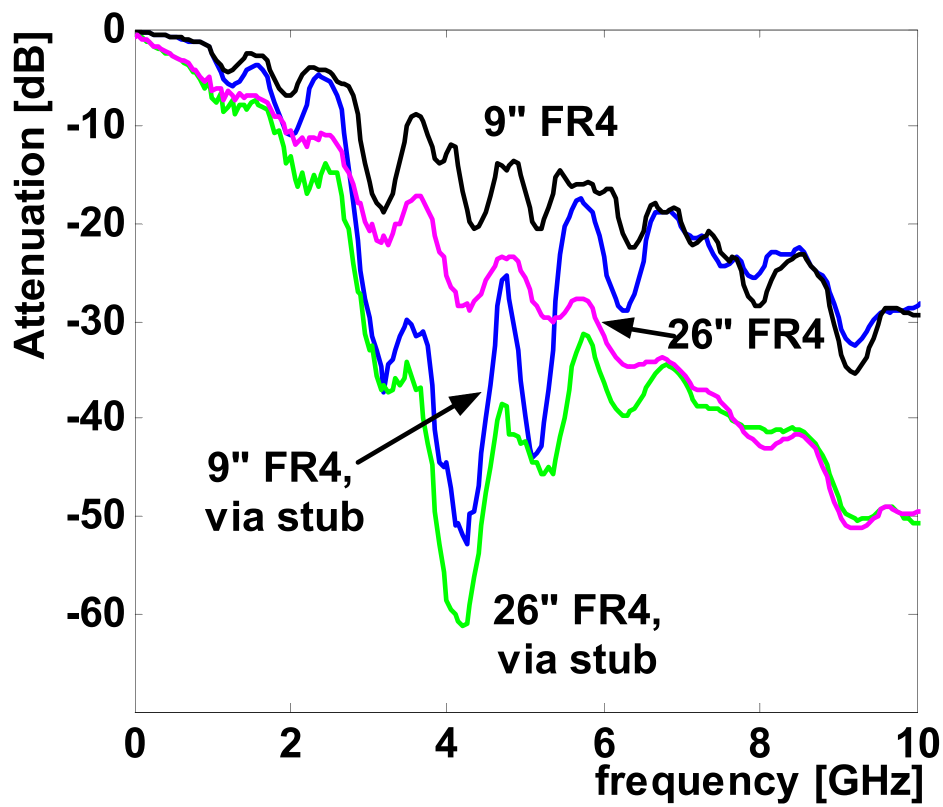
Optimal Linear Precoding with Theoretical and Practical Data Rates in High-Speed Serial-Link Backplane Communication

Vladimir Stojanovic[1,2], Amir Amirkhany[1], Mark Horowitz[1]

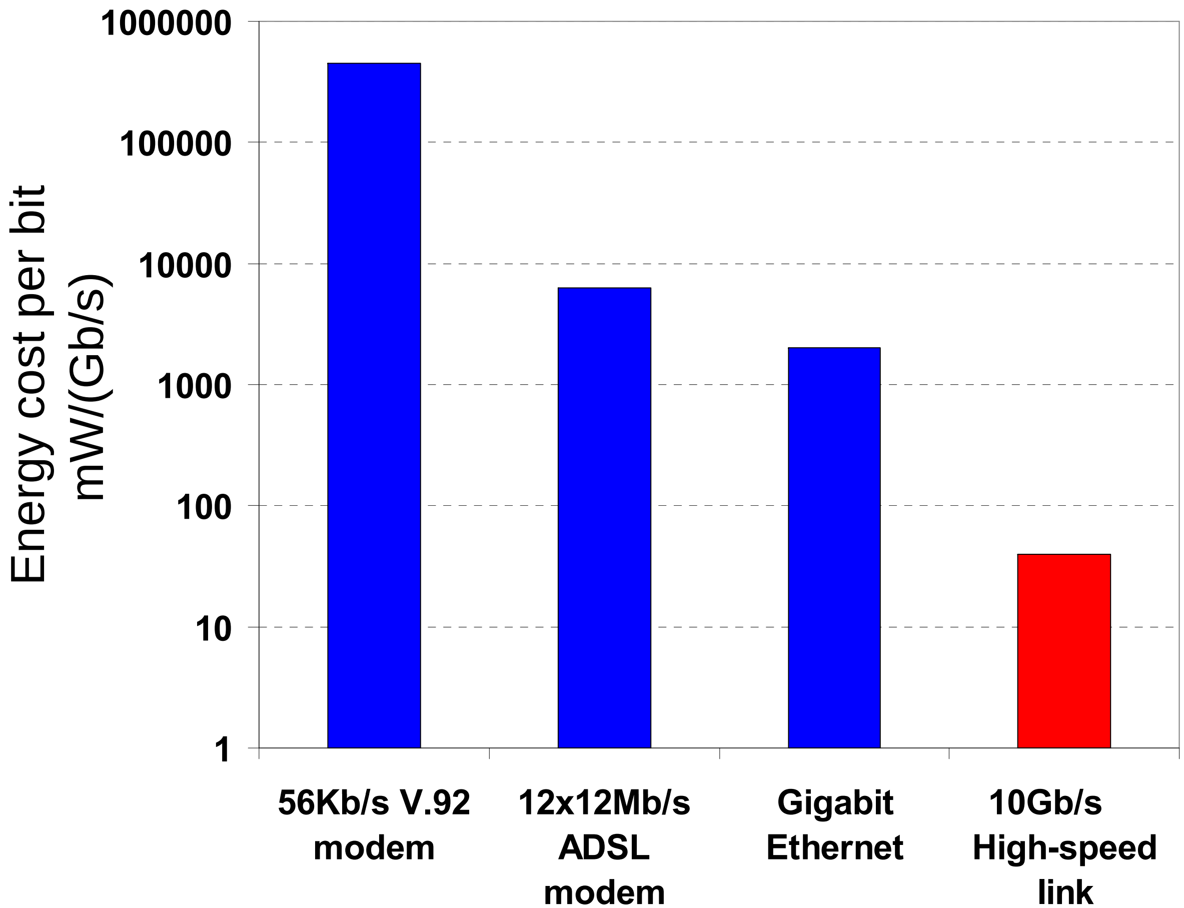
[1]Stanford University
[2]Rambus Inc.

Backplane channel

- Loss is variable
  - Same backplane
  - Different lengths
  - Different stubs
- Attenuation is large
  - >30dB @ 3GHz
  - But is that bad?
- Channel now a critical concern
  - Need communication techniques



Efficiency of communication



- Gigabit Ethernet or ADSL for links?
  - How do we get 50x improvement in efficiency?

