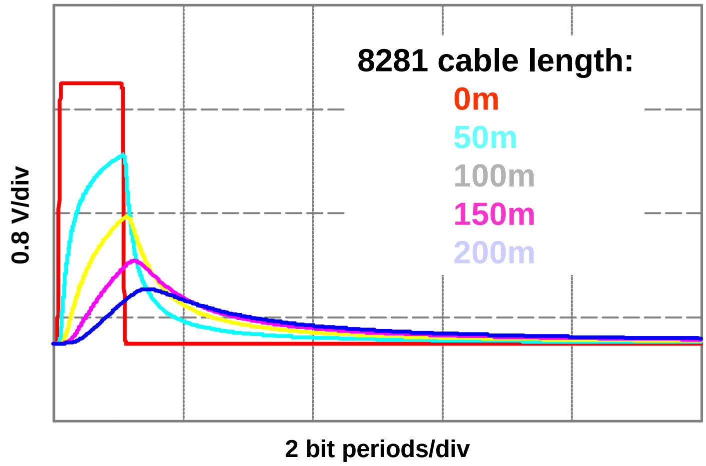
Equalization

- Isolated pulse responses
  - Pulse spreading
  - Group delay variation
- Equalization
  - Magnitude equalization
  - Phase equalization
  - The Comlinear CLC014 Equalizer
  - Equalizer bandwidth and noise
- Bit error probabilities

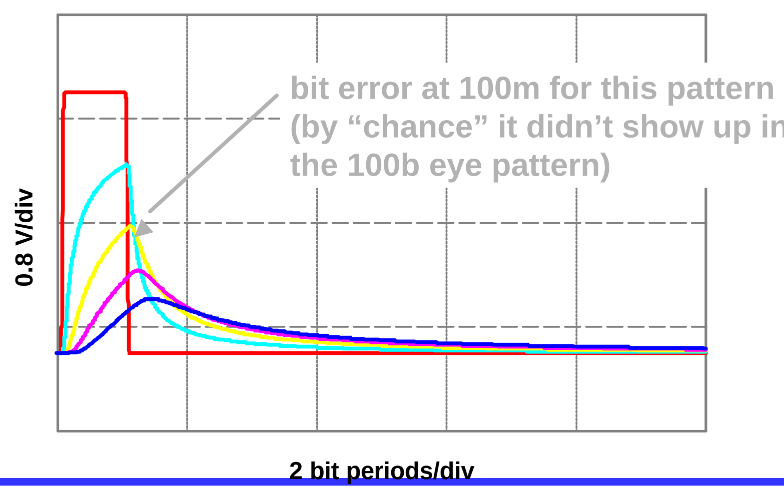
Isolated Pulse Responses

- Another way of looking at NRZ waveform degradation is to examine transmission line response to an isolated pulse
- For purely random binary data, the pattern
  [0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0]
  appears, on average, once in every 2^{20} 20b patterns
  - That's once every 20e6 bits
  - The transmission line output to this pattern is shown on the following slide

Isolated +1 Data Bit



Isolated +1 Data Bit

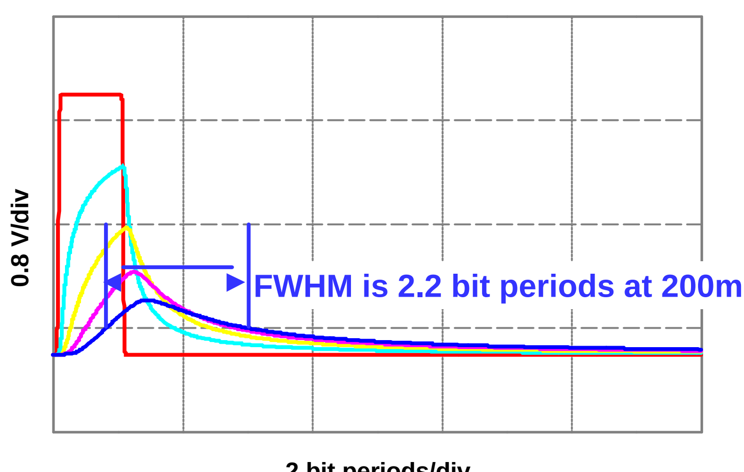


Isolated +1 Data Bit

- Pulse widths increase as the NRZ signal moves down the cable
  - A common measure of pulse width is the Full Width at Half Maximum, or FWHM
  - Isolated pulse width after 200m of cable is 2.2 bit periods are shown in the next slide

