Signal Integrity

Agenda

9:00	start of the seminar
9:05	signal integrity basics
10:30	coffee break
11:00	oscilloscopes and SI; part 1
12:00	lunch break
13:00	oscilloscopes and SI; part 2
13:30	vector network analyzers
15:00	discussion
15:30	end of the seminar

Signal integrity - introduction

- “signal integrity” – slightly vague; not very clearly defined concept:
  - „a set of measures of the quality of an electrical signal“
  - „study of pulse distortion“
  - …
  - signal integrity is related mostly to digital signals
    - measurement and description of a signal during and after transition through the trasmission path
    - different technologies place different demands on the signal quality; signal quality evaluation is always relative to these requirements
- ideal digital signal is just a theoretical construct
  - in real electronic circuits, the signal is represented by an instantaneous value of voltage (usually) or current and becomes an analog signal

Signal integrity - introduction

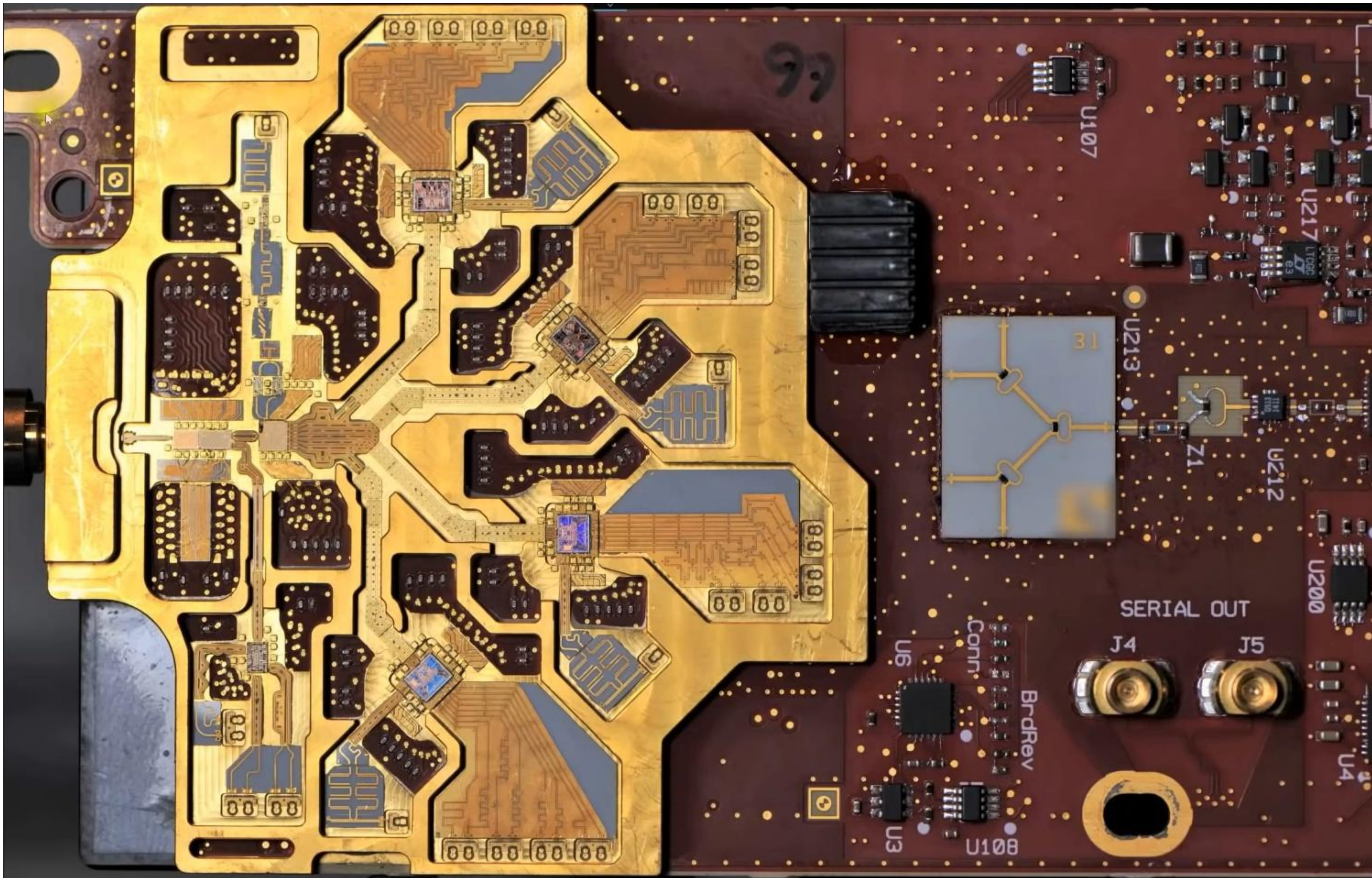
- signal integrity is closely related to power integrity and generally also to electromagnetic compatibility
  - power and data circuits in modern devices influence each other with various disruptive effects
  - circuits which are poorly designed in terms of the signal integrity may also have bad EMC characteristics
    - radiating transmission lines and discontinuities, … (EMI)
    - or, on the other hand, susceptibility to external EM fileds (EMS)