Link modeling issues

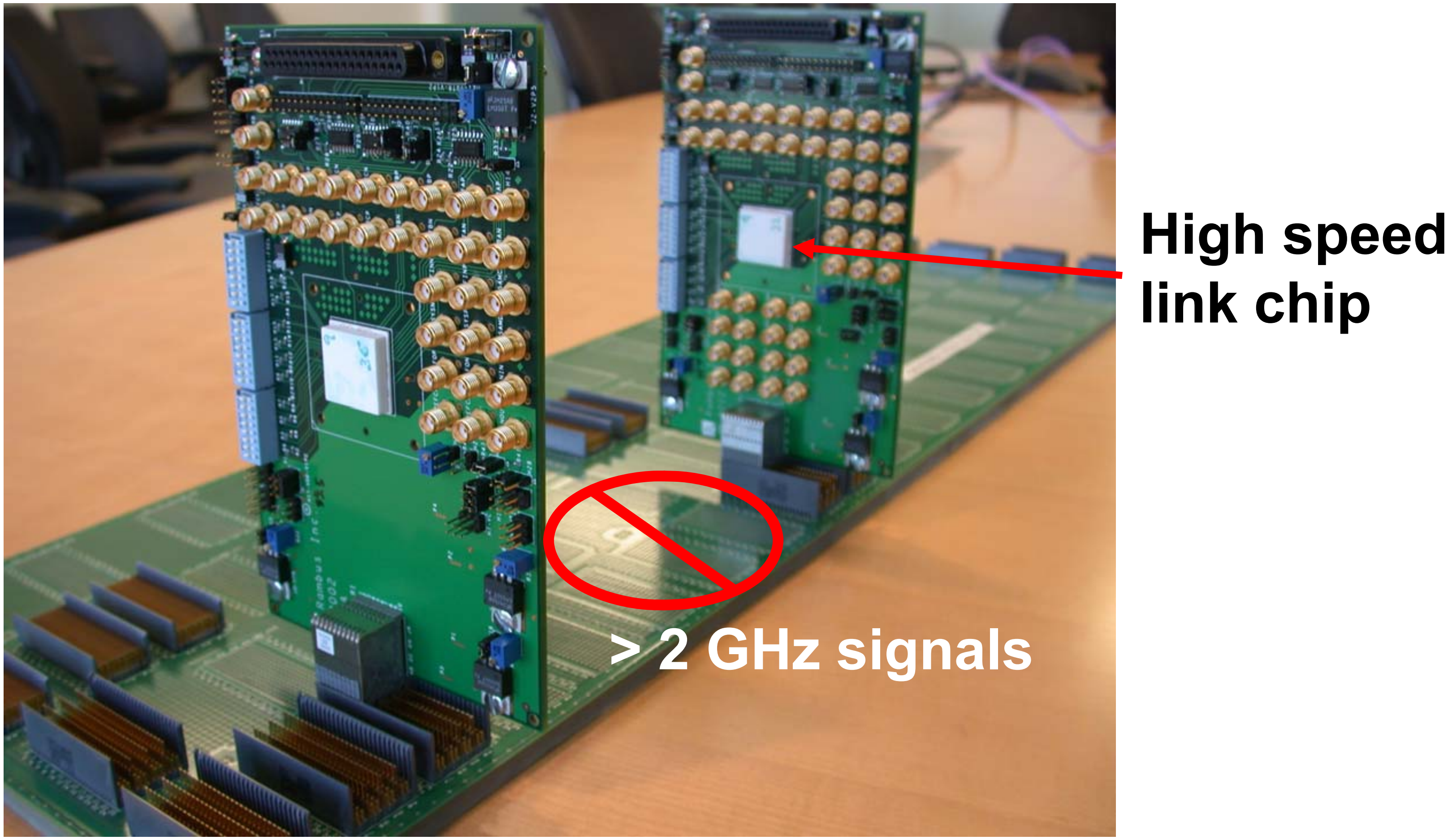
- No good link system and noise models
  - Hard to make performance/power tradeoff
  - Cannot predict the “right” architecture
- Maximum achievable data rates – unknown
  - Limited link communication system design
- Peak power constraint in the transmitter
  - No solution for optimal transmit equalization
  - No solution for automatic equalization

Outline

- Create system level optimization for links
  - Address the issues in link modeling

- High-speed link modeling
- System level optimization
- Energy-efficiency

A look at the system

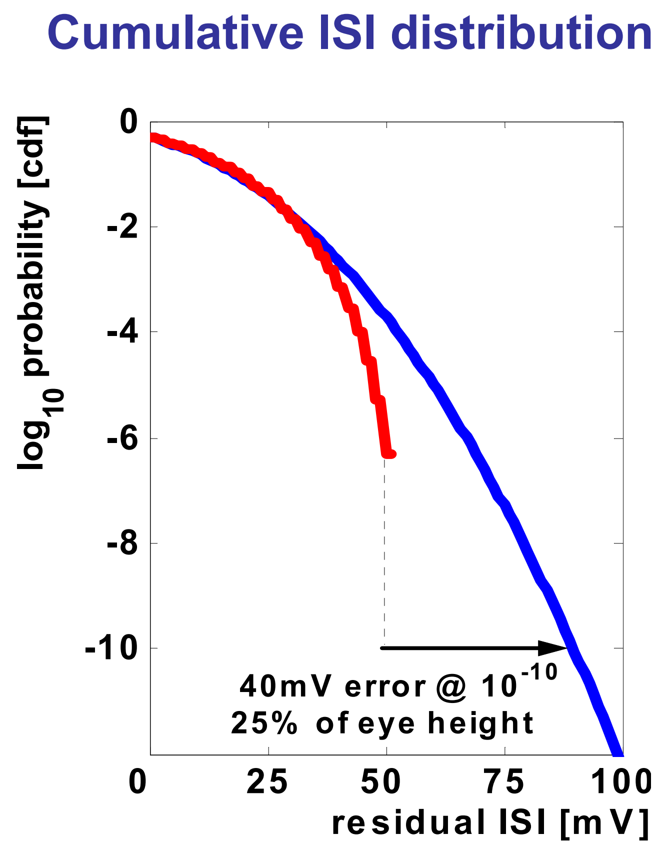


- Now, the bandwidth limit is in wires

Previous system models

- Borrowed from computer systems
  - Worst case analysis
    - Can be too pessimistic in links
- Borrowed from data communications
  - Gaussian distributions
    - Works well near mean
    - Often way off at tails
      - ISI distribution is bounded
- Need accurate models
  - To relate the power/complexity to performance

How bad is Gaussian model?

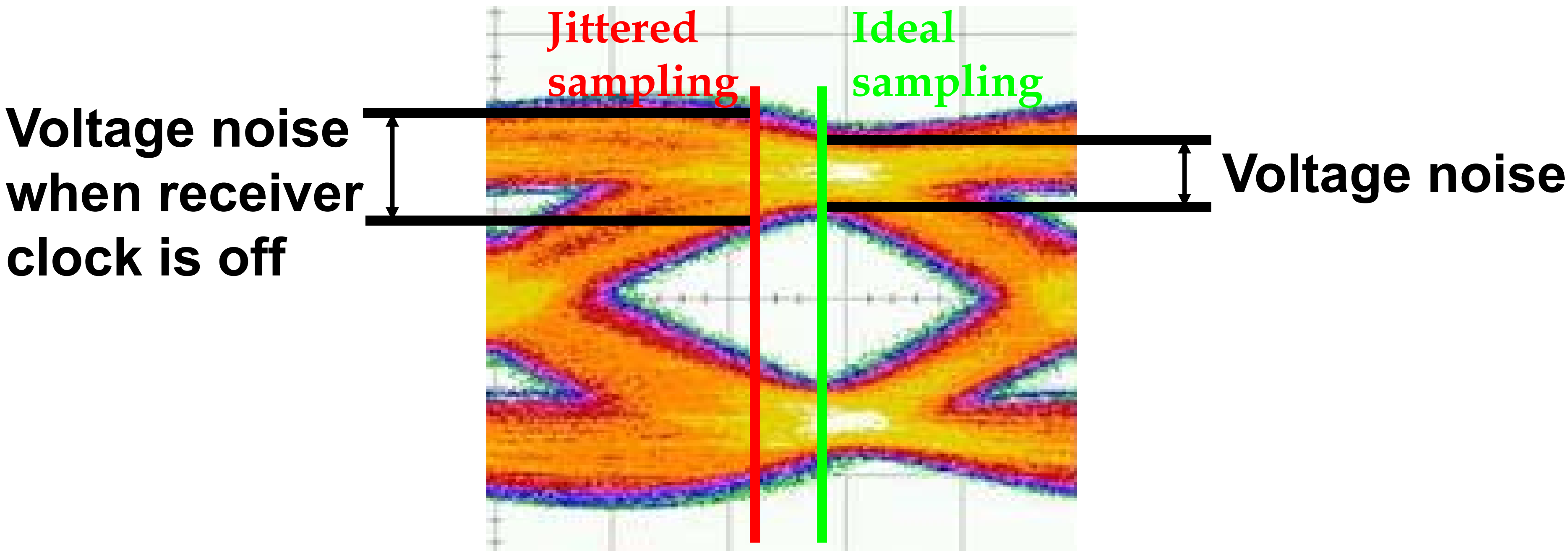


- Gaussian model only good down to 10^{-3} probability
- Way pessimistic for much lower probabilities