- They are a sure sign of group delay variation with frequency
  - If all frequency components receive the same delay, pulses can't spread out
  - Pulse widths of multiple bit periods obviously wreak havoc on eye diagrams and data recovery

Isolated +1 Data Bit



Transmission Line Group Delay

- Cable transfer function:

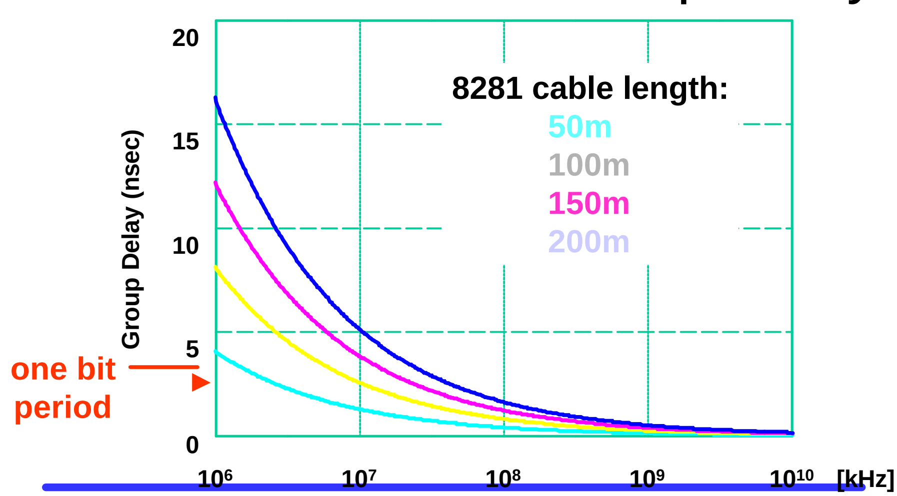
$$H_C(f) = e^{-kL(1+j)\sqrt{f}}$$

- Group delay $\tau_{GR} \equiv -d\theta(\omega)/d\omega$:

$$\Theta(w) = -kL\sqrt{\frac{w}{2p}}$$

$$t_{GR}(f) = \frac{kL}{4p\sqrt{f}}$$

Belden 8281 Cable Group Delay



Transmission Line Group Delay

- Note that each 50m cable segment adds the same amount of group delay at each frequency
  - Consider each 50m segment of cable as a filter
  - Group delays of cable lengths in series add just like group delays for filters in series

- NRZ spectral density is constant below 10^8 Hz
  - Increasing amounts of low frequency group delay are applied to decreasing amounts of signal energy

Equalization

- Equalization is a pretty simple concept
- If the cable response is:

$$H_C(f) = e^{-kL(1+j)\sqrt{f}}$$

- A perfect equalizer built into the data receiver will have response:

$$H_E(f) = e^{+kL(1+j)\sqrt{f}}$$

- So that

$$H_C H_E = 1$$

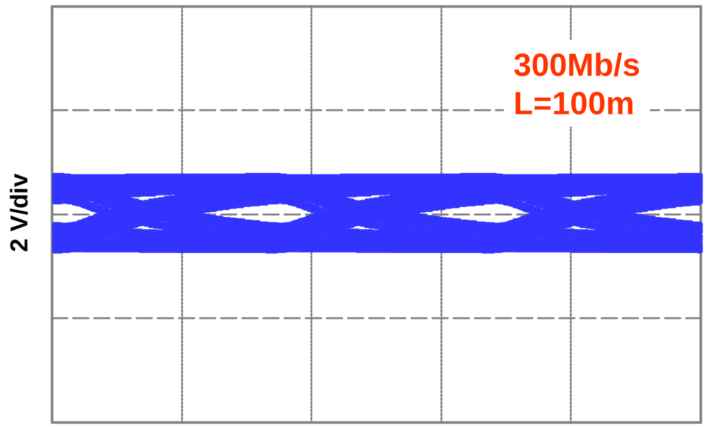
Equalization

- In a world of perfect equalizers, we'd never need to worry about channel response
  - The receiver's equalizer output would match the signal transmitted into the cable
- In the real world, equalizers aren't perfect
  - Modeling their nonidealities is essential
- Let's look at the significance of several equalizer nonidealities …

