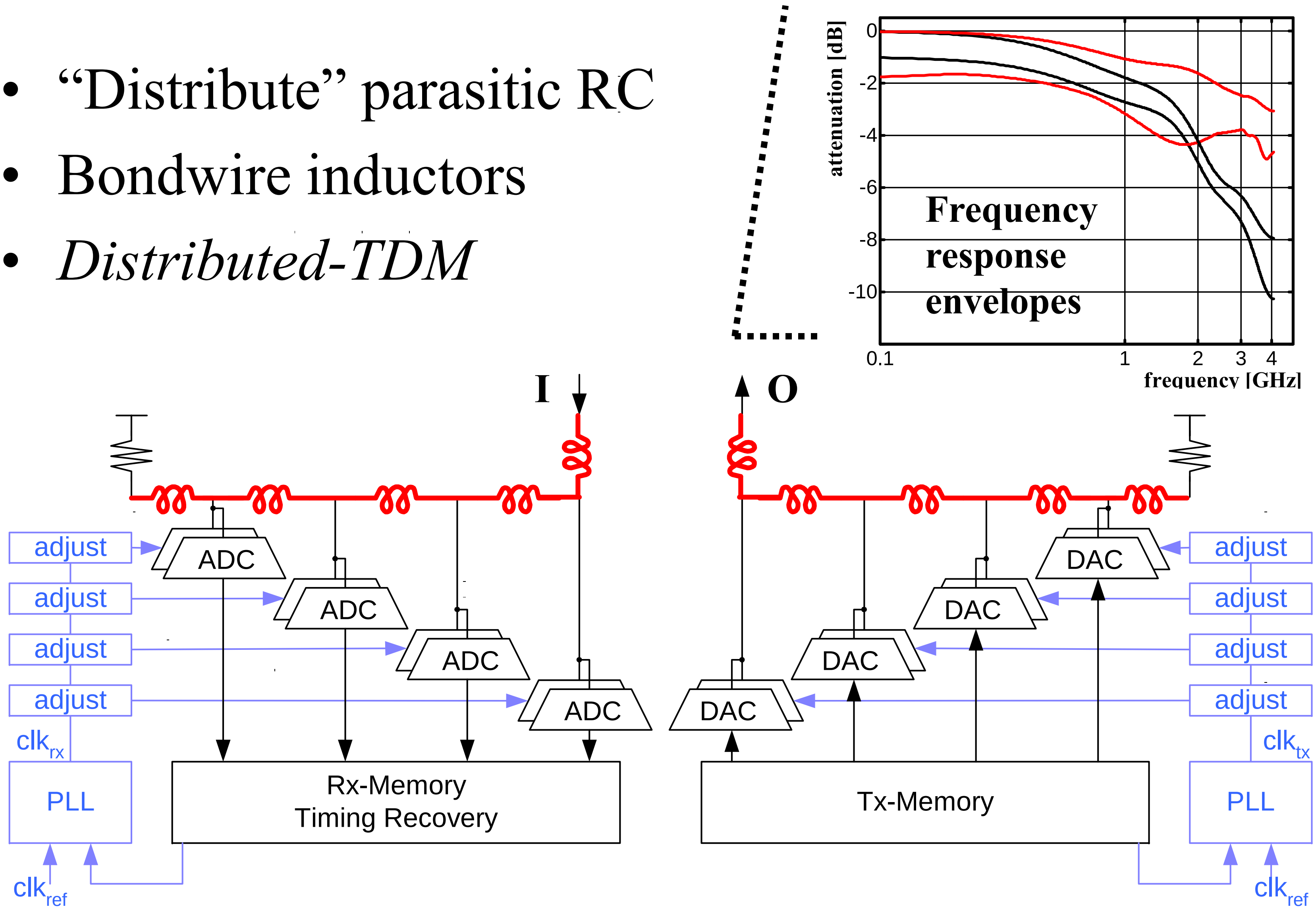
- 8GSa/s rate
- On chip clock freq limit
- TDM (8 DACs & 8 ADCs)
- Parasitic RC low-pass filtering