A new model

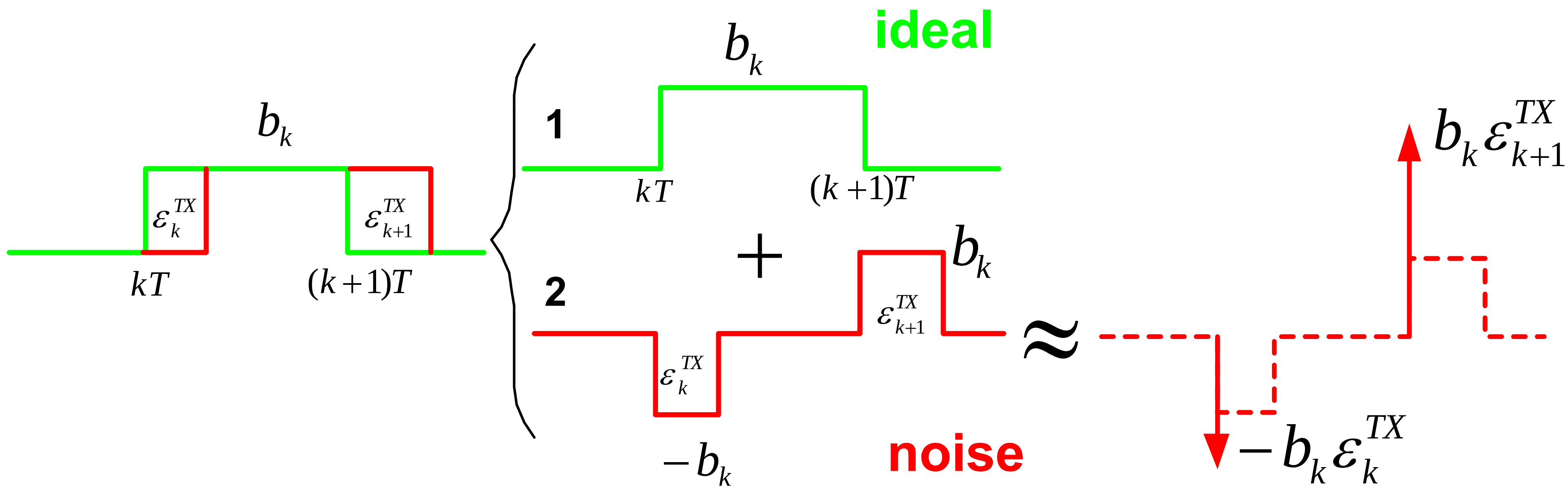
- Use direct noise and interference statistics
- Main system impairments
  - Interference
  - Voltage noise (thermal, supply, offsets, quantization)
  - Timing noise – always looked at separately
    - Key to integrate with voltage noise sources
    - Need to map from time to voltage

Effect of timing noise



- The effect depends on the size of the jitter, the input sequence, and the channel
- Need effective voltage noise distribution

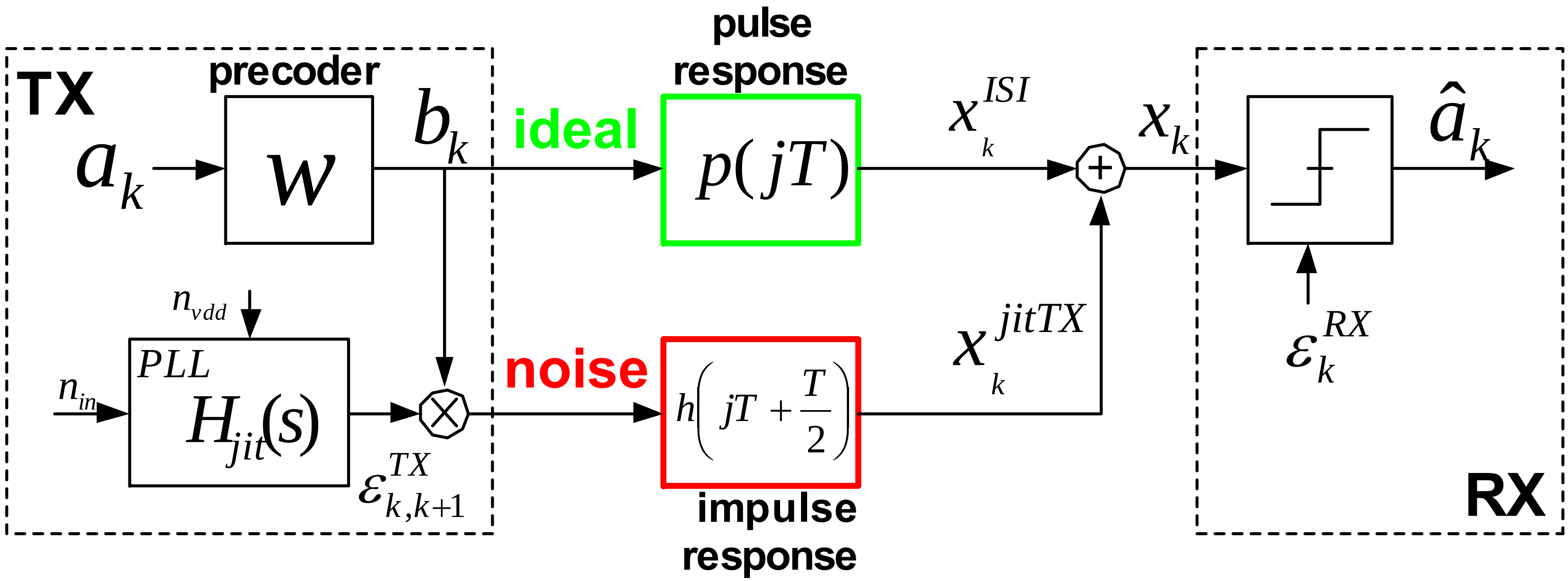
Example: Effect of transmitter jitter



- Decompose output into ideal and noise
- Noise are pulses at front and end of symbol
  - Width of pulse is equal to jitter
- Approximate with deltas on bandlimited channels

V. Stojanović, M. Horowitz, "Modeling and Analysis of High-Speed Links,"
***IEEE Custom Integrated Circuits Conference*, September 2003. (invited)**