Equalization

- Nonidealities to consider:
  - Equalizer bandwidth limitations
  - Imperfect gain equalization
  - Imperfect phase equalization
  - Noise
- Our tool of choice for evaluating equalizer effectiveness will be the eye diagram
  - The eye diagram for the receiver input after 100m of Belden 8281 cable appears on the next slide …

100m 8281 Cable Eye Diagram

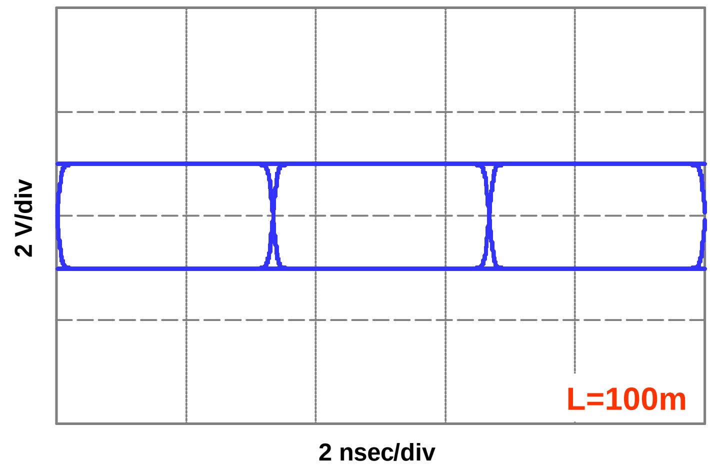


Ideal Equalization (#1)

$$H_{E1}(f) = e^{+kL\sqrt{f}}\, e^{-af^2}\, e^{+jkL\sqrt{f}}$$

magnitude phase

Equalizer #1 Eye Diagram

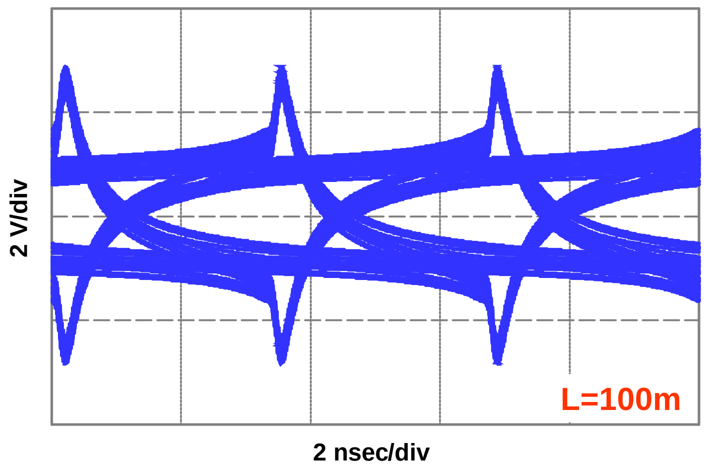


Gain Equalization (#2)

- In order to assess the relative importance of gain and phase equalization, we'll look at the 100m eye diagram for a "perfect" magnitude equalizer which ignores phase completely
  - Note that if you use a Parks-McClellan linear phase FIR gain equalizer, you ignore nonlinear phase completely
- Equalizer #2:

$$H_{E2}(f) = e^{+kL\sqrt{f}}\, e^{-af^2}$$

Equalizer #2 Eye Diagram



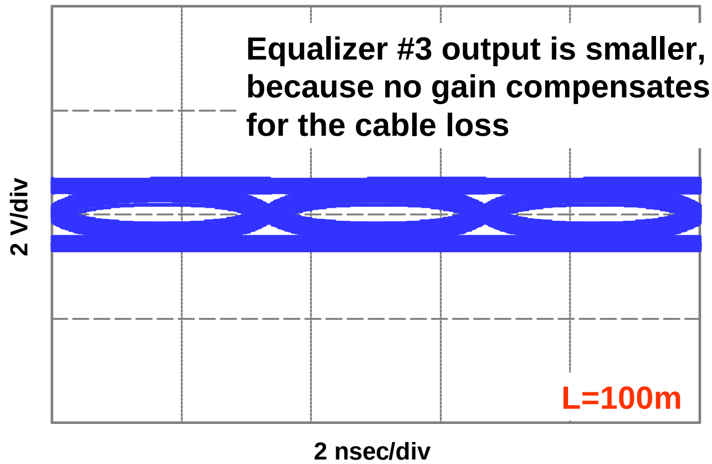
Phase Equalization (#3)

- Next, we'll check out the 100m eye diagram for a perfect phase equalizer which ignores magnitude completely