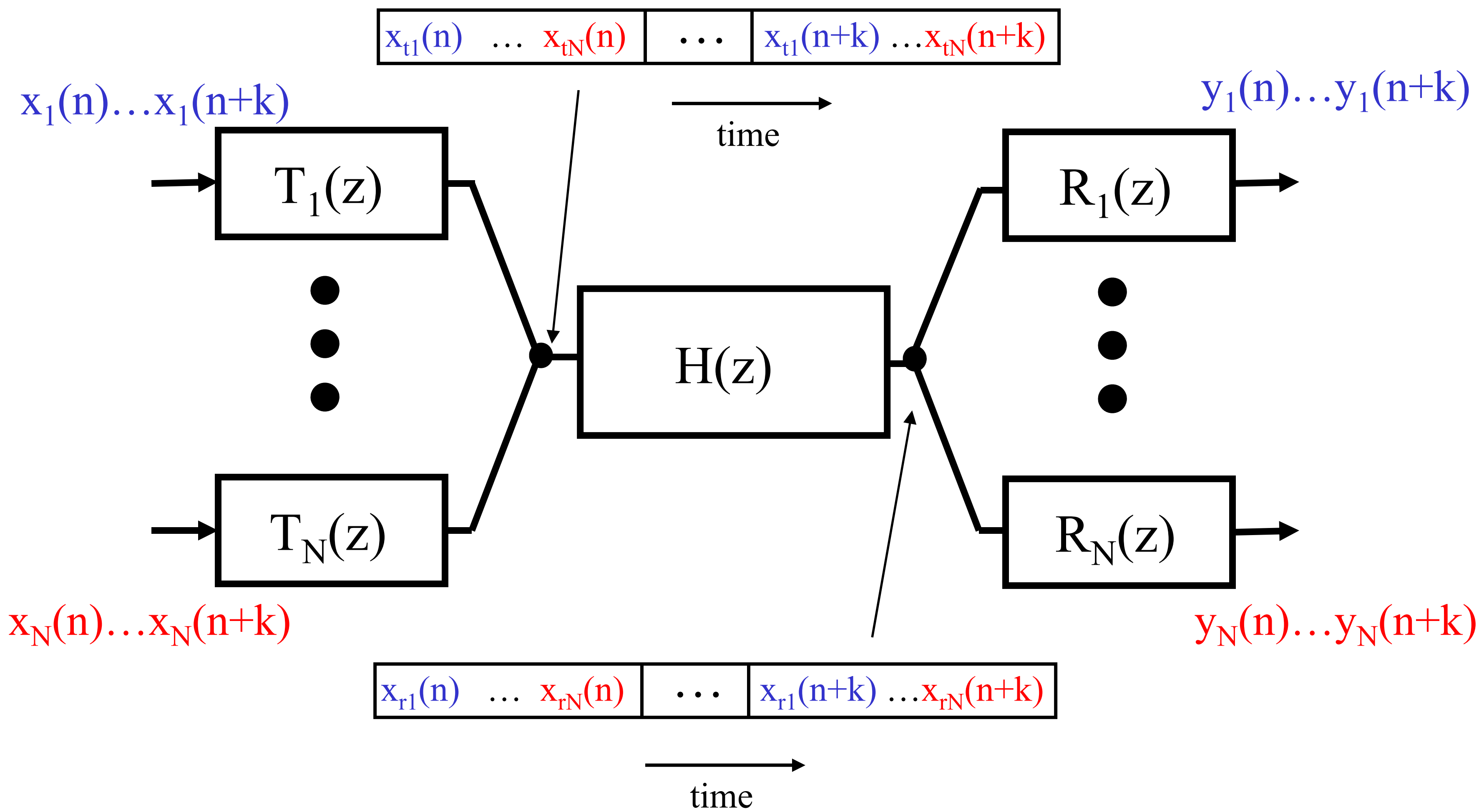



# Passive, continuous time equalization

