# Data Receivers

- Digital data receivers
  - Equalization
  - Data detection
  - Timing recovery
- NRZ data spectra
  - Eye diagrams
- Transmission line response

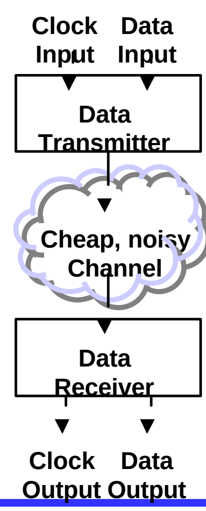
- Think of it as another example for a 247 project …



# Digital Data Receivers

- Way back in Lecture 1, we looked briefly at the digital communication problem

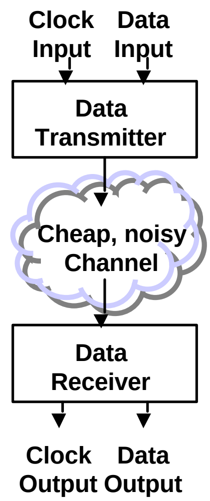
- Everyone wants to send bits as far as they can, as fast as they can, through the cheapest possible media, until recovery of those bits is a complex signal processing problem



# Digital Data Receivers

- Also, since nobody wants to invest in a separate channel to send a clock alongside the data, timing recovery is a second key responsibility of digital data receivers

- Today, data detection / timing recovery is the biggest mixed-signal processing market there is






# Digital Data Receivers

- We'll examine digital communications using high-speed digital video over coaxial cable as our underlying example
  - 300Mb/s over distances of 200m
  - It illustrates many key principles of data detection and timing recovery [2, 3]

# NRZ Data Spectrum

- NRZ (<u>N</u>on <u>R</u>eturn to <u>Z</u>ero) data is a complicated-sounding name for a very simple two-level transmission scheme
  - The data transmitter produces two output levels, and holds the appropriate binary level for a full bit period
  - We'll assume the two levels are +1 and –1
- What's the spectrum of random NRZ data?

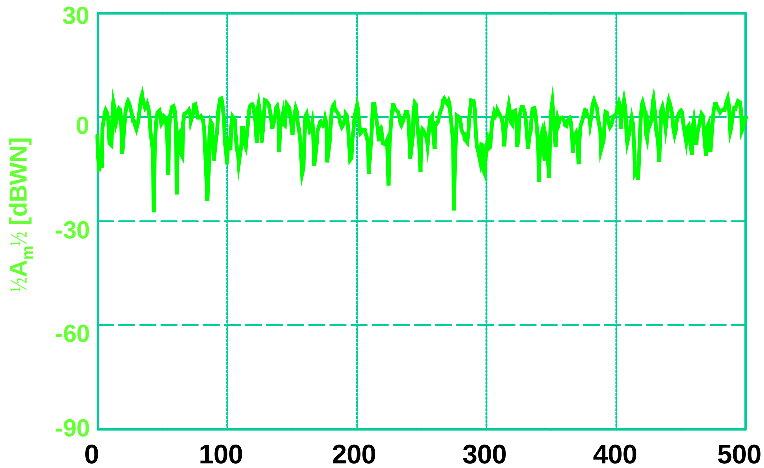


# Ideal NRZ Data Spectrum

- We looked at random 1b sequences in Lecture 15 (slides 15.4-15.5)
  - Random sequences yield white noise
- An ideal NRZ data transmitter convolves (in time) digital data impulses with a zero-order hold function (slides 12.11-12.12)
  - The resulting spectrum is the product of the digital data's white spectrum and the zero-order hold's sinx/x response:

$$H(f) = Te^{-j\pi fT}\frac{\sin(\pi fT)}{\pi fT}$$

# Ideal NRZ Data Spectrum

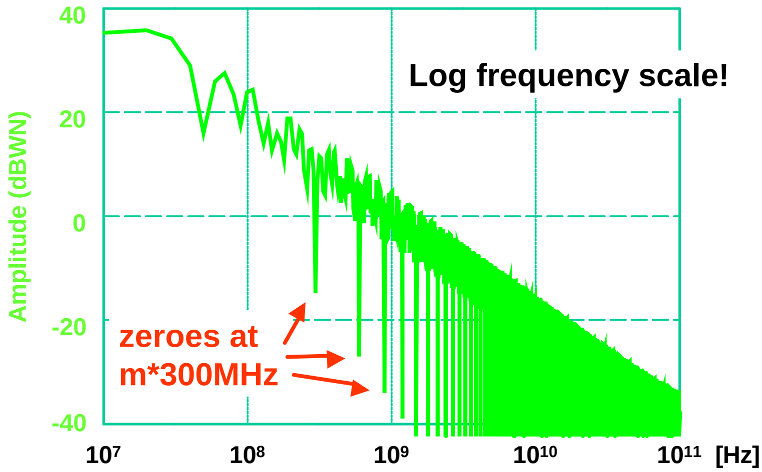





# Ideal NRZ Data Spectrum

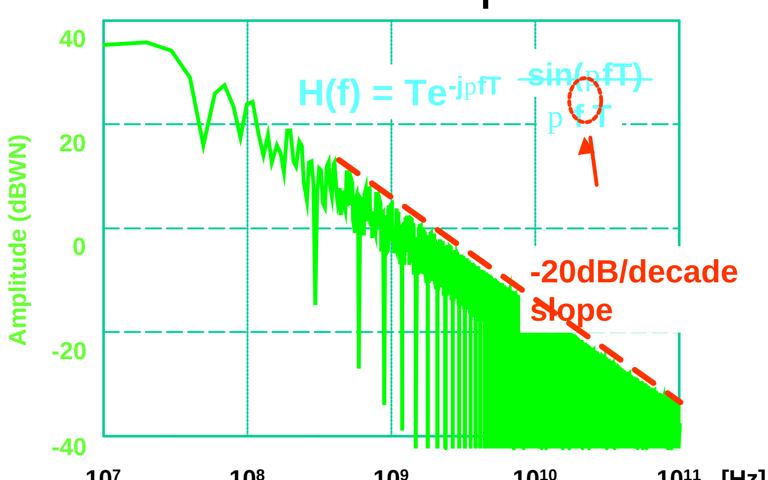
- Communication channels are not "sampled data" systems
  - The digital data is passed through a ZOH
- Let's look at 300Mb/s NRZ data
  - Expect nulls at multiples of 300MHz (from sinc)

# Ideal NRZ Data Spectrum






# Ideal NRZ Data Spectrum

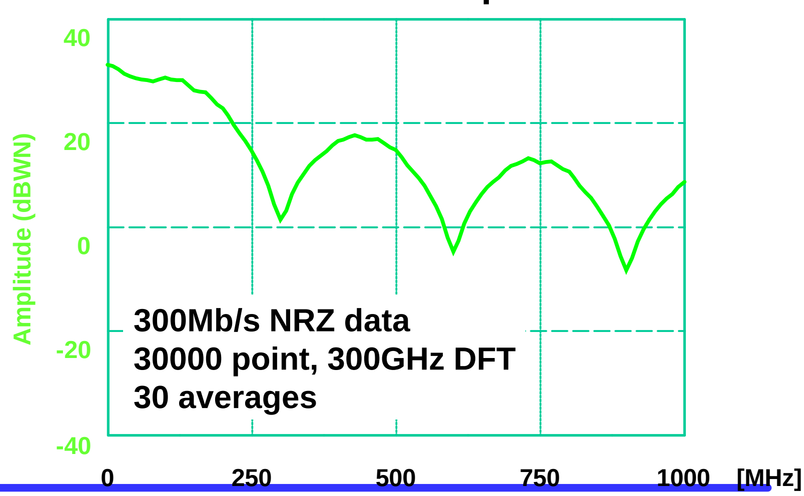


# Ideal NRZ Data Spectrum

- Averaging can provide a better indication of long term bin amplitudes
  - 30 averages here produce a DFT plot based on 900 unique transmitted bits
  - Results conform much more closely to the sinx/x response
- We'll return to our more customary linear frequency scale for DFT plots at 1GHz and below…



# Ideal NRZ Data Spectrum



# Non-Zero Transition Times

- The zero-order hold NRZ spectrum assumes zero transition times between binary levels
- All real-world NRZ data drivers take some time to switch from one level to the other
  - How does this change the ideal NRZ data spectrum?