Jitter Propagation Model



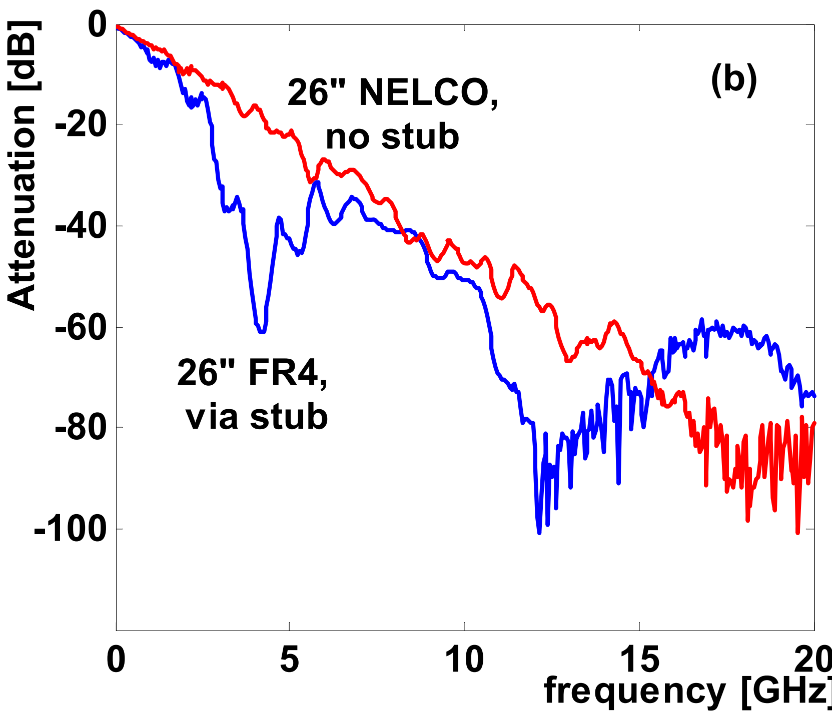
$$x^{ISI}(kT+\phi_i+\varepsilon_k^{RX}) = \sum_{j=-sbS}^{sbE} b_{k-j}\, p(jT+\phi_i)$$

$$x^{jitter}(kT+\phi_i+\varepsilon_k^{RX}) = \sum_{j=-sbS}^{sbE} b_{k-j}\left[h(jT+\frac{T}{2}+\phi_i)\left(\varepsilon_k^{RX}-\varepsilon_{k-j}^{TX}\right)-h(jT-\frac{T}{2}+\phi_i)\left(\varepsilon_k^{RX}-\varepsilon_{k+1-j}^{TX}\right)\right]$$

Outline

- Show system level optimization for links
  - Create a framework to evaluate trade-offs
- High-speed link modeling
- System level optimization
  - Limits – What is the capacity of these links?
  - Improving today's baseband signaling
- Energy-efficiency

Baseline channels



- Legacy (FR4) - lots of reflections
- Microwave engineered (NELCO)

Capacity calculation

- Modified waterfilling
  - Add phase noise

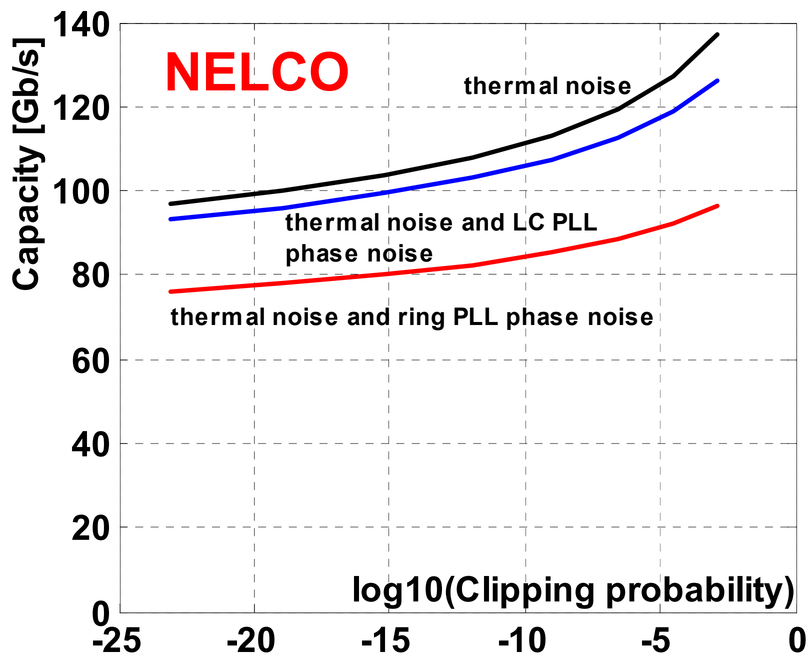
$$\lim_{N\to\infty}\left(\underset{E_n}{\text{maximize}}\ \ b = \frac{1}{2}\sum_{n=1}^{N}\log_2\left(1+\frac{E_n\|H_n\|^2}{\Gamma\left(\sigma_{thermal}^2 + E_n\|H_n\|^2\sigma_{\theta n}^2\right)}\right)\right)$$

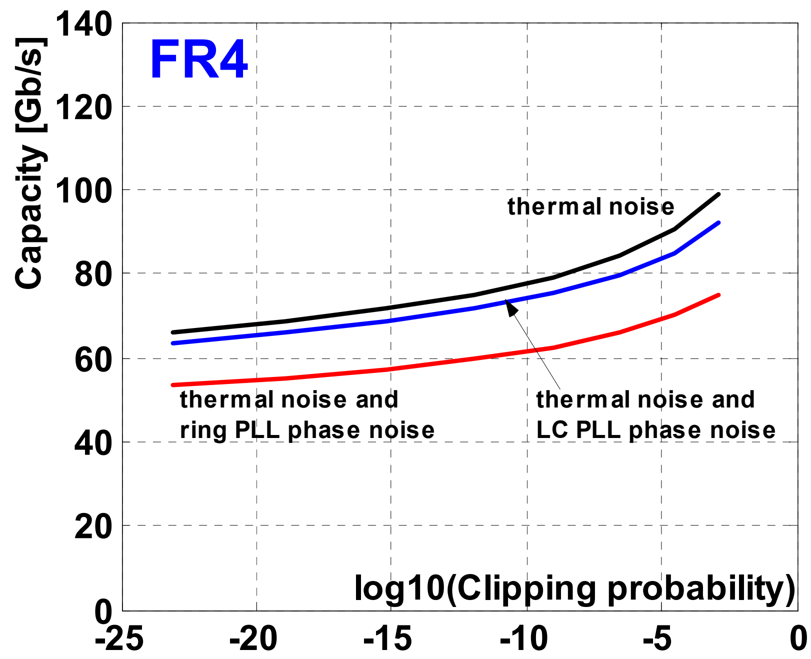
$$s.t.\qquad \sum_{n=1}^{N} E_n = NE_{avg} = NE_{peak}PAR^{-1}$$