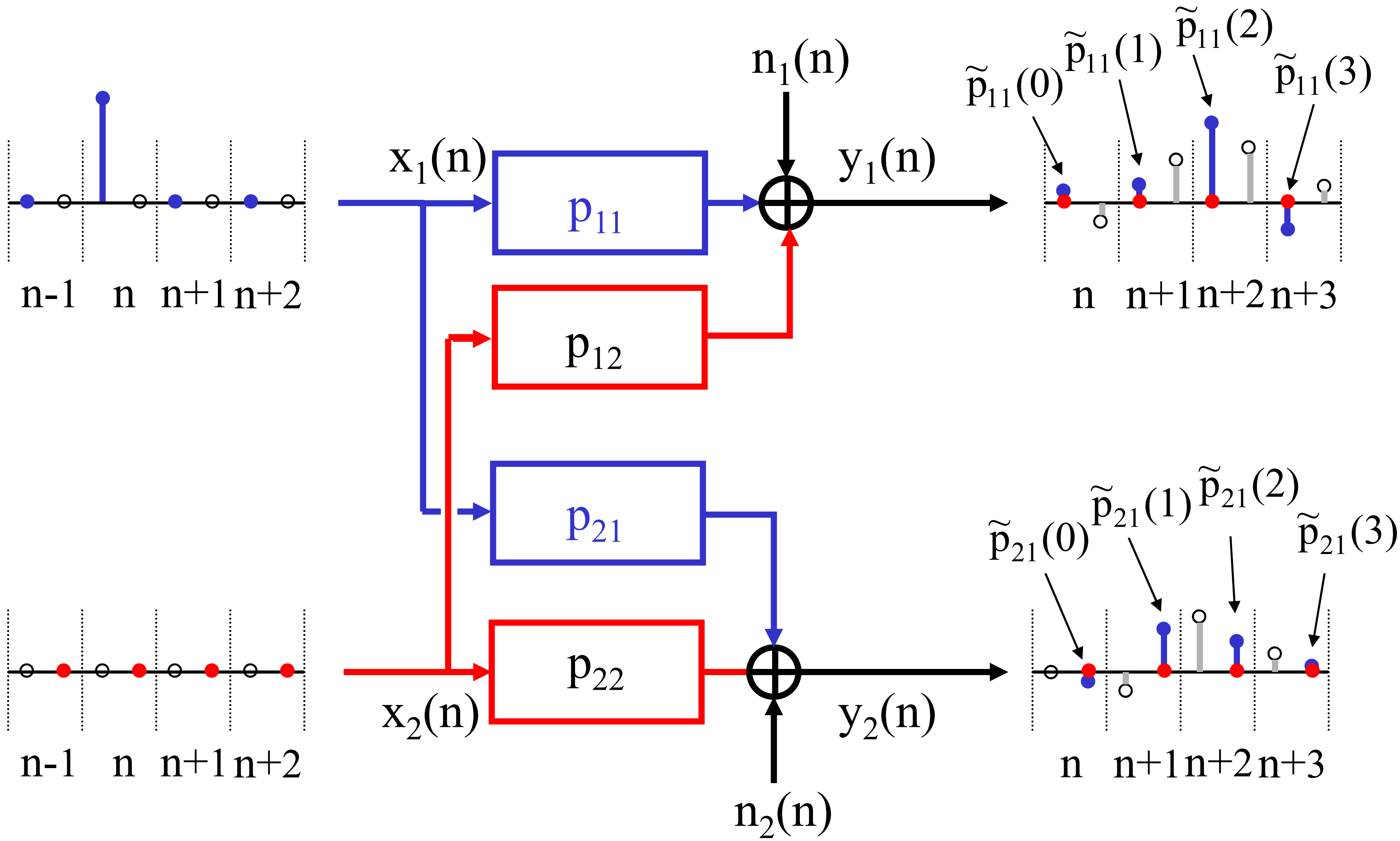
- “Distribute” parasitic RC
- Bondwire inductors
- *Distributed-TDM*



