

# Lecture 16: Digital Carrier Modulation

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# Digital Carrier Modulation

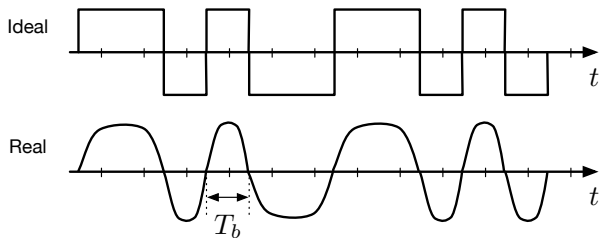
## Lecture topics

- ▶ Eye diagrams
- ▶ Pulse amplitude modulation (PAM)
- ▶ Binary digital modulation
  - ▶ Amplitude shift keying (ASK)
  - ▶ Frequency shift keying (FSK)
  - ▶ Phase shift keying (PSK)
- ▶ Example of a high-speed 8b/10b serial link

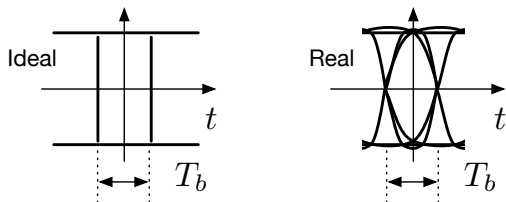
## Eye Diagrams

We have an idea digital waveform we want to transmit

The actual waveform is smoother and may be distorted.

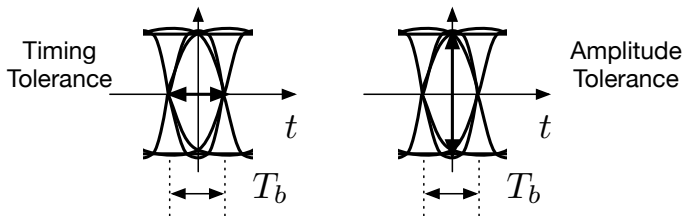


To visualize how readily the bits can be recovered, we plot each symbol superimposed.



## Eye Diagram

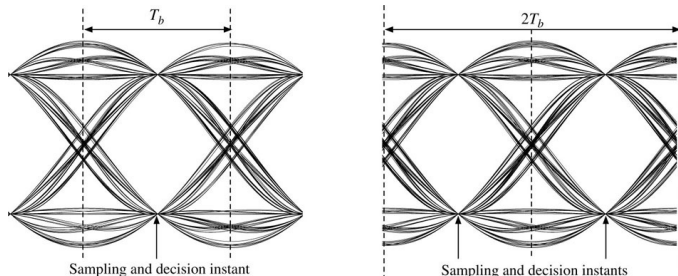
- ▶ When we decide if a particular bit is  $\pm 1$ , we choose a threshold level and a time.
- ▶ If the eye diagram is open, we can make that decision without error.
- ▶ The dimensions of the "eye" tell you the tolerance to timing and noise



- ▶ Timing jitter will make the eye narrower, and noise will make the height of the eye smaller
- ▶ The shape of the eye depends on the pulse shape (last time), channel distortion, and timing errors.

## Polar Signaling with Raised Cosine Transform ( $r = 0.5$ )

Last time we talked about Nyquist pulses. These were designed to be zero at the adjacent samples, but  $(1 + r)$  times wider in bandwidth than a sinc.



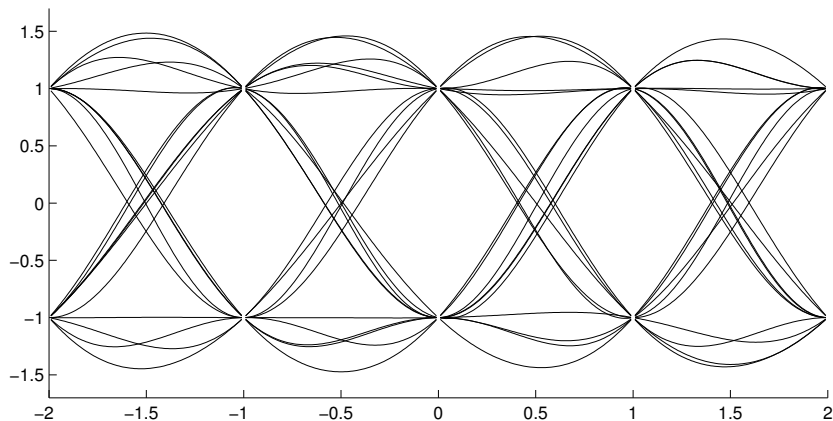
The timing sensitivity is less than  $T_b$ , and the noise sensitivity increases roughly linearly with timing error.