$$E_n \geq 0,\ \ n = 1,\ldots,N$$

- Concave problem

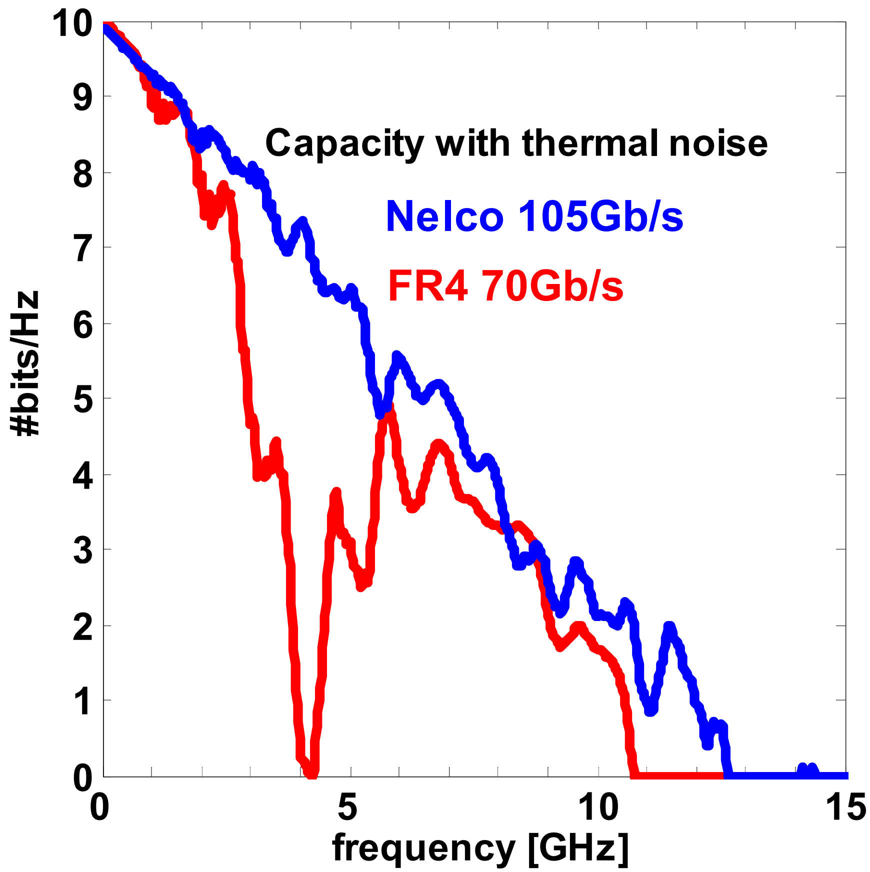
Capacity with link-specific noise





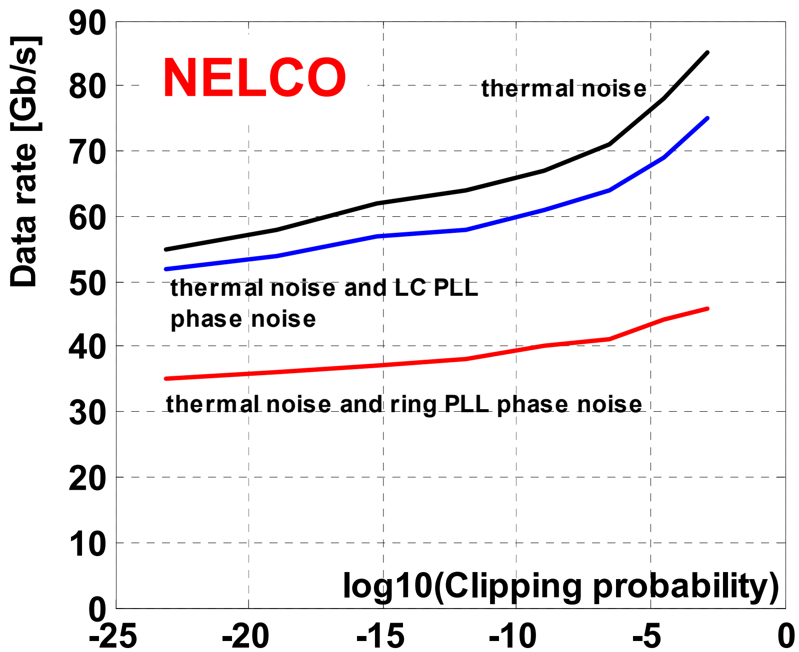
- Given E_{peak}
  - Find E_{avg} from PAR (desired clipping probability)
- Capacity much higher than data rates in today's links

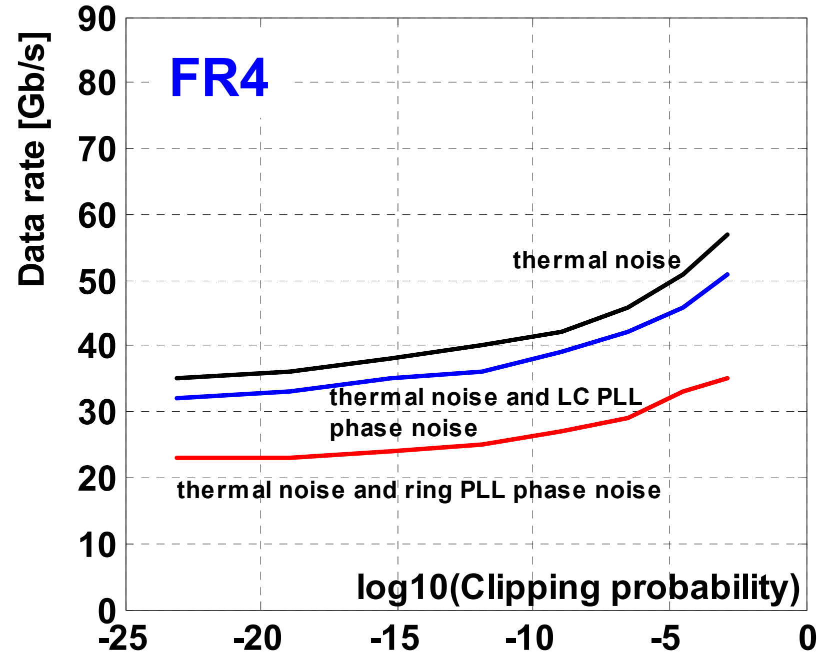
Available bandwidth



- Up to 12GHz
- No need to build 40Gs/s transceivers

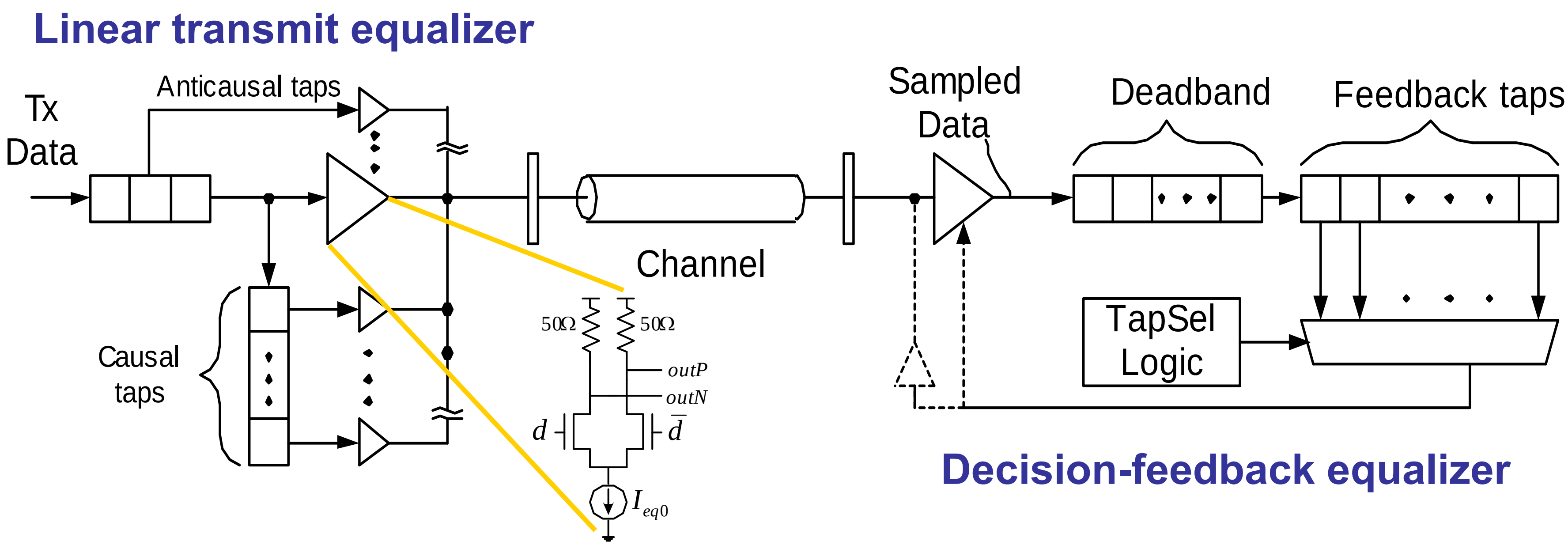
Uncoded Discrete-multitone





- Modified Levin-Campello loading for phase noise
- ***Gap*** is huge for BER=10^{-15}
  - Too costly to use soft decoders
- Still, data rates much better than in today's baseband links
  - Baseband links ISI limited