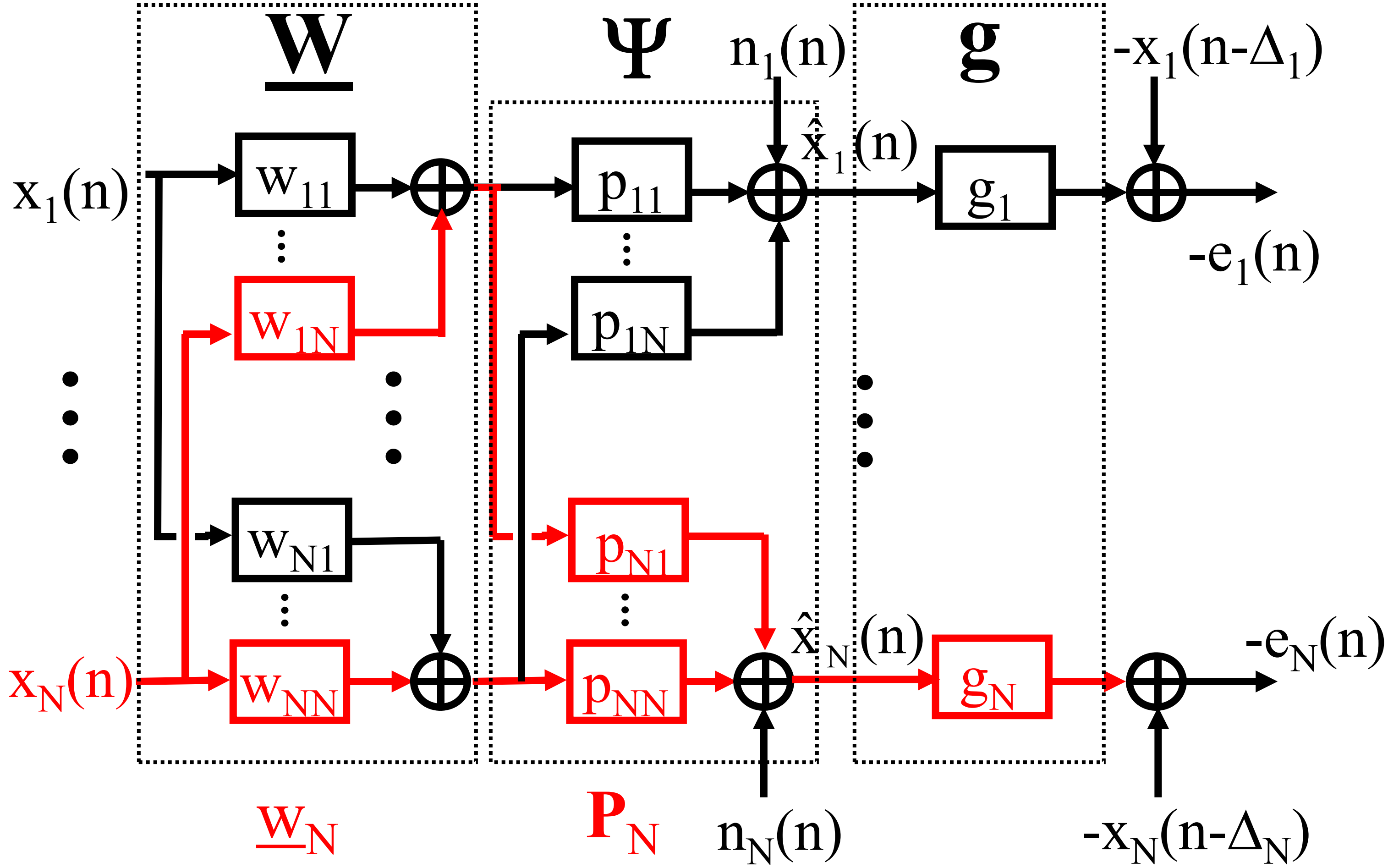
# NxN *Distributed-TDM* System



# Example: 2x2 Multi-channel System



# System Model




Unbiased error: $\underline{\mathbf{e}}(n)_{\mathbf{N\times 1}} = \frac{1}{\sqrt{\overline{E}_x}}\left(\underline{\mathbf{x}}(n-\underline{\mathbf{\Delta}})_{\mathbf{N\times 1}} - \mathbf{g}_{\mathbf{N\times N}}\,\underline{\hat{\mathbf{x}}}(n)_{\mathbf{N\times 1}}\right)$

# Optimal Solution Formulation

- Formulate pre-emphasis as optimization problem
- Output $k$ receives ***unbiased*** data from input $k$:

$$g_k \underline{\mathbf{w}}_k^{\mathbf{T}} \mathbf{P}_k^{\mathbf{T}} \underline{\mathbf{1}}_{\Delta_k}^{T} = 1, \forall k = 1 \ldots N$$