$$P(f) = \begin{cases} 1 & |f| < \frac{1}{4}R_b \\ \frac{1}{2} \left( 1 - \sin \pi \left( \frac{f - \frac{1}{2}R_b}{R_b} \right) \right) & \left| |f| - \frac{1}{2}R_b \right| < \frac{1}{2}R_b \\ 0 & |f| > \frac{3}{4}R_b \end{cases}$$

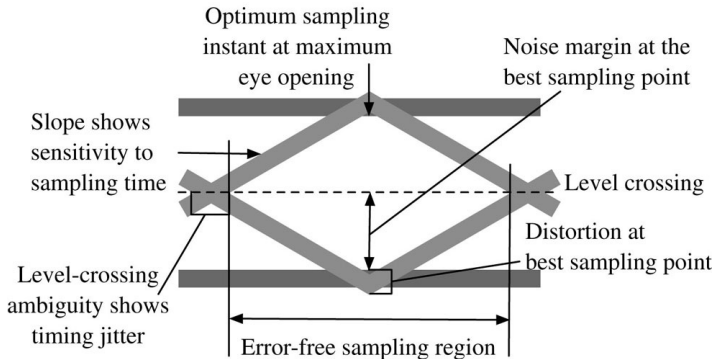
## Polar Signaling with Raised Cosine Transform ( $r = 0.5$ )

The pulse corresponding to  $P(f)$  is

$$p(t) = \text{sinc}(\pi R_b t) \frac{\cos(\pi r R_b t)}{1 - 4r^2 R_b^2 t^2}$$



# Eye Diagram Measurements



- ▶ Maximum opening affects noise margin
- ▶ Slope of signal determines sensitivity to timing jitter
- ▶ Level crossing timing jitter affects clock extraction
- ▶ Area of opening is also related to noise margin

## Eye Diagrams and PAM: $M$ -ary Baseband Signaling

- ▶ So far we've just been considering the case where we are sending one bit at a time. We can also vary the pulses to convey information, and send multiple bits of information with each pulse, or symbol.
- ▶ We'll talk much more about this next time. For now, we just consider the simple case where there is just one pulse  $p(t)$ , and we vary the amplitude.

$$y(t) = \sum_k a_k p(t - kT_b)$$

where  $a_k$  is chosen from a set of more than two values (i.e., not just  $\pm 1$ ).

- ▶ Eye diagrams are useful for understanding this case also.

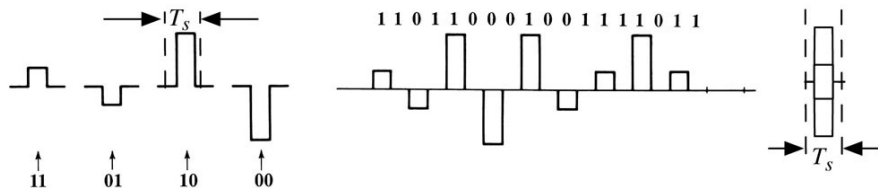


## Example: ISDN

One widely used encoding of two bits into four levels is

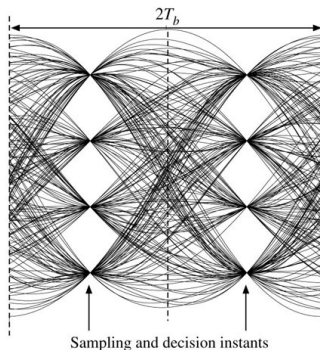
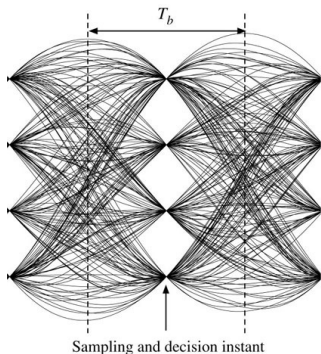
$$a_k = \begin{cases} -3 & \text{message bits } 00 \\ -1 & \text{message bits } 01 \\ +1 & \text{message bits } 11 \\ +3 & \text{message bits } 10 \end{cases}$$

This is used in ISDN, a digital home and office network connection since replaced by DSL.