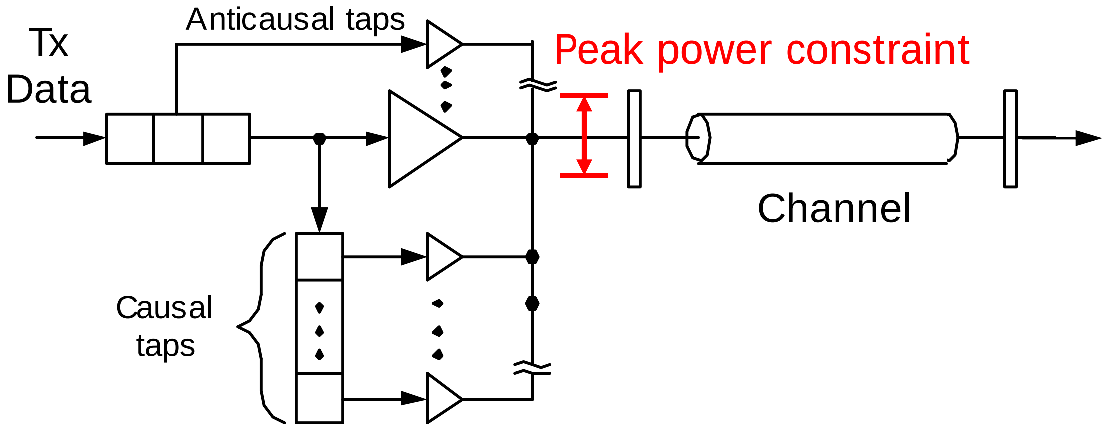
Removing ISI

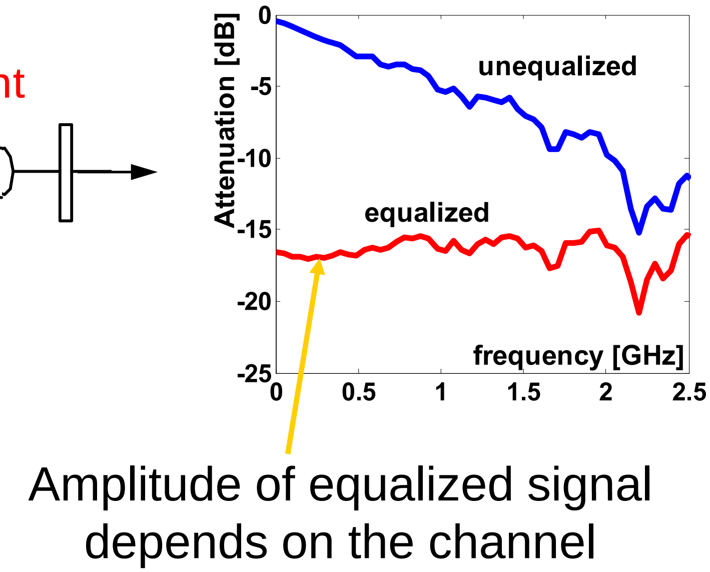


- Transmit and Receive Equalization
  - Changes signal to correct for ISI
  - Often easier to work at transmitter
    - DACs easier than ADCs

J. Zerbe et al, "Design, Equalization and Clock Recovery for a 2.5-10Gb/s 2-PAM/4-PAM Backplane Transceiver Cell," *IEEE Journal Solid-State Circuits*, Dec. 2003.

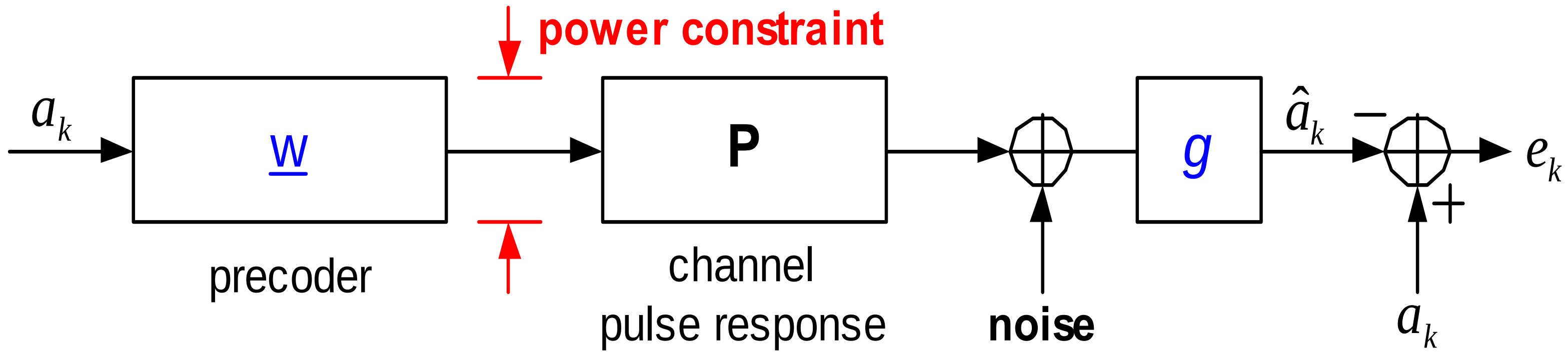
Transmit equalization – headroom constraint





- Transmit DAC has limited voltage headroom
- Unknown target signal levels
  - Hard to formulate error or objective function
- Need to tune the equalizer and receive comparator levels

Optimization example: Power constrained linear precoding



$$MSE(\underline{w}, g) = E_a\left(1 - 2g\underline{w}^T \mathbf{P}\underline{1}_\Delta + g^2 \underline{w}^T \mathbf{P}\mathbf{P}^T \underline{w}\right) + g^2\sigma^2$$

$$SINR_{unbiased}(\underline{w}) \stackrel{\Delta}{=} \frac{E_a(\underline{w}^T \mathbf{P}\underline{1}_\Delta)^2}{E_a \underline{w}^T \mathbf{P}(\mathbf{I} - \underline{1}_\Delta \underline{1}_\Delta^T)(\mathbf{I} - \underline{1}_\Delta \underline{1}_\Delta^T)^T \mathbf{P}^T \underline{w} + \sigma^2}$$

- Add variable gain to amplify to known target level
  - Formulate the objective function from error
- *SINR* is not concave in $\underline{w}$ in general
- Change objective to quasiconcave $\sqrt{SINR_{unbiased}}$

Optimal linear precoding

- Still, does this objective really relate to link performance?
- Need to look at noise and interference distributions