- Cost function – ***Unbiased*** mean-square error

**k=l (signal + ISI)**

**Noise**

$$\xi = -N + \sum_{k=1}^{N} \underline{\mathbf{w}}_k^{\mathbf{T}} \left( \sum_{l=1}^{N} \frac{\mathbf{P}_l^{\mathbf{T}} \mathbf{P}_l}{\left( \underline{\mathbf{1}}_{\Delta_l} \mathbf{P}_l \underline{\mathbf{w}}_l \right)^2} \right) \underline{\mathbf{w}}_k + \frac{1}{SNR_0} \sum_{k=1}^{N} \left( \underline{\mathbf{1}}_{\Delta_k} \mathbf{P}_k \underline{\mathbf{w}}_k \right)^{-2}$$

**k≠l (crosstalk)**

- Transmitter peak output power constraint:

$$\tilde{h}_j \left( \underline{\mathbf{W}} \right) = \sum_{k=1}^{N} \sum_{i=0}^{L-1} \left| w_{jk}(i) \right| \le 1, \quad \forall j = 1 \ldots \quad N$$

# Non-convexity Argument

- Assume 2x2 system with attenuation and crosstalk (no ISI)

$$\xi = \frac{1}{\left(\mathbf{P}_1 \underline{\mathbf{w}}_1\right)^2}\left[\frac{1}{SNR_o} + \left(\mathbf{P}_1 \underline{\mathbf{w}}_2\right)^2\right] + \frac{1}{\left(\mathbf{P}_2 \underline{\mathbf{w}}_2\right)^2}\left[\frac{1}{SNR_o} + \left(\mathbf{P}_2 \underline{\mathbf{w}}_1\right)^2\right]$$

- A function is convex only if it is convex on all lines. Let:

$$\left[\underline{\mathbf{w}}_1 \quad \underline{\mathbf{w}}_2\right] = \left[\underline{\mathbf{w}}_{o,1} \quad \underline{\mathbf{w}}_{o,2}\right] + t \cdot \left[\underline{\mathbf{w}}_{s,1} \quad \underline{\mathbf{w}}_{s,2}\right]$$

- $\xi$ is convex in $[\underline{\mathbf{w}}_1\ \underline{\mathbf{w}}_2]$ only if it is convex in $t$ for all $[\underline{\mathbf{w}}_{o,1}\ \underline{\mathbf{w}}_{o,2}]$ and $[\underline{\mathbf{w}}_{s,1}\ \underline{\mathbf{w}}_{s,2}]$.
- Each of the two terms in $\xi$ becomes a ratio of quadratic expressions in t, which are known to be non-convex.
- Therefore, $\xi$ is not convex in general.

# Sub-optimal Solution

- First sub-optimal solution – change the constraint

$$\tilde{h}_{j,new}\left(\underline{\mathbf{W}}\right) = \sum_{k=1}^{N}\sum_{i=0}^{L-1}\left|w_{jk}(i)\right| = 1, \quad \forall j = 1\ldots \quad N$$

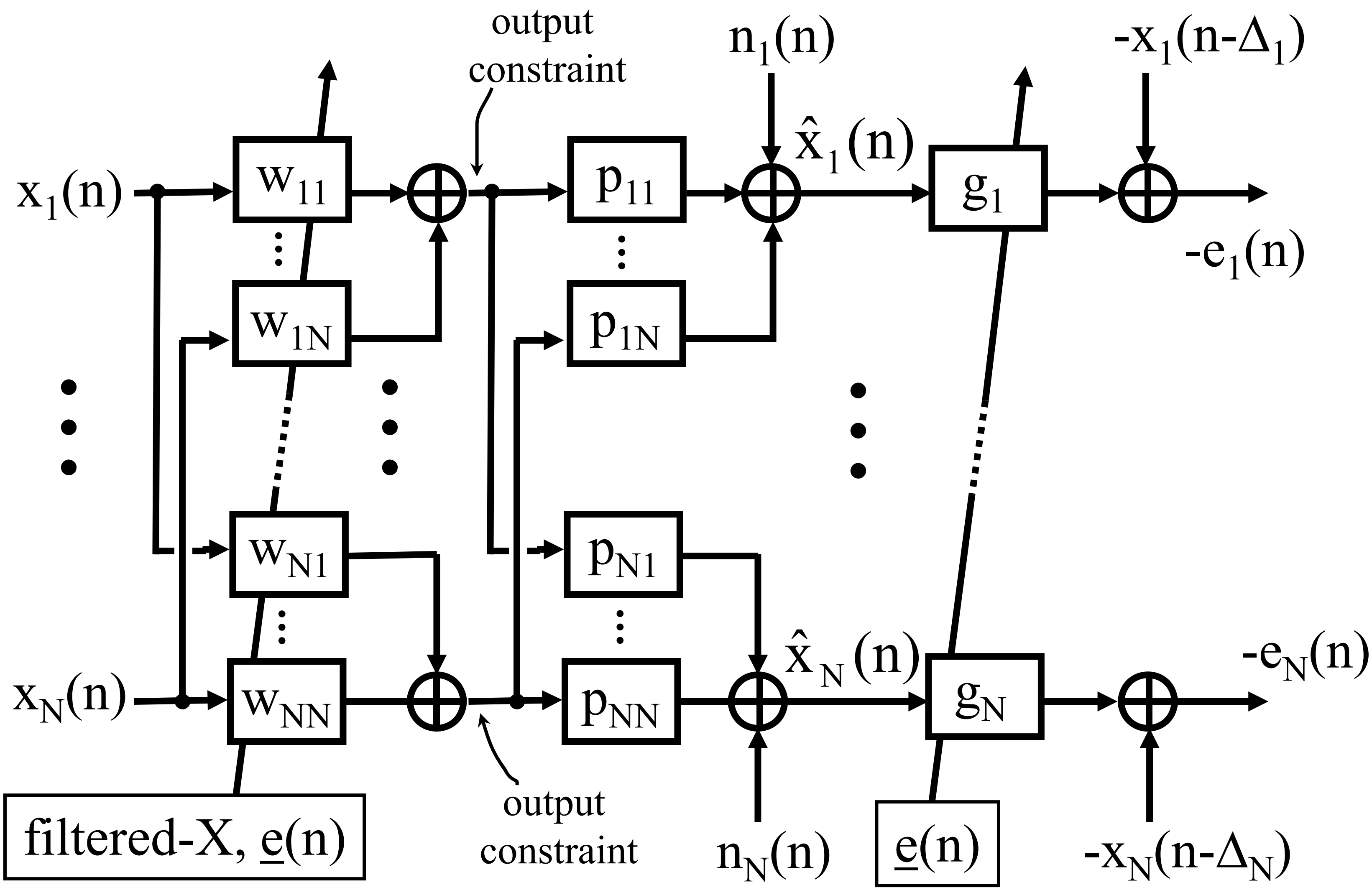
(every transmitter achieves peak output power)