## PAM Eye Diagram

- ▶ The eye diagram for 4-level PAM using Nyquist  $r = 0.5$  pulses looks like this



- ▶ Timing is even more critical
- ▶ The noise sensitivity is increased by a factor of 4, since each eye is  $1/4$  the height.

## ISDN Power Spectrum

- ▶ Power of 4-ary signaling:

$$R_0 = \frac{1}{4}((-3)^2 + (-1)^2 + 1^2 + 3^2) = \frac{1}{4} \cdot 20 = 5.$$

If digital values are independent,  $R_n = 0$  for  $n \neq 0$ .

- ▶ Thus PSD is

$$S_y(f) = \frac{5}{T_s} |P_x(f)|^2,$$

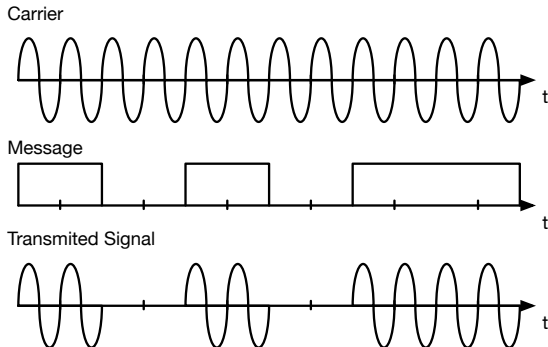
- ▶ The PSD is the same as binary signaling.
- ▶ More bits use more power.
- ▶ We'll return to M-ary signaling next class.

# Digital Carrier Modulation

- ▶ In class so far we've just talked about baseband modulation of digital signals
  - ▶ Ethernet
  - ▶ Fiber
  - ▶ USB
- ▶ As you've seen in the labs, the same ideas work for sending bits over a carrier, such as RF
- ▶ We'll look at several simple ways to encode bits on a carrier
  - ▶ On-Off Keying (OOK)
  - ▶ Phase-Shift Keying (PSK)
  - ▶ Frequency Shift Keying (FSK)
- ▶ These are designed to be simple to generate, and simple to decode.

## On-Off Keying (OOK)

- ▶ A simple version of ASK
- ▶ Modulated signal is  $m(t) \cos 2\pi f_c t$ .

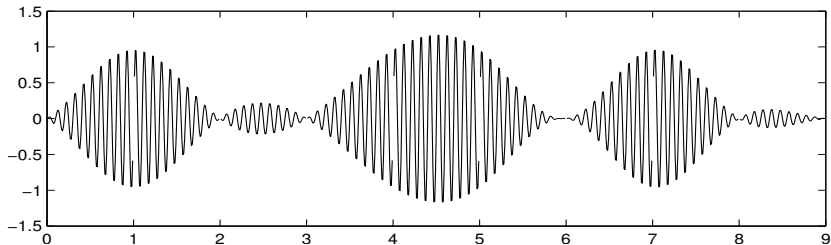
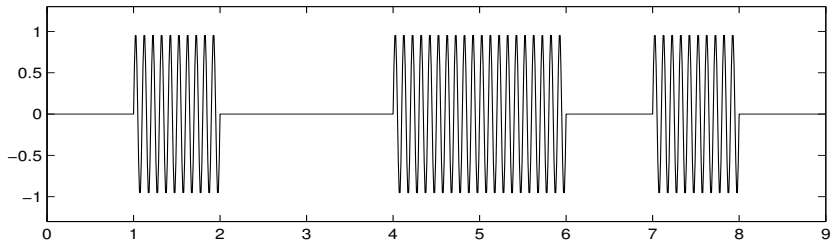


- ▶ Easy to generate, gate an oscillator on and off
- ▶ Easy to receive, a simple envelope detector suffices

# OOK Example

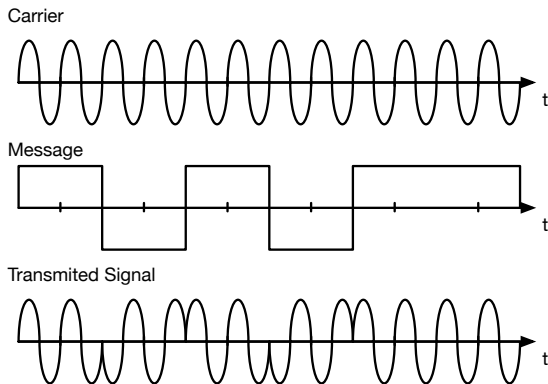
Baseband signal may use shaped pulses, so cosine amplitude varies.