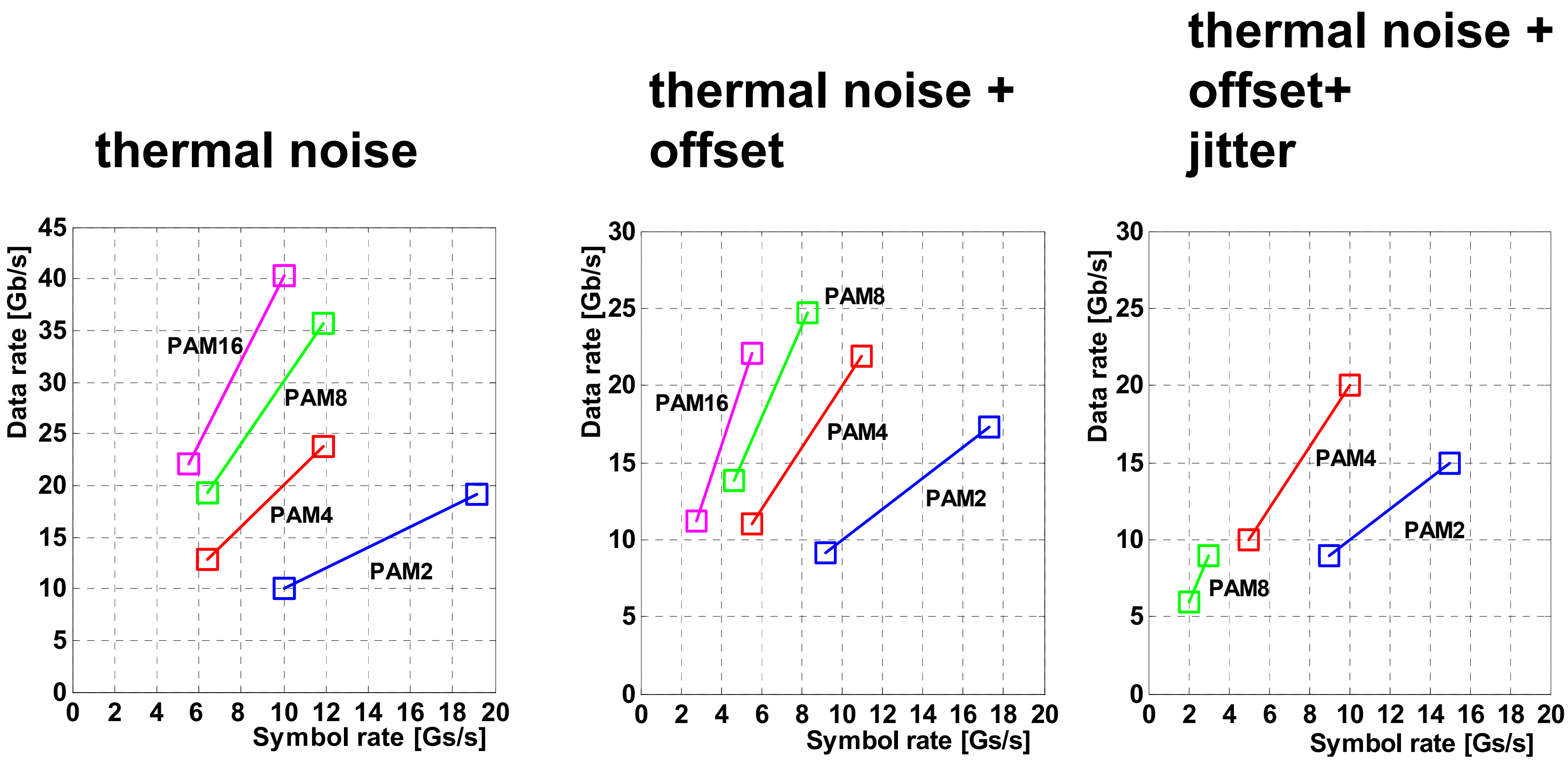
$$\underset{\underline{w}}{\text{maximize}} \quad \gamma = \frac{0.5 d_{\min} \underline{w}^T \mathbf{P} \underline{1}_{\Delta} - V_{peak} \left\| \underline{w} \mathbf{P} \mathbf{I}_{PD} \right\|_1 - offset}{\left(E_a \underline{w}^T \mathbf{P} (\mathbf{I} - \underline{1}_{\Delta} \underline{1}_{\Delta}^T - \mathbf{I}_{PD})(\mathbf{I} - \underline{1}_{\Delta} \underline{1}_{\Delta}^T - \mathbf{I}_{PD})^T \mathbf{P}^T \underline{w} + \sigma^2 \right)^{1/2}}$$

$$s.t. \quad \left\| \underline{w} \right\|_1 \leq 1$$

$$\sigma^2 = \underline{w}^T \boldsymbol{S_0}^{\boldsymbol{TX}} \underline{w} + \underline{w}^T \boldsymbol{S_0}^{\boldsymbol{RX}} \underline{w} + \sigma^2_{thermal}$$

- Minimize BER
  - Residual dispersion into peak distortion
  - Reflections into mean distortion
- Includes all link-specific noise sources

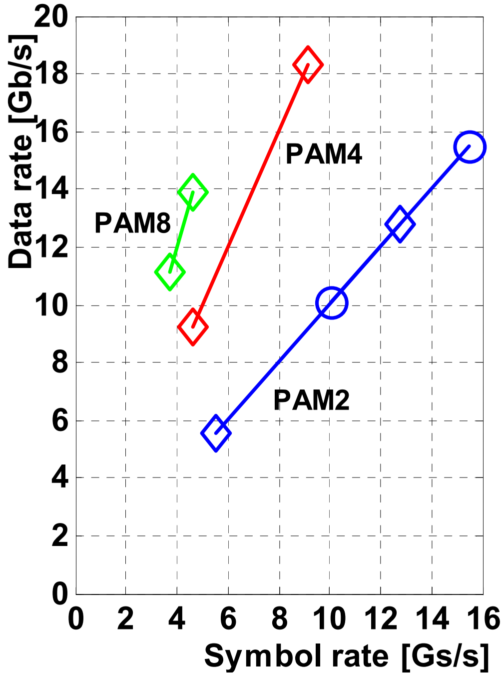
Multi-level: Offset and jitter are crucial



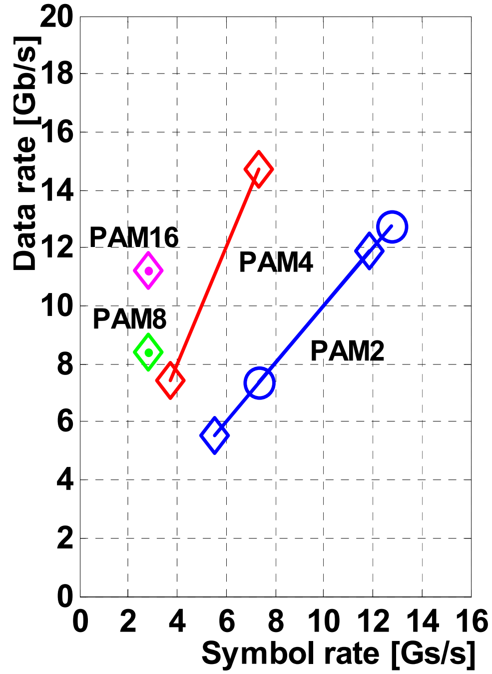
- To make better use of available bandwidth, need better circuits
- PAM2/PAM4 robust candidate for next generation links