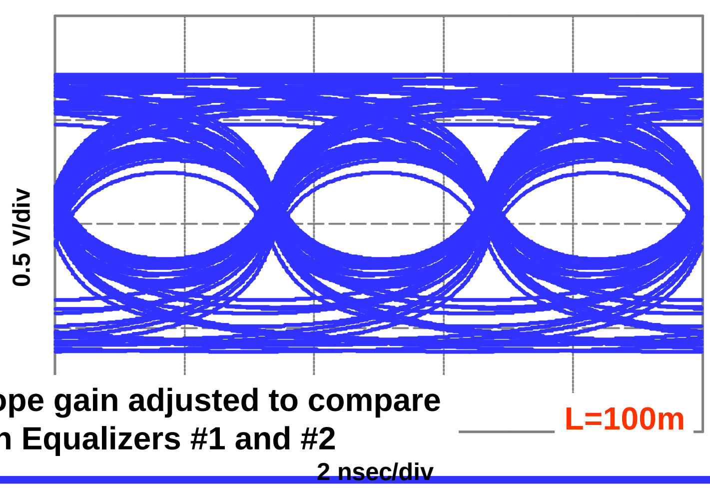
$$H_{E3}(f) = e^{-af^2} e^{+jkL\sqrt{f}}$$

- Note that the 100psec Gaussian response is still there to limit bandwidth

Equalizer #3 Eye Diagram



Equalizer #3 Eye Diagram



Scope gain adjusted to compare with Equalizers #1 and #2

Gain and Phase Equalization

- If anything, phase equalization alone produces better eye patterns than gain equalization alone
- Gain equalizers are high pass filters and produce spikey, high amplitude outputs
  - Scale analog signals to avoid clipping
- **Both gain and phase must be considered in channel equalization**

Equalizer #4

- In the real world, nobody can afford equalizer #1
  - Reasonably robust approximations to the inverse of cable transfer functions can be built with surprisingly simple analog circuits
- Let's see how Comlinear's Alan Baker [1] built an analog domain equalizer ("equalizer #4") using just 6 analog poles …

Equalizer #4

- While Comlinear's approach seems to violate our 5-pole analog signal processing limit, Baker gets a waiver because he cascades two identical 3-pole stages
- Only one adjustable parameter is needed to equalize cable lengths from 0m-300m
- Each of the two identical stages compensates for 0-150m of cable loss
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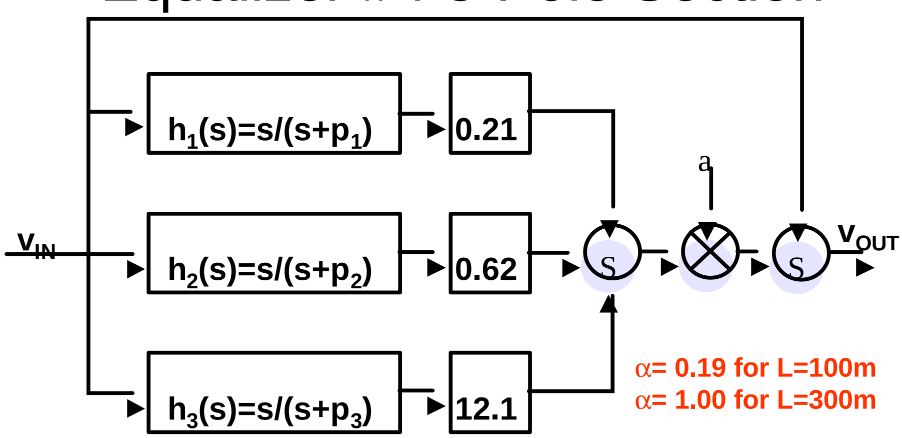
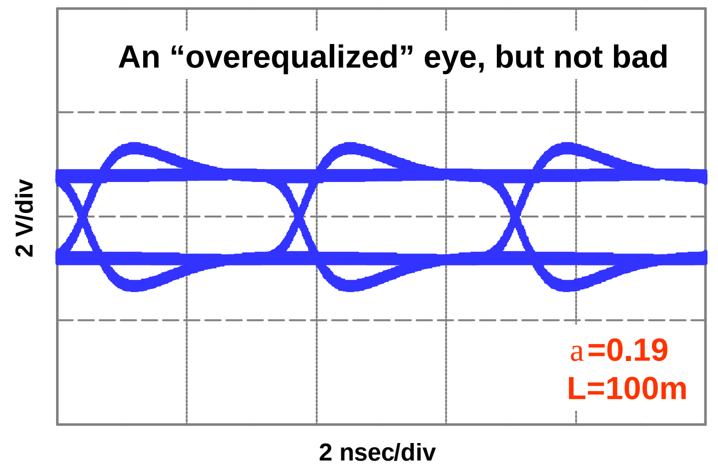
Equalizer #4 3-Pole Section



