Motivation

- Does eqn. above predict everything?

\[ BER = \frac{1}{2} \text{erfc} \left( \frac{V_{\text{in,ampl}} - V_{\text{off}}}{\sqrt{2}\sigma_{\text{noise}}} \right) \]
Traditional Approach

- Borrowed from computer systems
  - Built to be “error free” \(\rightarrow\) Worst-case analysis

- Voltage/Time (VT) Budget
  - Also called link budget (especially in wireless)
  - Key: separate random vs. deterministic error sources

Voltage Budget Example
Voltage Budget Example

Timing Budget: Jitter Definitions

- Like voltage – need to separate deterministic (bounded) from random (unbounded)

- Total jitter (TJ) = Deterministic (DJ) + random (RJ)

- DJ is measured as peak-to-peak, added linearly
- RJ is measured as rms
  - For BER = 10\(^{-12}\), “peak-to-peak” RJ is 14*RMS value

- Don’t forget that jitter gets filtered too
  - E.g., source synchronous, CDR
Jitter Tolerance Mask

- Specifies amplitude of sinusoidal jitter (SJ) vs. frequency for which link must maintain BER spec
- Mask drives CDR loop filter characteristics
Jitter in Source Synchronous Systems

• Is worst-case realistic?
  • What if you had 100 taps of residual ISI?

• Can you really treat timing and voltage noise completely separately?
Communications Approach

- Model small deterministic errors as Gaussian
  - Find \( \sigma \), multiply it to get “peak-to-peak” value at given BER

- Works well at low BER (1e-3), but…

Issues with Communications Approach

- Gaussian model breaks at lower probabilities
A More Modern Approach

• Use direct noise and ISI statistics

• Don’t treat timing noise separately
  • Integrate with voltage noise sources
  • I.e., need to map from time to voltage

• Ref: V. Stojanovic, Ph.D. thesis

Residual ISI

• Generally can’t correct for all ISI
  • Equalizers are finite length
  • Even with infinite equalizers, the coefficients are quantized
  • And you may not be able to estimate coefficient values perfectly

• Need to find distribution of this residual ISI
Generating ISI Distributions

Equalized pulse response

Convolution

ISI distribution

Real ISI Dist.: 5-tap TX FIR

Data sample distribution

Edge sample distribution
Effect of Timing Noise

- Need to map from time to voltage
- Effect depends on jitter magnitude, input sequence, and channel

Effect of TX Jitter: Decomposition

- Decompose output into ideal + noise
- “Jitter” is pulse at front and end of symbol
  - Width of pulse set by jitter magnitude
Converting to Voltage

- Variable width pulses annoying to deal with
- Approximate noise pulses with deltas of same area
  - Channel is low-pass and will filter them anyways

Jitter Propagation Model

• Channel bandwidth matters
  • If $h(T/2)$ is small, jitter voltage noise is small
Implications

- **TX Jitter**
  - High frequency (period) jitter is bad
    - Changes the energy (area) of the symbol
    - Uncorrelated noise sources add up
  - Low frequency jitter isn’t as bad
    - Just shifts waveform
    - Correlated noise sources partially cancel

- **RX jitter**
  - Shifts TX sequence – same as low $f$ TX jitter

For same source jitter (white)
- Noise from TX jitter larger than RX jitter
- TX jitter “enhanced” by channel

- Bandwidth of jitter sets final magnitude
  - Like any other white noise source
Including the CDR

- Need jitter on actual sampling clock
  - Not just jitter from source, PLL

CDR Model

- Model as a state machine
  - Current phase position is the state
  - Transitions caused by early/late signals

- On average move to right position
  - But probability of incorrect transition not small
What You Really Care About

• Final steady-state probability of being in each phase position (state)

\[ P_{\text{hold}}, P_{\text{up}}, P_{\text{dn}} \]

• Can find using “Markov model”
  • Fancy way of saying that you iteratively apply the transition probabilities

Result: CDR Phase PDF

• This is the “jitter” distribution
  • (With nominal phase subtracted out)
ISI and CDR Distributions

- Vertical slice: ISI distribution @ given time
- Horizontal weight: CDR phase distribution

Putting It All Together: BER Contours

- Voltage margin @ given BER:
  - Distance from probability contour to threshold (0)
Model and Measurements