# Non-Zero Transition Times

- We'll shape the edge rate of the ideal NRZ signal via a low pass filter
- The low pass filter we'll use is a Gaussian LPF, commonly used in digital signal analysis applications [4]
- A Gaussian filter's magnitude response is given by:

$$|H(f)| = e^{-\frac{f^2}{2s^2}} \qquad s \approx \frac{t_{rise} f_s}{2.56}$$

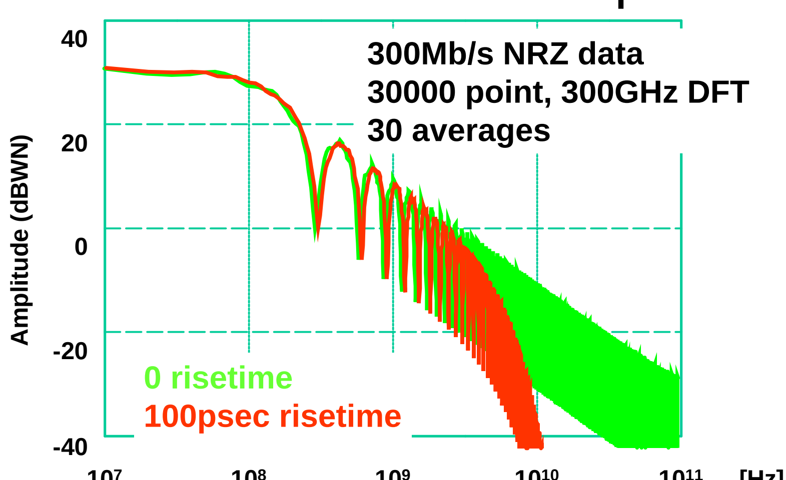
# Non-Zero Transition Times

- Let's check the effect of a Gaussian Filter
  - Set the 10% to 90% rise times (and fall times) of the NRZ signal to 100psec
  - 100psec transitions times are still very fast relative to our 3.3nsec data period
- The filtered NRZ data spectrum appears in red on the following slide …





# Ideal vs. Filtered Data Spectra



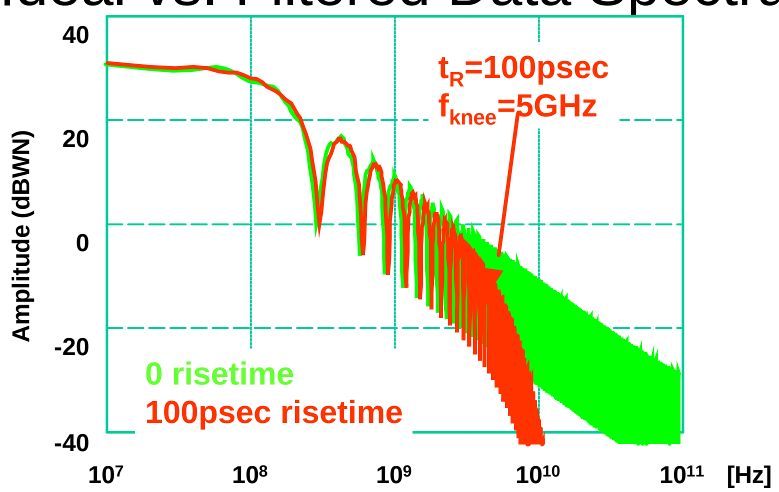
# Ideal vs. Filtered Data Spectra

- The frequency at which the ideal and filtered NRZ spectra begin to diverge (by 6.8dB, in fact) is called the "knee frequency", $f_{knee}$
  - Knee frequencies depend only on transition times, not NRZ data rates
  - There's not enough energy above $f_{knee}$ to have much effect on even the simplest data receiver (a CMOS inverter)
- For digital signals with 10/90 transition times:

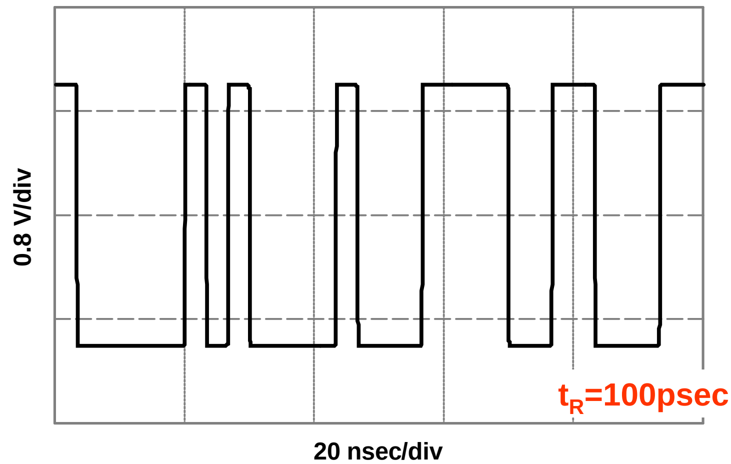
$$f_{knee} = \frac{1}{2t_{rise}}$$



# Ideal vs. Filtered Data Spectra

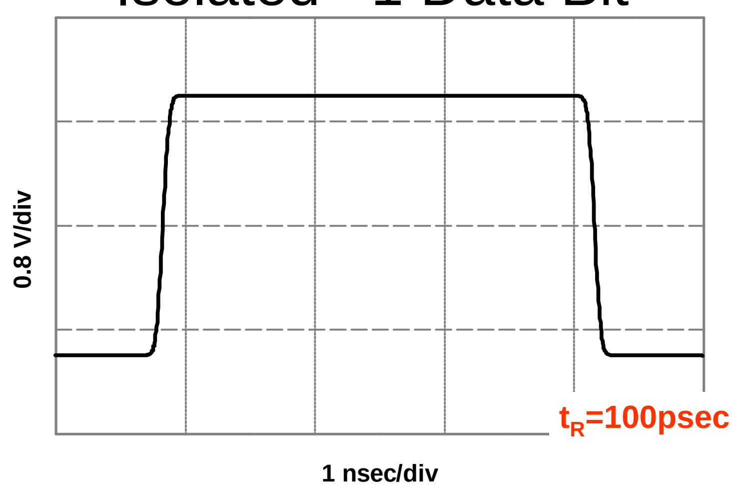


# NRZ Data in the Time-Domain






# Isolated +1 Data Bit

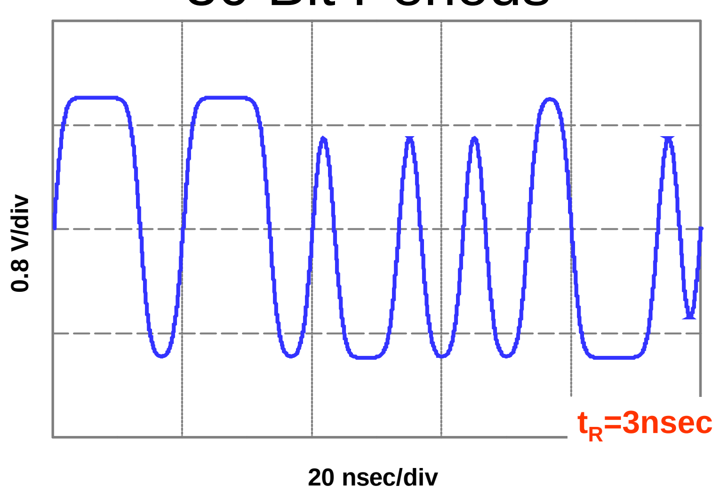


# Filtered NRZ Data

- In high-speed communications applications, the transition times are usually comparable to the bit period
  - Then, filtered outputs reach the full +1 and –1 levels only if ≥2 consecutive data bits are identical
  - Isolated +1 and –1 pulses yield smaller swings
- Let's see what happens when $t_R$=3nsec …
  - $f_{knee}$= 167MHz



# 30 Bit Periods



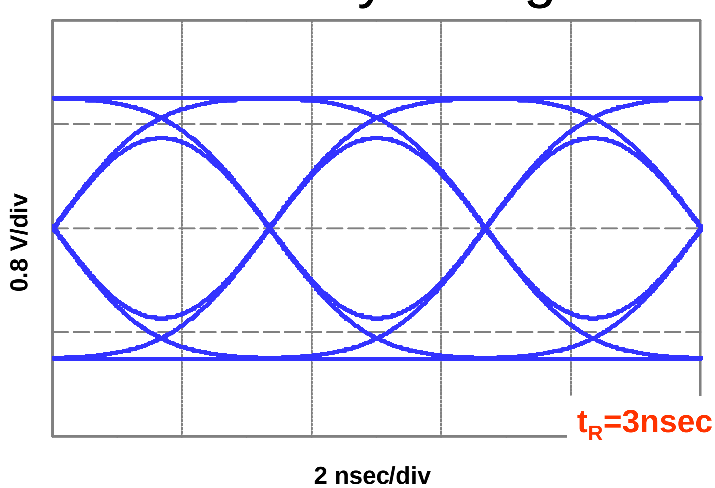
# Eye Diagrams

- Random NRZ data patterns are difficult to study in the time domain
  - Every data set is different
  - Finding isolated pulses is a pain
- In 1962, John Mayo at Bell Laboratories found a better way [5]
  - Scope traces are launched using the transmit clock as an external trigger
  - The resulting oscillogram overlays every data-pattern-dependent variation of the filtered NRZ spectrum
  - For obvious reasons, these are called “eye diagrams” …