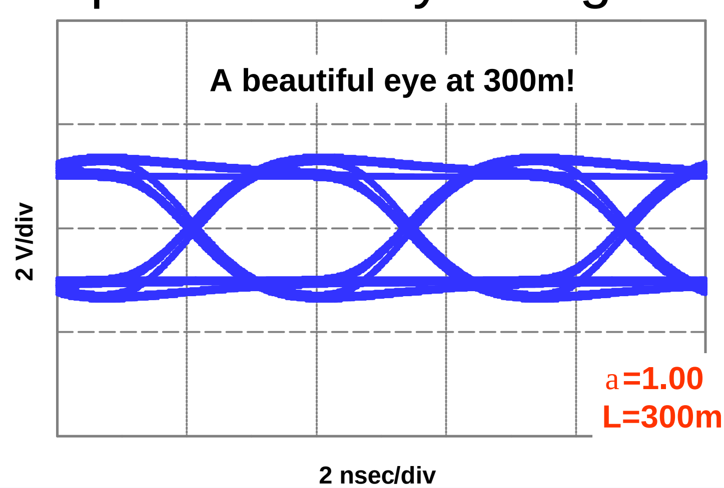
α= 0.19 for L=100m
α= 1.00 for L=300m

[p_1 p_2 p_3] = 2p [0.62MHz 14.1MHz 282MHz]

Equalizer #4 Eye Diagram



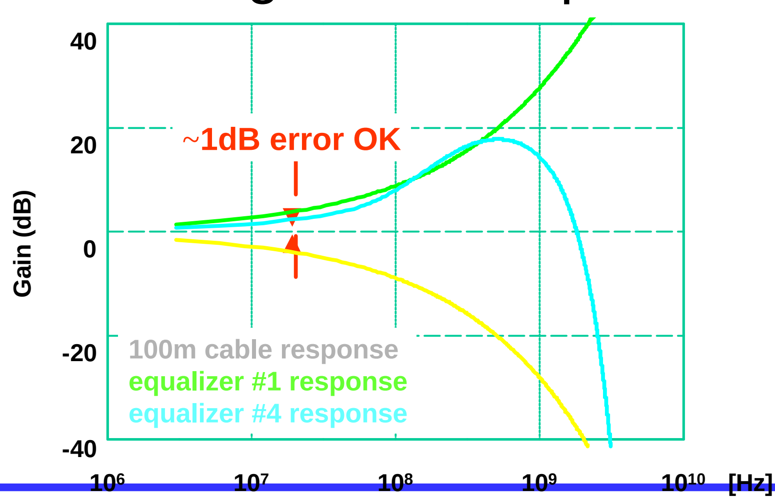
Equalizer #4 Eye Diagram



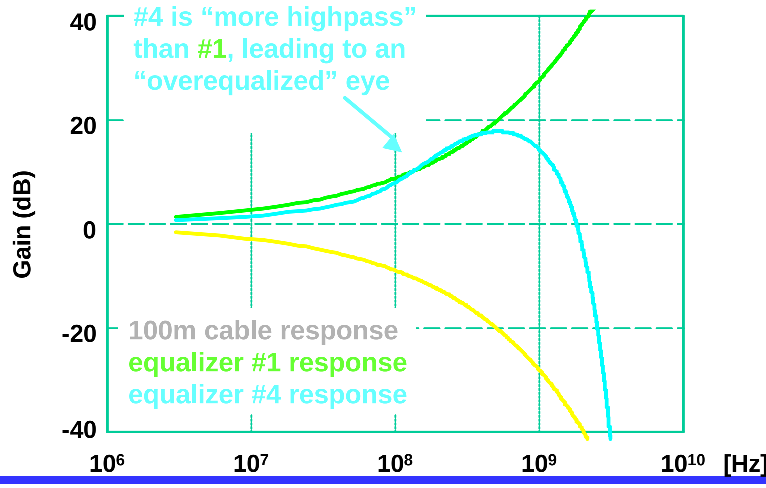
Equalizer #4

- While not approaching the ideal equalizer #1 response, equalizer #4 demonstrates the eye quality you'll see in real-world data receivers
- Let's compare the equalizer #1 and #4 responses in the frequency domain
  - This provides an idea of how closely responses have to match for the observed eye quality