Digital input: 1 0 0 1 1 0 1 0 0. Square wave and shaped pulses.



## Phase Shift Keying (PSK)

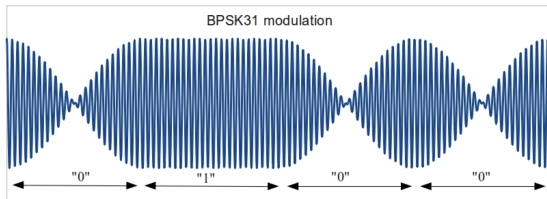
- ▶ Binary PSK is the same as polar ASK. M-ary versions are next time.



- ▶ Usually use an integer number of cycles of an offset frequency, and modulate that up to the carrier
- ▶ Phase changes at zero crossing to minimize bandwidth
- ▶ Detection generally must be synchronous, since the envelope is constant

## Example: BPSK31

- ▶ One PSK methods that is easy to decode is BPSK31, widely used in amateur radio.
- ▶ A "1" is a constant phase interval , and a "0" is sent with a phase inversion.

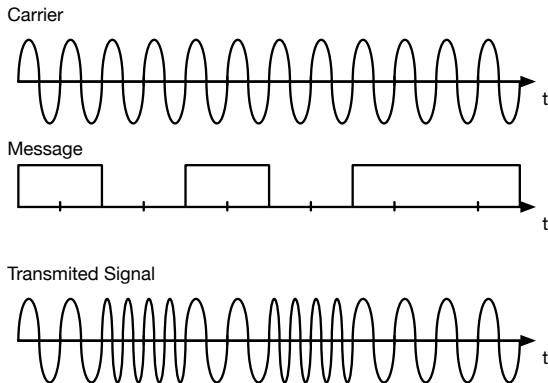


- ▶ The shaped pulses minimize the bandwidth
- ▶ After demodulating to baseband, lowpass filter follow by an envelope detector will decode the bits.



## Frequency Shift (FSK)

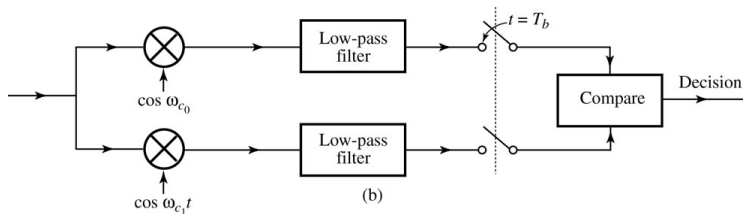
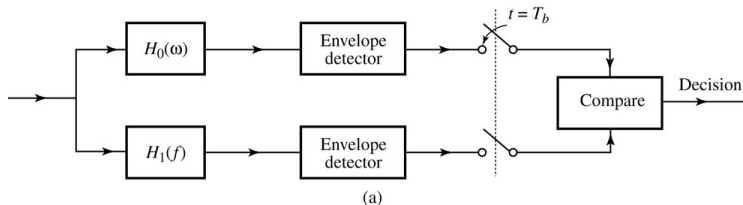
- ▶ Binary FSK uses two frequencies for 1 and zero. M-ary will be next time.



- ▶ Usually integer numbers of cycles of each offset frequency, so that they are orthogonal
- ▶ Easy to receive, can be done with filters and an envelope detector (see this week's lab!). Does not need to be synchronous.