- Second sub-optimal solution -
find unconstrained ZFE & scale to meet the constraint

$$\underline{\mathbf{W}}_{ZFEU} = \left(\mathbf{\Psi}^{T}\mathbf{\Psi}\right)^{-1}\mathbf{\Psi}^{T}\mathbf{G}^{T}\underline{\mathbf{I}}_{\Delta}^{T} \quad ; \quad \underline{\mathbf{W}} = \frac{\underline{\mathbf{W}}_{ZFEU}}{\max\limits_{j=1\ldots N}\left(\tilde{h}_{j}\left(\underline{\mathbf{W}}_{ZFEU}\right)\right)}$$

- These solutions allow the implementation of simple LMS-type adaptive algorithms

# Adaptive System Model



# Adaptive Solution

- Multi-channel, multi-error, filtered-X LMS algorithm
- **Pre-emphasis loop:** $\underline{\mathbf{U}}(n) = \mathbf{X}(n)\mathbf{\Psi}$ - filtered-X

$$\underline{\tilde{\mathbf{W}}}_{n+1} = \underline{\mathbf{W}}_n - \mu_w \hat{\nabla}_n \left(\underline{\mathbf{W}}\right) = \underline{\mathbf{W}}_n + \frac{2\mu_w}{\sqrt{\overline{\overline{E_x}}}} \underline{\mathbf{U}}(n)^{\mathrm{T}} \mathbf{g}^{\mathrm{T}} \underline{\mathbf{e}}(n)$$

  – Individual scaling (like first sub-optimal approach)

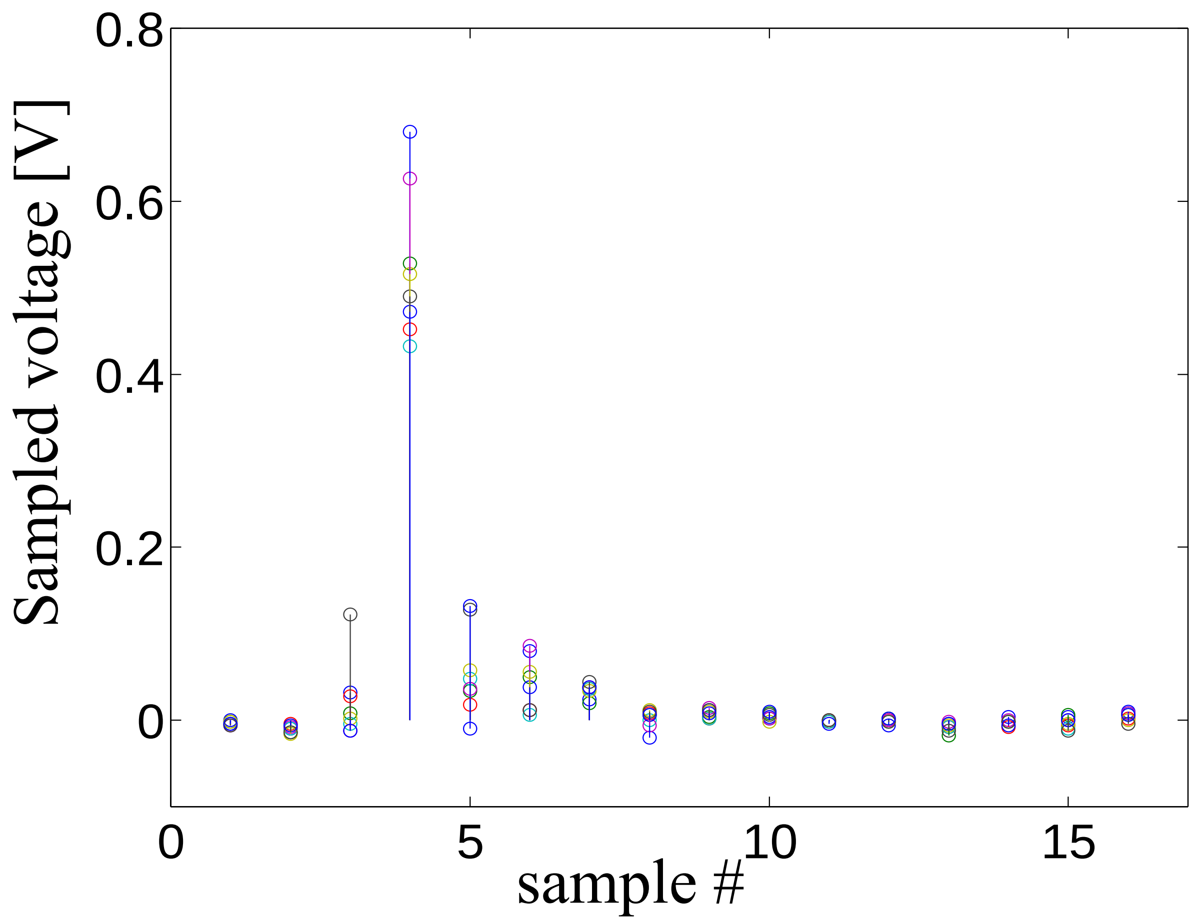
$$\underline{\mathbf{W}}_{n+1} = \left[ \frac{\underline{\tilde{\mathbf{w}}}_{11}^{\mathrm{T}}(n+1)}{\tilde{h}_1(\underline{\tilde{\mathbf{W}}}_{n+1})}_{1\times L} \quad \cdots \quad \frac{\underline{\tilde{\mathbf{w}}}_{jk}^{\mathrm{T}}(n+1)}{\tilde{h}_j(\underline{\tilde{\mathbf{W}}}_{n+1})}_{1\times L} \quad \cdots \quad \frac{\underline{\tilde{\mathbf{w}}}_{NN}^{\mathrm{T}}(n+1)}{\tilde{h}_N(\underline{\tilde{\mathbf{W}}}_{n+1})}_{1\times L} \right]^{\mathrm{T}}_{N^2L\times 1}$$