100m Magnitude Responses



100m Magnitude Responses



Adaptive Equalization

- Now that we know something optimal equalization, how can a data receiver learn what equalization to apply?
  - Cable lengths vary from 0-300m in the Comlinear application
  - How does the CLC014 determine α?
- Adaptive equalization is a complex topic, with many different methods used in practice

Adaptive Equalization

- Equalizers may be trained at data link startup, or they may be continuously adaptive
  - Cable lengths don't change often, and service is interrupted when they do
- Adaptive analog methods include
  - Mapping equalizer p-p input voltage to α (John Mayo's method, [4])
  - Finding the value of α that minimizes equalizer output jitter
  - Finding the value of α that minimizes the difference between the decision circuit output and the equalizer output (Comlinear's method)

Adaptive Equalization

- Adaptive digital methods include Decision Feedback Equalization and many others
  - DFE builds adaptive digital FIR filters whose coefficients adjust to eliminate signal in bit periods N+1, N+2,… that's correlated with the signal in bit period N
  - Minimization of intersymbol interference leads to optimal equalization
- Digital-domain processing requires either a DAC or an ADC
  - Excessive converter resolution can make DSP expensive or infeasible at high data rates

Adaptive Equalization

- Analog-digital adaptive hybrids are usually found in IC data receivers
  - Minimal analog-domain pre-equalization reduces ADC (or DAC) resolution and DSP datapath width (and digital power)
  - Maximal digital-domain adaptive FIR equalizers finish the job
- 29%/yr DSP cost reduction leads to steady migration of equalization functions from the analog to digital domain
  - In the limit, analog signal processing becomes a low Q antialiasing filter and an ADC

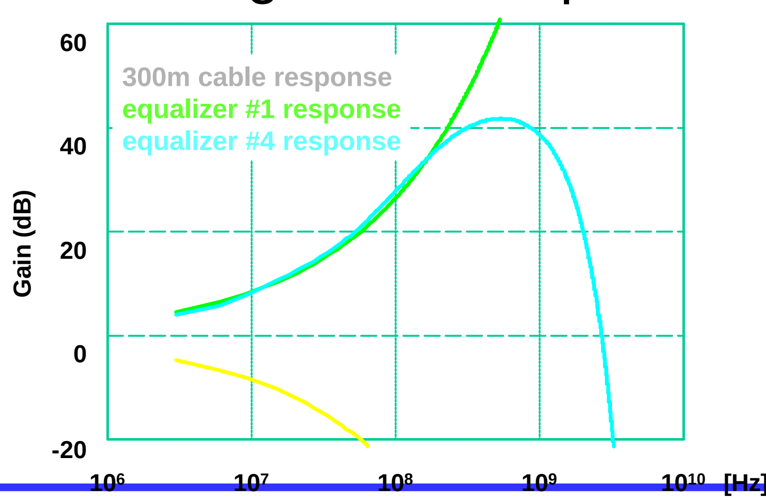
Equalizer Models

- Use equalizer behavioral models to understand
  - Communication channel variations
  - Analog equalizer component sensitivities
  - Analog signal swings
  - Adaptive equalization algorithms
  - Digital datapath specifications (bit-true, cycle-true DSP models)
- Equalizers are filters, so there's another important performance consideration
  - NOISE

Equalizer Noise

- For 300m cable lengths, the CLC014 equalizer provides lots of high frequency gain to compensate for cable loss
- The 300m equalizer magnitude response appears on the following slide …