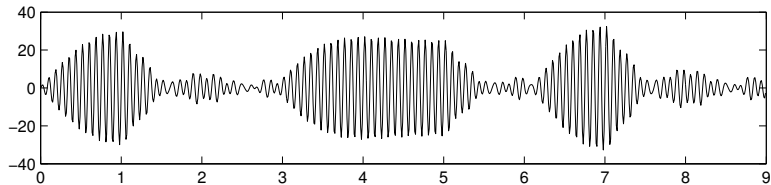
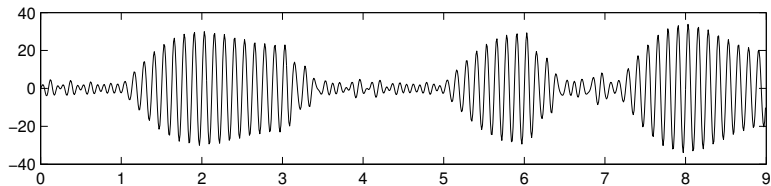
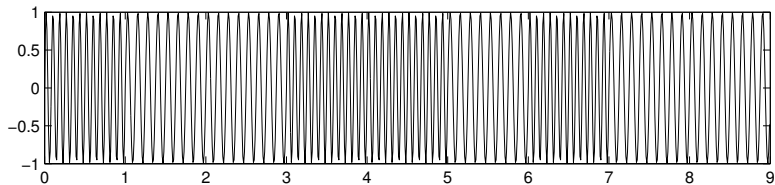
# Demodulation of FSK

FSK can use envelope or coherent detector.



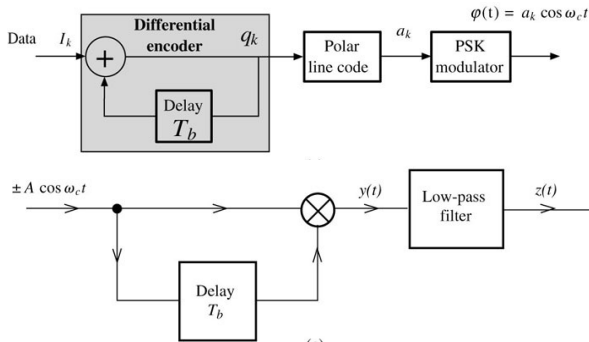
Example: Bell 103 modem (V.21, 300 bps) uses 1270 Hz and 1070 Hz for originating station, only 3 or 4 cycles per bit

FSK Example:  $f_0 = 8$ ,  $f_1 = 12$



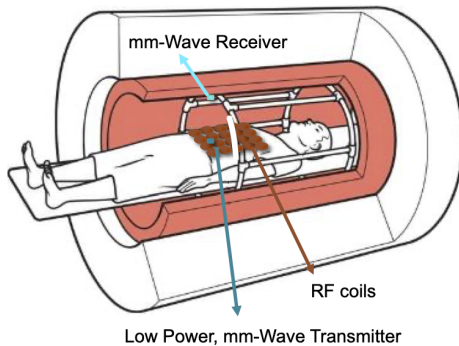
# Differential PSK (DPSK)

- ▶ Differential PSK encodes the bits as the phase difference between two PSK pulses.
- ▶ "1" is a change of phase, and "0" is the same phase.
- ▶ This doesn't need a synchronous receiver! The signal is its own reference.



## Example: A High-Speed Serial Link

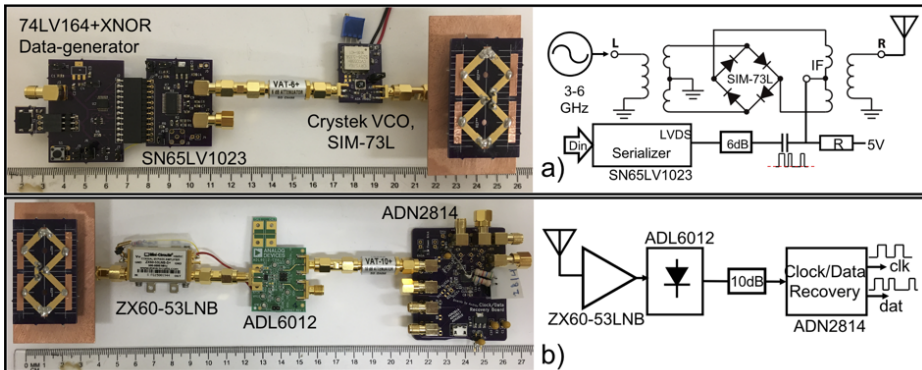
- ▶ Transport data from a receive array in an MR scanner wirelessly
- ▶ Approximately 500 Mbps data rate
- ▶ At most 1 m distance
- ▶ Carrier in 3.2 or 5 GHz band