Full ISI compensation too costly

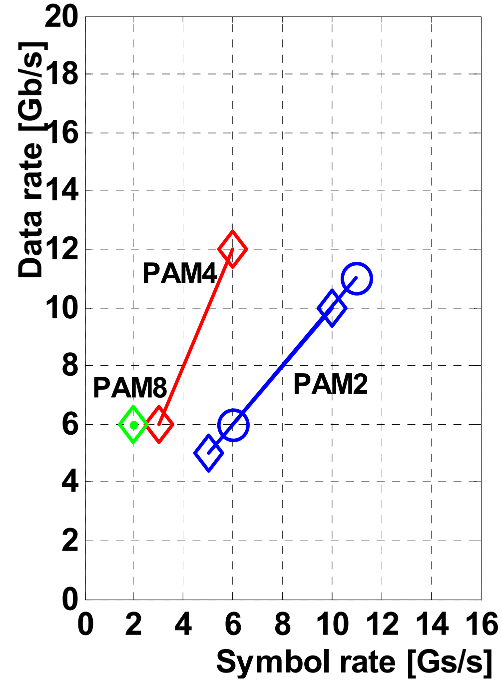
thermal noise



thermal noise + offset



thermal noise + offset+ jitter

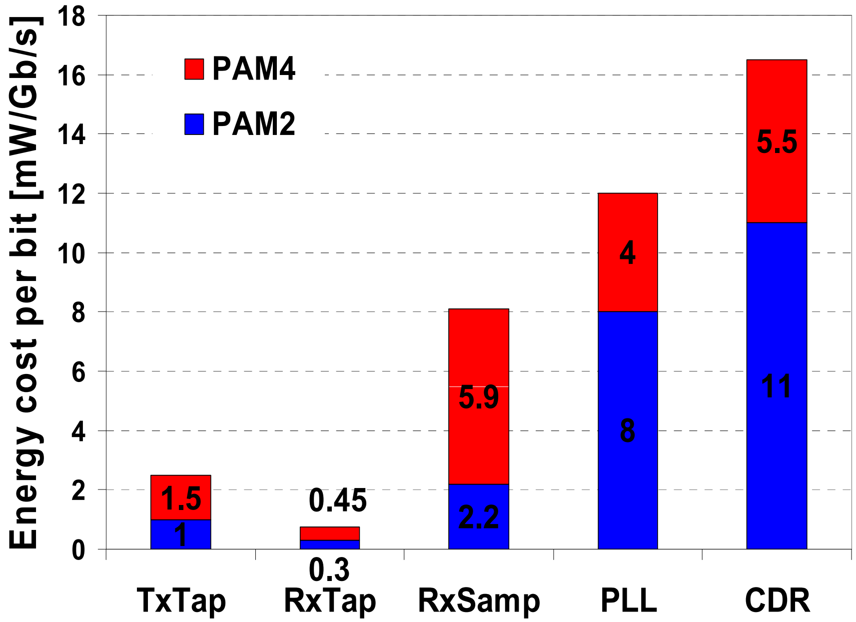


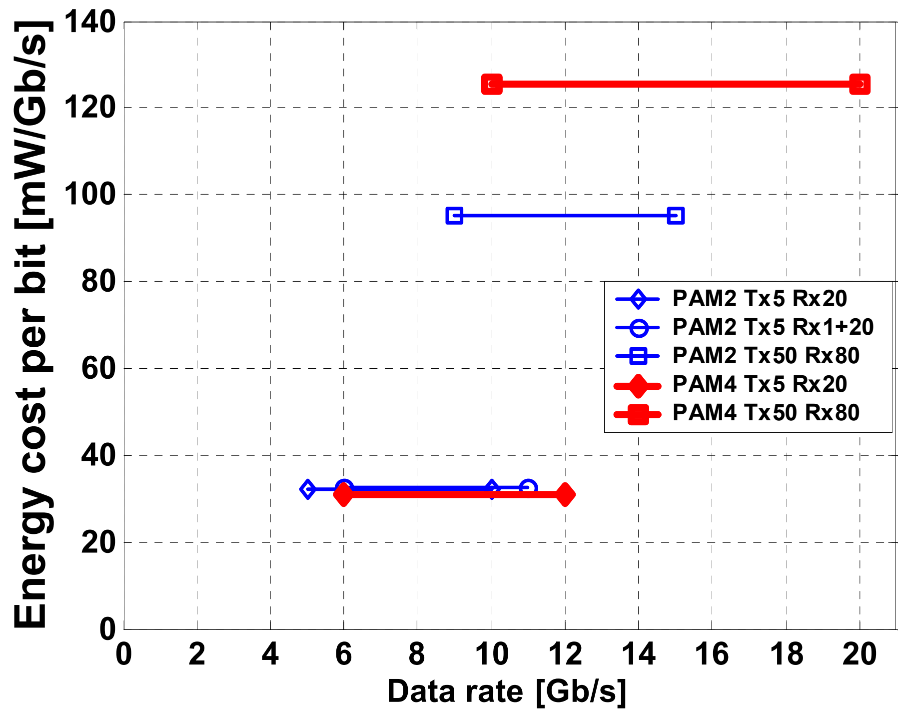
- Today's links cannot afford to compensate all ISI
  - Limits today's maximum achievable data rates

Outline

- Show system level optimization for links
  - Create a framework to evaluate trade-offs
- High-speed link modeling
- System level optimization
  - Limits – What is the capacity of these links?
  - Improving today's baseband signaling
- Energy-efficiency

Energy efficiency of link components



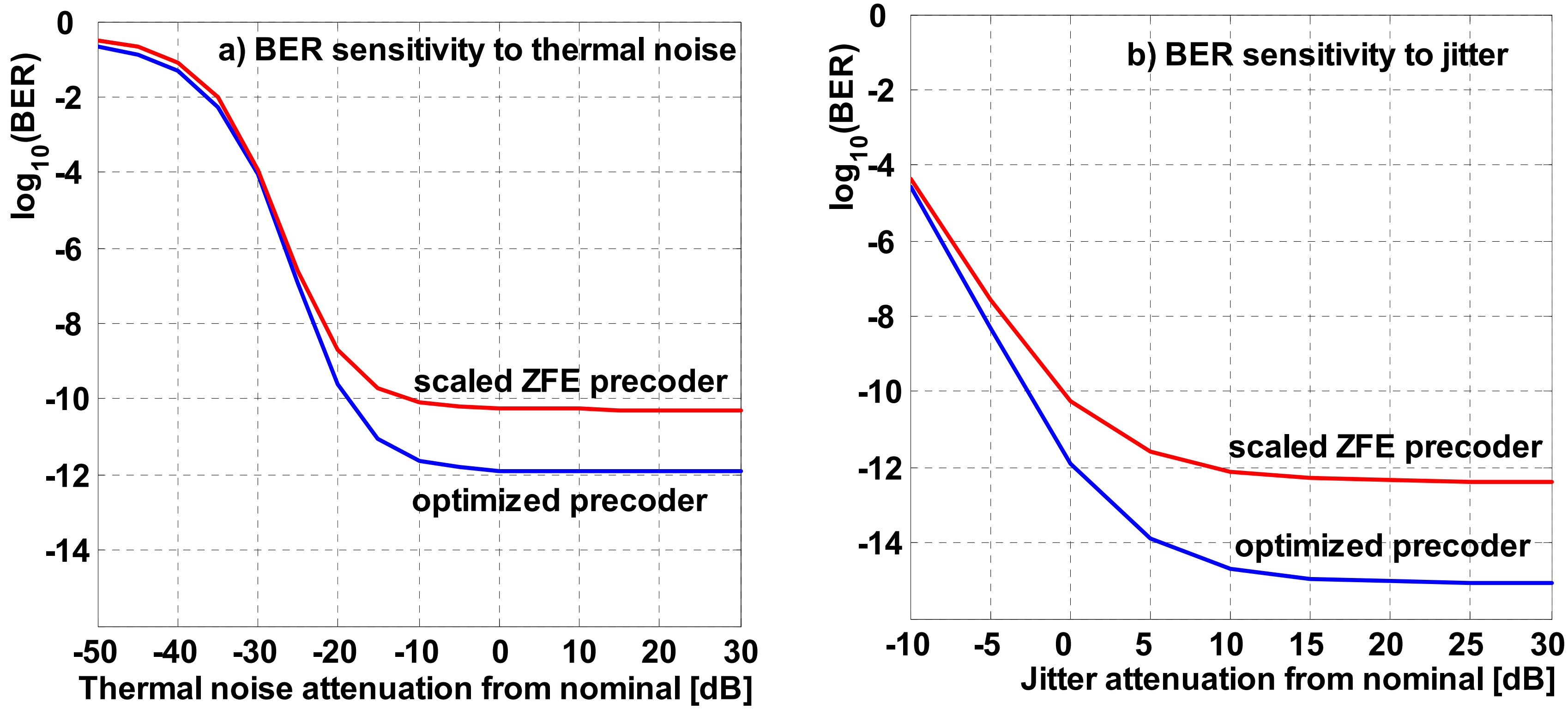


- Large chunk of energy on timing sub-system (PLL, CDR)
  - Different scaling for PAM2/PAM4
- Energy scales linearly with technology
  - Likely to remain a key constraint
  - Can't count on very complex filters

Conclusions

- Interfaces are challenging system designs
  - Good space to explore system level optimization
- Baseband links limited to PAM2,4
  - Residual ISI biggest factor
  - Also by offset and jitter
- Still, far from the capacity of these links
  - Looking into multi-tone to mitigate ISI
  - Improves energy efficiency

BER sensitivity



- Optimized BER 2-3 orders better than ZFE
- Thermal noise not critical
- Jitter is critical