  – Maximal scaling (like second sub-optimal approach)

$$\underline{\mathbf{W}}_{n+1} = \frac{1}{\max\limits_{j=1\ldots N}\left(\tilde{h}_j\left(\underline{\tilde{\mathbf{W}}}_{n+1}\right)\right)} \underline{\tilde{\mathbf{W}}}_{n+1}$$

- **Gain loop:** $diag(\mathbf{g}_{n+1}) = diag(\mathbf{g}_n) + \frac{2\mu_g}{\sqrt{\overline{\overline{E_x}}}} diag(\underline{\hat{\mathbf{x}}}(n)\underline{\mathbf{e}}^{\mathrm{T}}(n))$

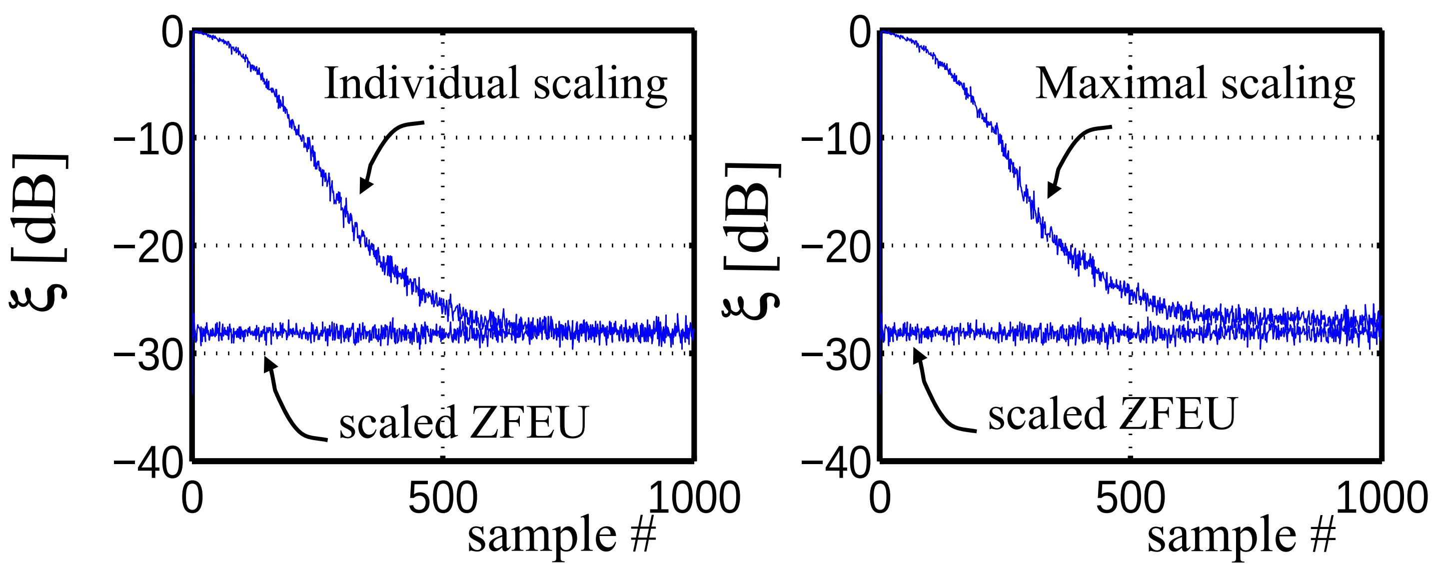
# Pulse Responses – 8x8 TDM




- 8GSa/s rate
- 1GSa/s/channel
- Peak output swing 0.75V

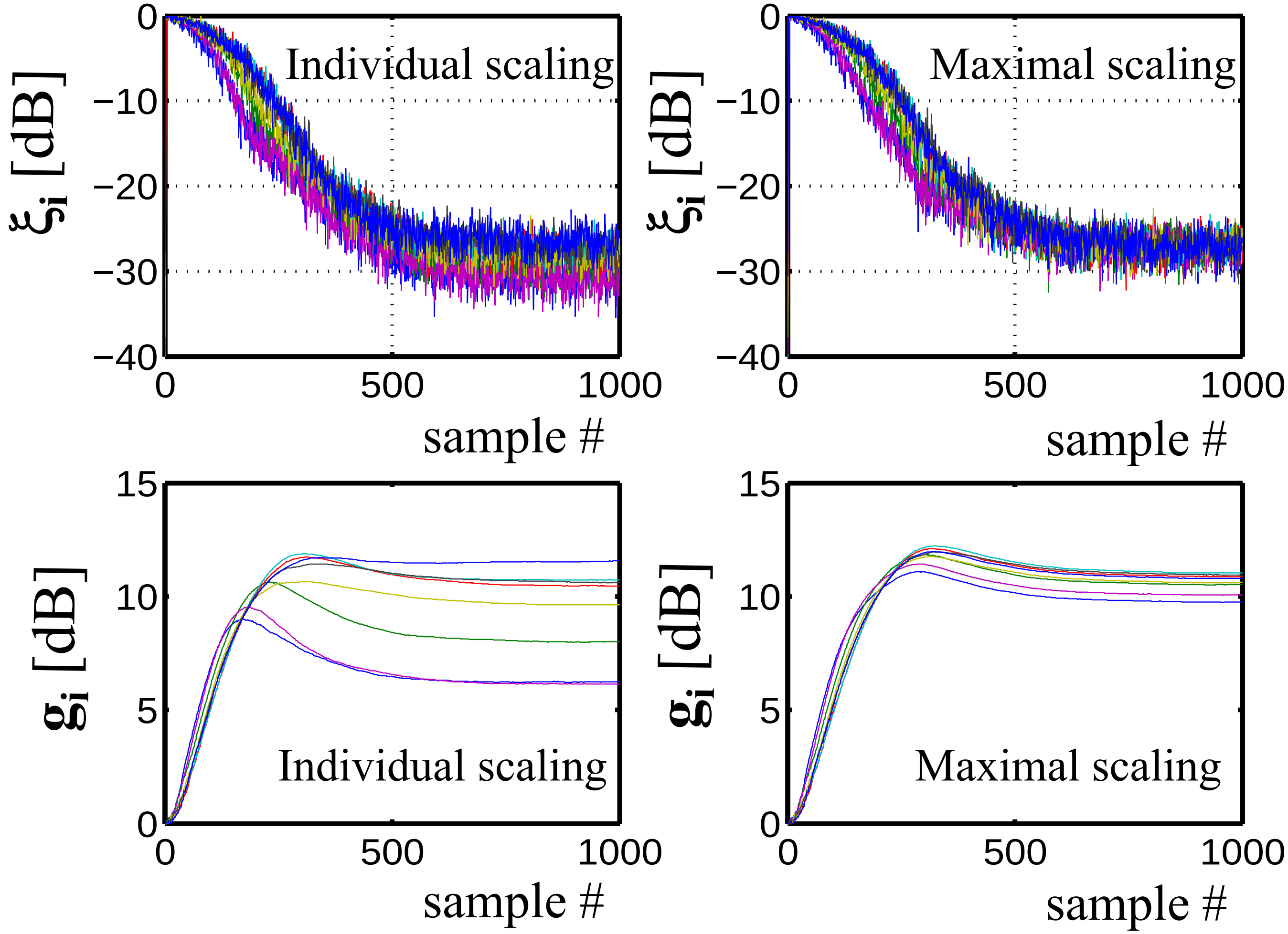
- Different gain and ISI "profiles" per channel