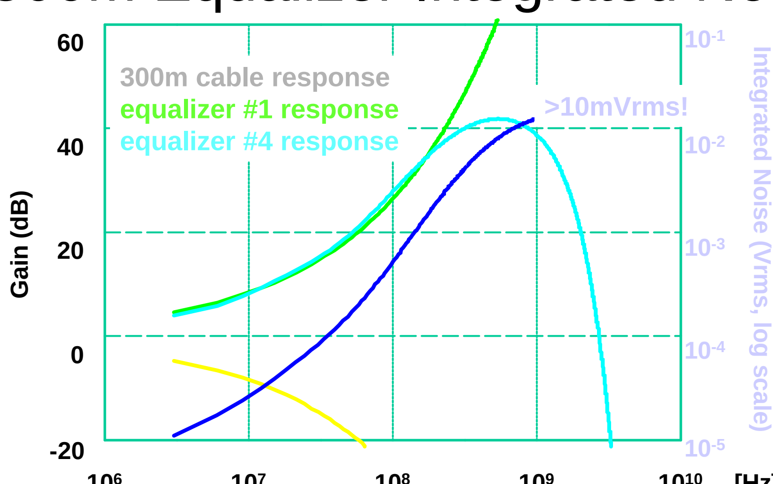
300m Magnitude Responses



Equalizer Noise

- Right at the input to the equalizer, there's bound to be a thermal noise source with a transfer function to the equalizer output equal to the equalizer transfer function itself
- We'll assume that this noise source is equivalent to that of a single 1kΩ resistor; that is, 4nV/√Hz
- The integrated noise at the equalizer #4 output appears on the next slide …

300m Equalizer Integrated Noise

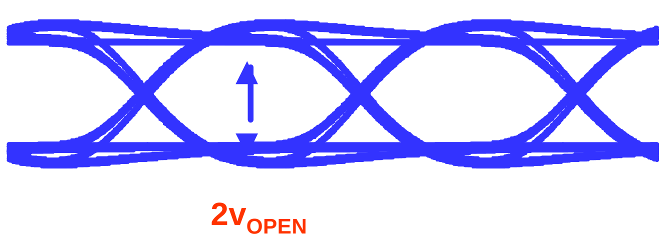


Equalizer Noise

- 10mVrms noise is a lot of noise!
  - Look at that noise on a scope and you'll see 60mV of peak to peak noise
  - Remember that this is the noise from just one 1kΩ source
  - Real world circuits have lots of noise sources
- Can we reliably detect digital bits with signal to noise ratios of ≈40dB?
  - Absolutely!
  - Let's find out why …

Equalizer Noise

- Suppose that we have an eye opening at the equalizer output of $2v_{OPEN}$
- Let's also suppose that our timing recovery system samples the equalizer output at the point where the eye is opened the widest



Equalizer Noise

- If the instantaneous noise voltage is greater than $+v_{OPEN}$ when we're trying to detect a –1, a bit error results
- If the instantaneous noise voltage is less than $-v_{OPEN}$ when we're trying to detect a +1, a bit error results
- To first order, the spectral distribution of the noise doesn't matter
  - Only the total integrated noise counts (it's sampled!)
- If the noise is Gaussian, error probabilities are a well understood statistical problem …

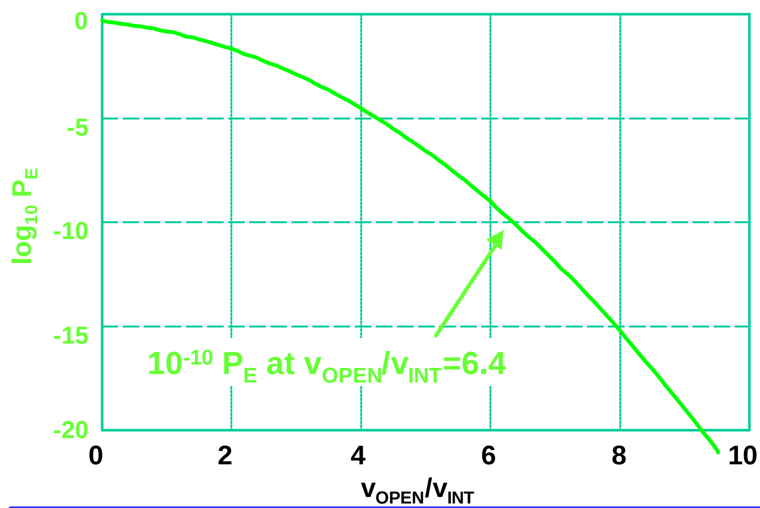
Bit Error Probabilities

- The bit error probability is [5]:

$$P_E = \frac{1}{2} erfc\left(\frac{V_{OPEN}}{\sqrt{2}V_{INT}}\right)$$

  - erfc(x) is the complementary error function and v_{INT} is the total rms integrated noise
- A plot of P_E vs. v_{OPEN}/v_{INT} appears on the following slide …