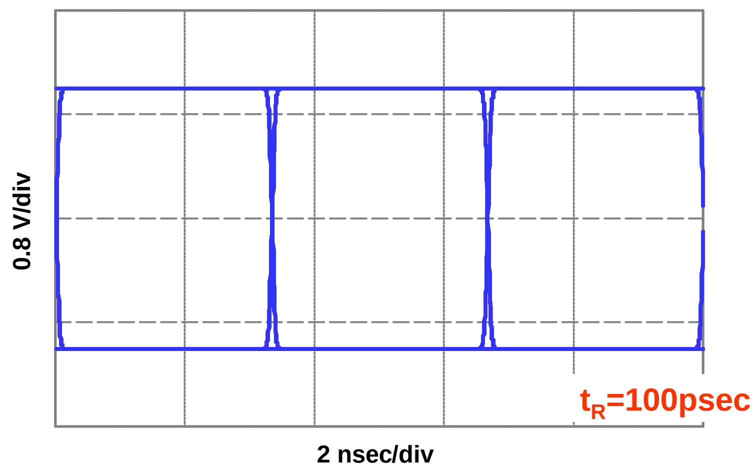




# 300Mb/s Eye Diagram



# 300Mb/s Eye Diagram

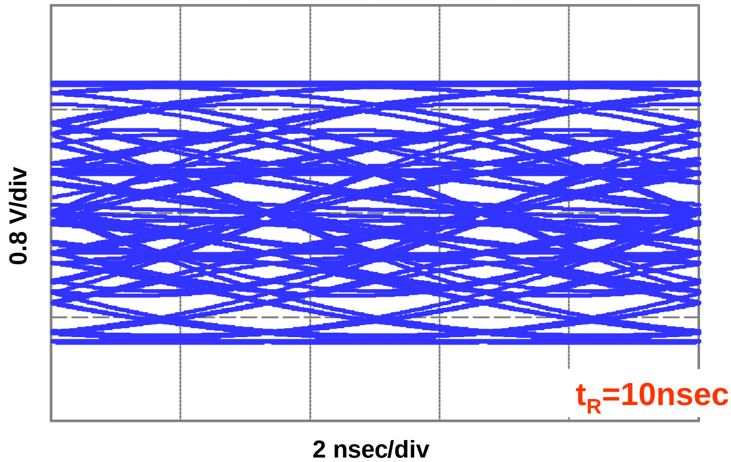





# Eye Diagrams

- Eye opening is an important indicator of the health of a NRZ channel
  - Eyes close completely if the channel bandwidth is insufficient to support the NRZ data rate
  - An eye diagram for $t_R$=10nsec appears on the next slide
- Closed eyes don't mean that all hope for digital communications is lost
  - The receiver can do some filtering prior to deciding what the transmitted bit was
  - A high pass equalizer added to a data receiver can compensate for a low pass channel

# 300Mb/s Eye Diagram



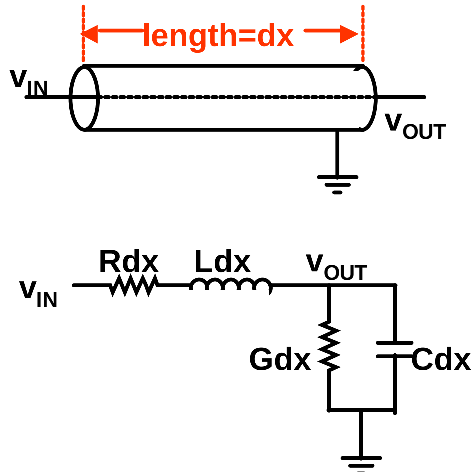



# Transmission Lines

- Now that we know something about the 300Mb/s NRZ signal we're sending into a coaxial transmission line, it's time to figure out what that signal will look like coming out the other end of the line
- We'll summarize a few key characteristics of transmission lines first