This is work by Greig Scott from the Stanford MRSRL

# A High-Speed Serial Link System

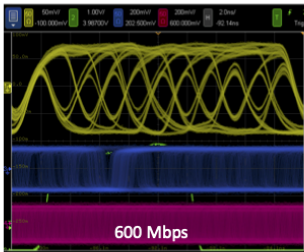
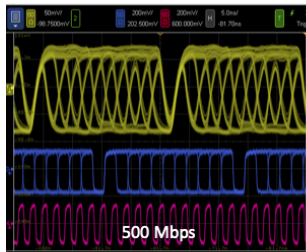
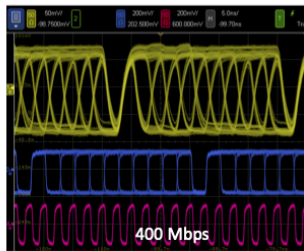
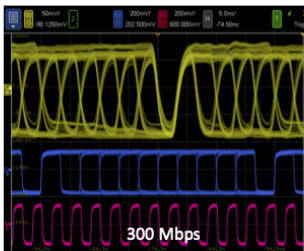
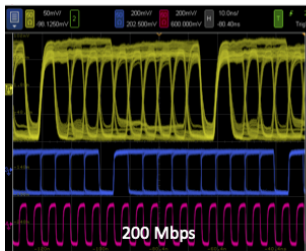
- ▶ Antenna and preamp pick up signal, demodulated, digitized to 16 bits
- ▶ Data is serialized using 8b/10b encoding, and modulated and transmitted with OOK
- ▶ Receiver envelope detects and deserializes the bits



## 8b/10b Encoding

- ▶ Common encoding for high-speed serial links, hardware implementations available
- ▶ Each 8-bit byte is represented by a 10 bit string
- ▶  $2^8 = 256$  values represented by  $2^{10} = 1024$  bit strings
- ▶ Only a few strings are used
- ▶ To represent the 256 values, strings are chosen that
  - ▶ 10b strings have a parity of 0 or,
  - ▶ Have a parity of  $\pm 2$ , in which case both the string and its complement are assigned the same value
  - ▶ No runs of more than 5 ones or zeros
- ▶ Running disparity of bits is always  $\pm 1$ , so almost do DC value
- ▶ Special strings for control and framing

# 8b/10b Waveforms, 3.2 GHz Carrier

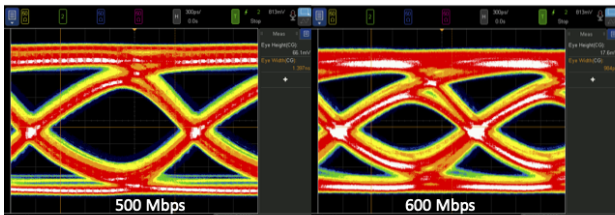
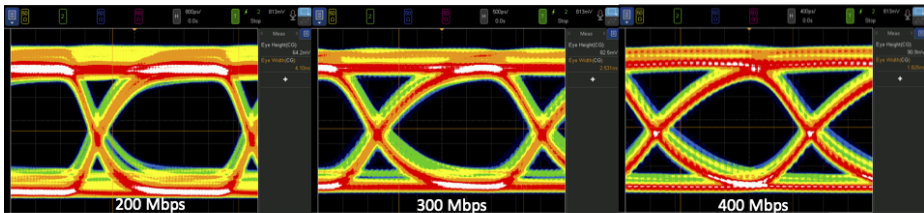