Bit Error Probability Plot



Equalizer Noise

- Error probability is an extremely strong function of integrated noise
  - Integrated noise is a strong function of cable length and equalizer bandwidth
- Error probability is an extremely strong function of eye opening
  - Eye opening is a strong function of equalization quality
- Lots of high sensitivities are a characteristic of data communication

Equalizer Noise

- Before you start gloating over how easy it is to get a P_E of 10^{-10}, talk to an analog designer
- The analog designer tells you that
  - A 1kΩ noise resistor is about 4X too low for a power-efficient equalizer ($\Rightarrow v_{INT}$>20mV)
  - Signal-swings in continuous time equalizers built in low voltage CMOS should be <100mVp-p ($\Rightarrow v_{OPEN}$<50mV)

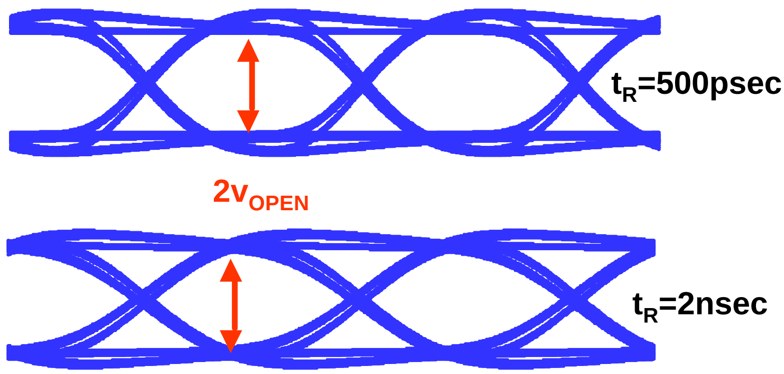
Equalizer Noise

- This digital communications system is closer to practical IC design limits than one might think
  - Future give-and-take sessions with the analog designer may pick up a dB or two of >100mV swings or <20mV noise
  - Every dB counts in the P_E business
- You resolve to apply one of the cardinal rules of analog design to your equalizer:

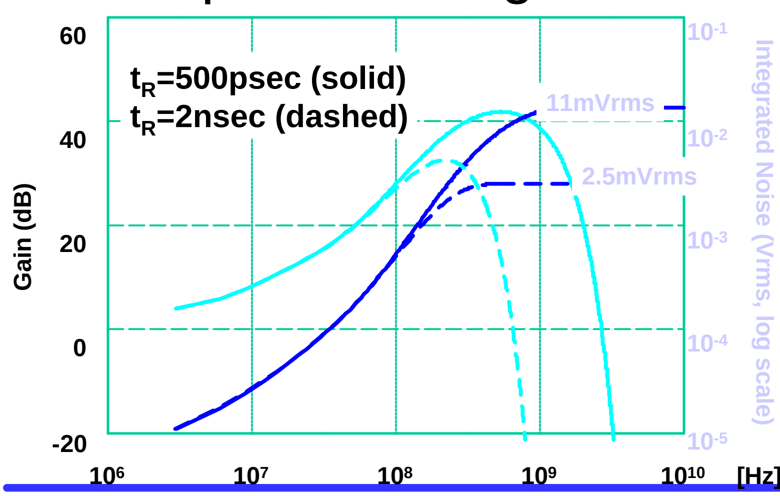
  Never use more bandwidth than you really need

Equalizer Noise

- Raising channel risetime from 500psec to 2nsec doesn't change the equalized v_{OPEN} much …



300m Equalizer Integrated Noise



Equalizer Noise

- Equalizer integrated noise grows linearly with bandwidth
  - Excess bandwidth can limit your range
- Optimizing both signals and noise is the real art of equalization (or any other filtering)!
- We'll examine the rest of the data recovery story next time …

References

1. Alan Baker, "An Adaptive Cable Equalizer for Serial Digital Video Rates to 400Mb/sec", ISSCC Dig. Tech. Papers, 39, 1996, pp. 174-175.
2. National Semiconductor (Comlinear division), CLC014 and CLC016 datasheets, 1998.
3. Belden Electronics, Type 8281 75Ω Precision Video Cable datasheet, 2001.
4. John Mayo, "Bipolar Repeater for Pulse Code Modulation Signals", Bell System Technical Journal, 41, Jan. 1962, pp. 25-47.
5. Bell Laboratories, Transmission Systems for Communications, 5th Edition, 1982, chapter 30.