# Transmission Lines

- Transmission lines are characterized by distributed electrical parameters specified on a per unit length basis
  - R: series resistance per meter (Ω/m)
  - L: series inductance per meter (H/m)
  - C: shunt capacitance per meter (F/m)
  - G: shunt conductance per meter ($\Omega^{-1}$/m)






# Transmission Lines

- At high frequencies, the characteristic impedance of a transmission line is given by

$$Z_0 = \sqrt{\frac{L}{C}}$$

- Transmission lines should be terminated with their characteristic impedance
  - Reflections caused by impedance mismatches are common sources of bad lab data
  - Or non-working systems

# Transmission Lines

- The Belden 8281 cable used in our example application is specified with (ref. 7):
  - L=379nH/m
  - C=67.3pF/m
  - $Z_0$=75.0Ω
- For lossless transmission lines (R=G=0), all frequency components present in an input signal move down the cable at a velocity given by:

$$\mathbf{v = \frac{1}{\sqrt{LC}}}$$

**2.0x10$^8$m/s for 8281 cable (2/3 the speed of light)**



# Transmission Lines

- A bit that we transmit into the cable at t=0 will start to come out of the end of a 200m cable 1μsec later
  - 2/3 speed-of-light delays range from zero (short links) to 300 bit periods (at 200m)
  - The linear phase (fixed time delay) component of cable response doesn't distort pulse shapes and cause trouble
- Is the lossless model reasonable for Belden 8281 cable?

# Transmission Lines

- Resistor R and conductance G at losses to the cable model
  - G≈0
  - R=0.0354Ω/m
- The impedance of the 8281 cable series inductance dominates the cable's series resistance once frequencies exceed 15kHz
  - Lossless models seem appropriate for f>>15kHz



# Skin Effect

- Unfortunately, at frequencies > 1MHz another loss mechanism comes into play …
  - The "skin effect" causes a cable's series resistance to increase with frequency (~√f )
  - The skin effect is the dominant coaxial cable loss mechanism at frequencies above 1MHz [7]

# Transmission Lines

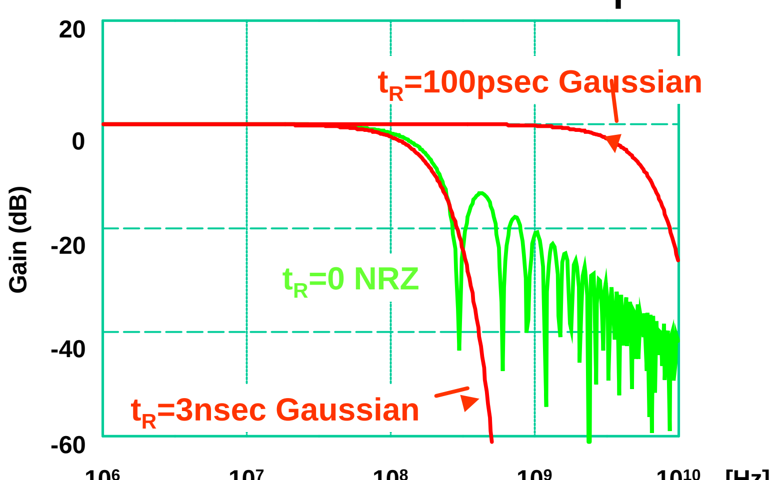
- The transfer function (excluding the linear phase component) of a length=L section of transmission line <u>properly terminated with its characteristic impedance</u> is given by