# Cost function learning curves

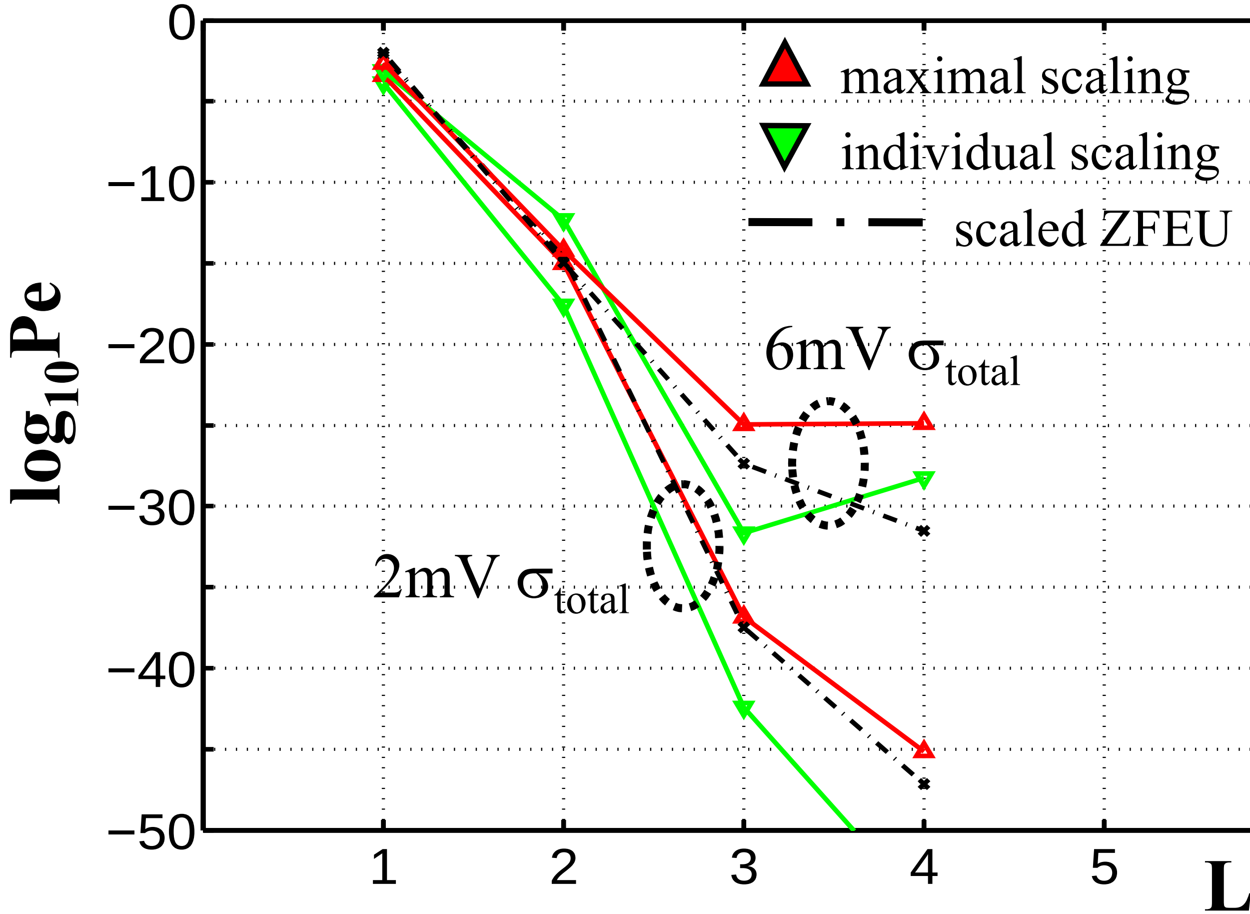



- L=8x4 taps of pre-emphasis per channel
- Transmitter output peak constraint = 750mV
- $\sigma_{total}$=4mV, $\sigma_{jitter}$=6ps
- Individual scaling performs slightly better (highly dependent on the type of the channel)

# Learning Curves per Channel



# BER vs. filter length




- Taps are found adaptively
- SNR calculated from tap values
- BER estimated from the SNR
- Noise: AWGN voltage noise & Gaussian timing noise

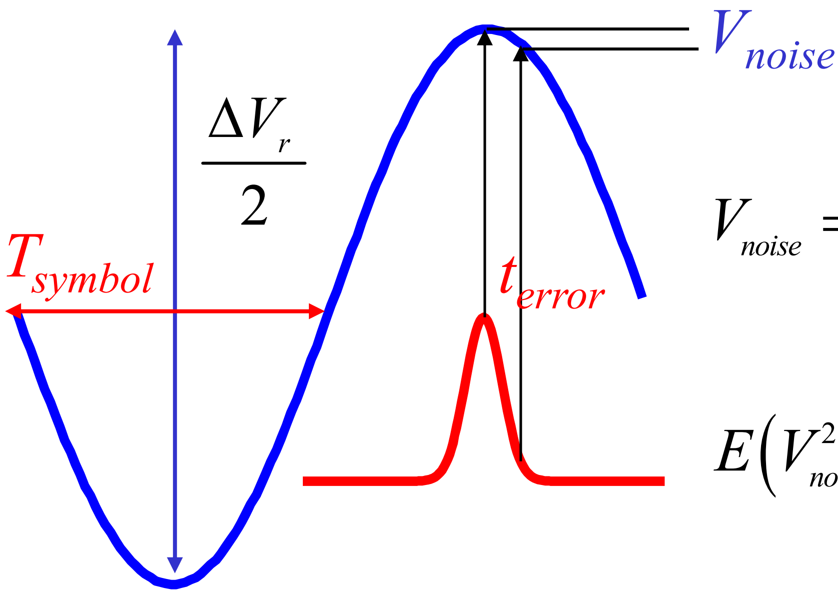
- Noise-ISI tradeoff point at 3-4 taps for higher noise setting

# Conclusion

- *Distributed-TDM* alleviates the bandwidth problem of standard TDM for high-speed links
- Methodology is proposed that maps *distributed-TDM* to MIMO system

- **Very low** BER requirements ($<10^{-14}$) impose **peak** power constraint
- Pre-emphasis/gain optimization is **non-convex**
  - Develop sub-optimal solutions that enable
  - Simple adaptive solutions (modification to filtered-X LMS)

# Appendix: Noise Analysis




$$V_{noise} = \frac{\Delta V_r}{2}\left(1 - \cos\left(\pi \frac{t_{error}}{T_{symbol}}\right)\right) \le \frac{\Delta V_r}{4}\left(\pi \frac{t_{error}}{T_{symbol}}\right)^2$$

$$E\left(V_{noise}^2\right) \le 3\Delta V_r^2 \left(\frac{\pi}{2T_{symbol}}\right)^4 \left(E\left(t_{error}^2\right)\right)^2$$

- Time to voltage noise mapping
- Time domain noise ($t_{error}$) – assume Gaussian pdf
- $V_{noise}$ proportional to data
- Independent voltage noise (thermal and voltage reference noise) is assumed to be AWGN