Lose Lock

3.2 GHz Biquad pair



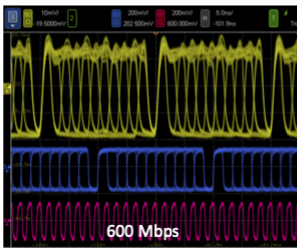
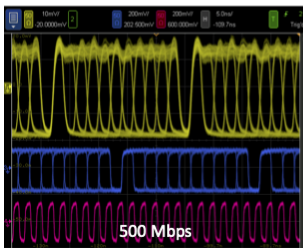
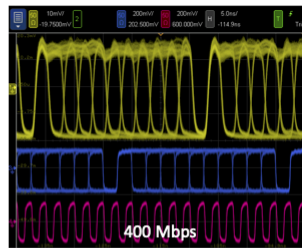
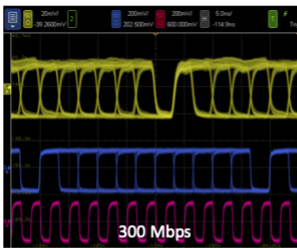
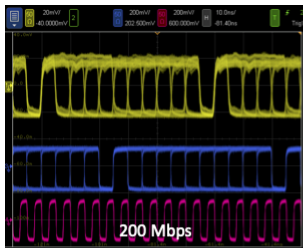
# 8b/10b Eye Diagram, 3.2 GHz Carrier



3.2 GHz Biquad pair

Lose Lock

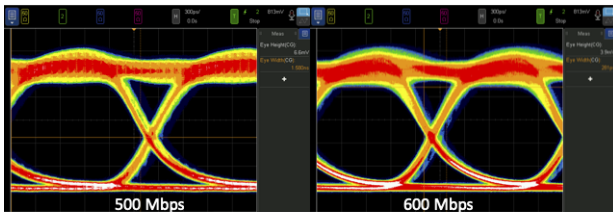
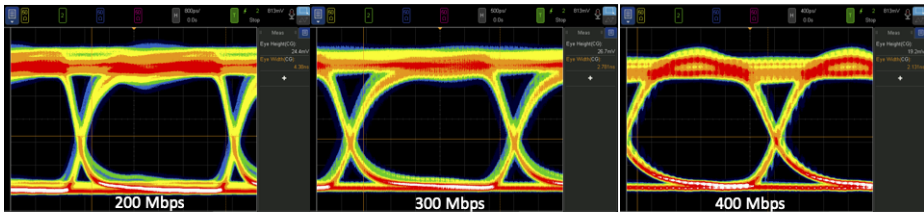
# 8b/10b Waveforms, 5 GHz Carrier



stays locked

5.0 GHz Biquad pair

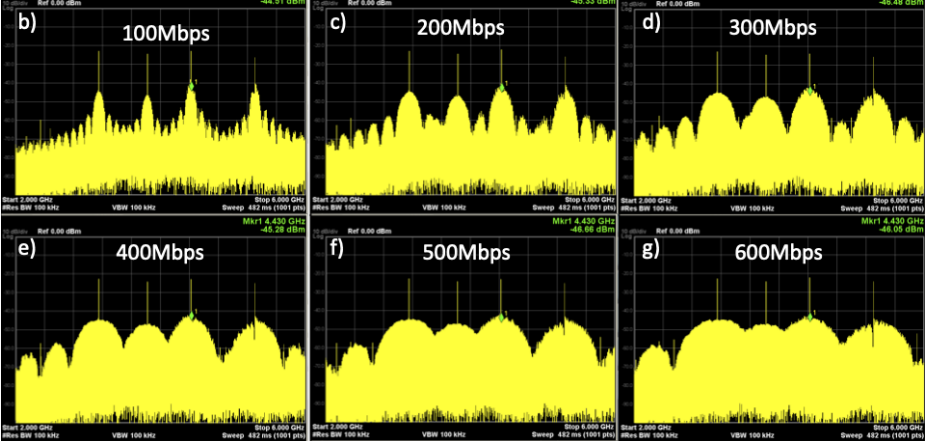
# 8b/10b Eye Diagram, 5 GHz Carrier



5.0 GHz Biquad pair

Stays Locked

# Power Spectra



At 500 Mbps the pulse spectrum is beginning to alias from adjacent replicas  
At 600 Mbps there is significant interference

## High Speed Serial Links

- ▶ 8b/10b very widely used
  - ▶ Digital audio
  - ▶ HDMI, USB-3.0, Firewire
  - ▶ Fibre Channel
- ▶ Many variants, for specific features
- ▶ extensions to 64b/66b, (10 Gb Ethernet) and 128b/130b (PCI Express)

## Next Couple of Classes

- ▶ Wednesday: M-Ary Coding, Error Correction
- ▶ Friday: Project ideas
- ▶ Next Week: Off
- ▶ Monday: Radar signals
- ▶ Wednesday: Spread Spectrum, Cell phones, GPS