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

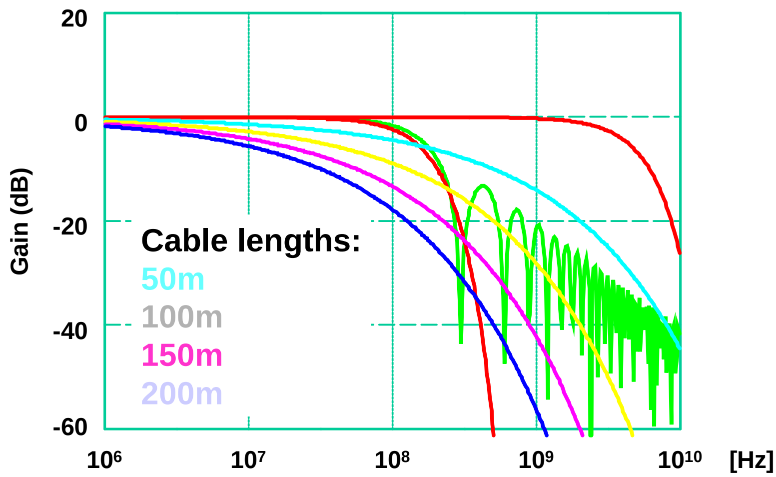
- For Belden 8281 cable, k=1.023e-6



# NRZ Data and Filter Responses



# Belden 8281 Cable Response

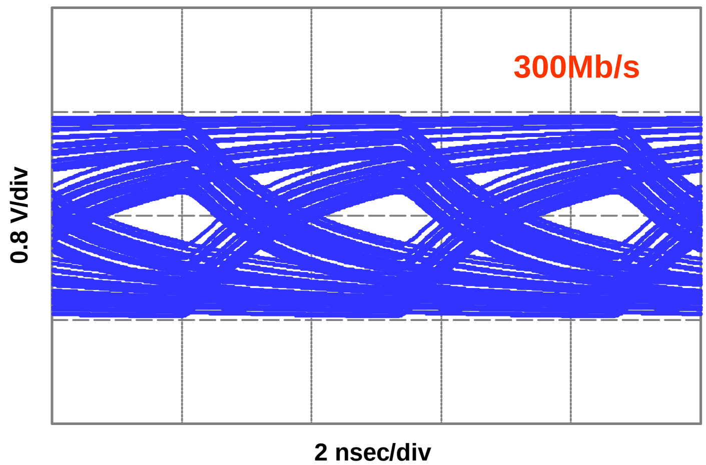





# Belden 8281 Cable Response

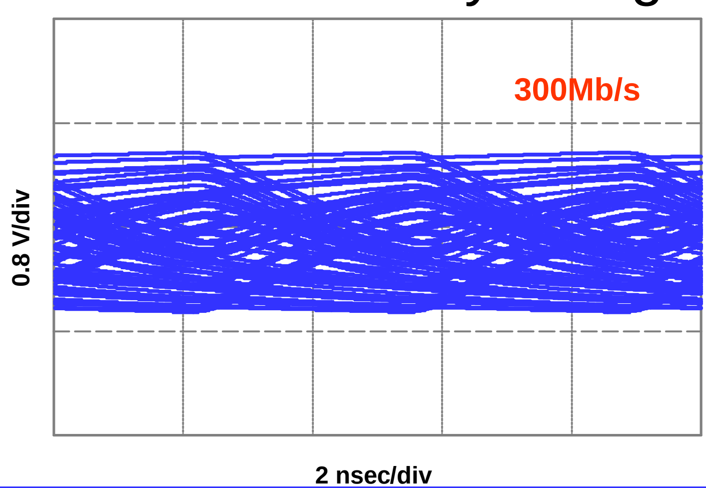
- Cable attenuation is a strong function of length L
- Especially at 200m it's worse than 3ns rise/fall times times
  - It's reasonable to expect severely degraded eye patterns at 100m and complete eye closure at 200m
  - Let's take a look at the 100m and 150m eye diagrams…

# 100m 8281 Cable Eye Diagram






# 150m 8281 Cable Eye Diagram



# 150m 8281 Cable Eye Diagram

- Coaxial cable bandlimiting of the NRZ data signal results in complete eye closure by 150m
  - And inadequate margins at 100m
- We'll have to do some signal processing on the degraded NRZ signal before deciding what bits were sent
- That signal processing is called **equalization**, and we'll examine equalization and noise next time



# References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3. David Potson and Alan Buchholz, "A 143-360Mb/sec Auto-Rate Selecting Data-Retimer Chip for Serial-Digital Video Signals", ISSCC Dig. Tech. Papers, 39, 1996, pp. 196-197.
4. Howard Johnson and Martin Graham, High-Speed Digital Design: A Handbook of Black Magic, 1993, chapter 1 and appendix B.
5. John Mayo, "Bipolar Repeater for Pulse Code Modulation Signals", Bell System Technical Journal, 41, Jan. 1962, pp. 25-47.
6. John Kraus and Keith Carver, Electromagnetics, 1973, chapter 13.
7. Bell Laboratories, Transmission Systems for Communications, 5th Edition, 1982, chapters 5 and 30.
8. Belden Electronics, Type 8281 75Ω Precision Video Cable datasheet, 2001.
9. National Semiconductor (Comlinear division), CLC014 and CLC016 datasheets, 1998.