Design challenges

- modern devices use mostly serial communication buses
  - single or just a few parallel high speed lanes
  - → high signal frequencies and resulting problems known previously rather from rf / mw communication technology
- continuing miniaturization of electronic circuits
  - multi-layer PCBs – transmission lines placed on top of each other; vias, …
  - space is at a premium; less space for individual transmission lines
  - decreasing of voltage levels in digital circuits
  - → discontinuities, crosstalks between lines, higher effect of interference
- design of modern digital circuits and measurement on them is much more challenging than in the past

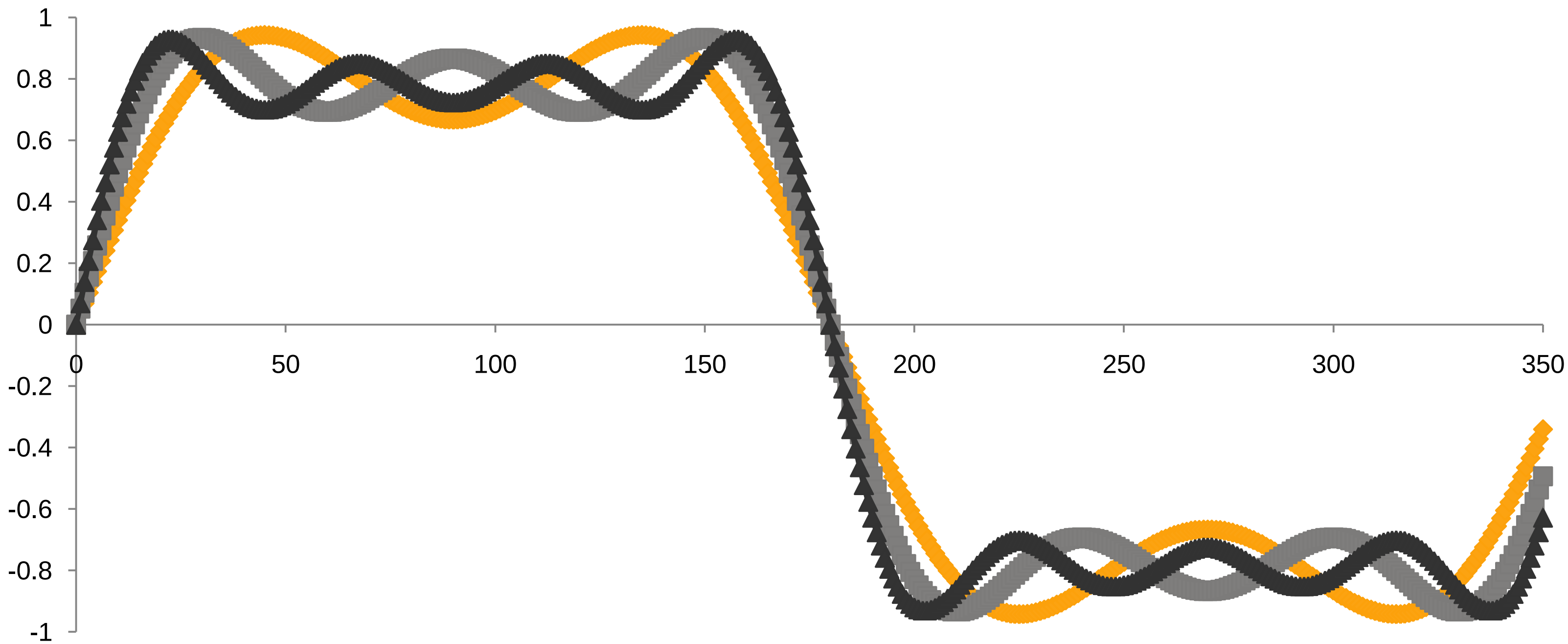
Design challenges

- signal „front end“ of the Keysight UXR oscilloscope (110 GHz BW):



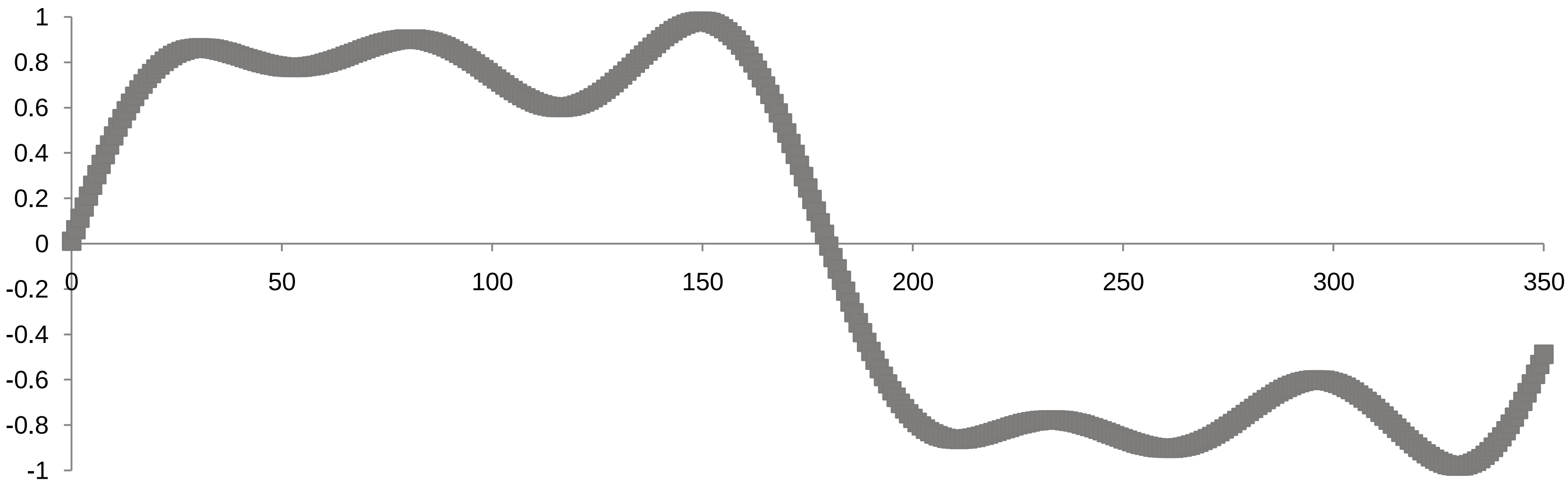
Rectangular waveform

- rectangular / impulse signals used in digital technology are composed of many harmonic (sinusoidal) components – fundamental + odd harmonics
  - each Nth harmonic component has amplitude *fundamental*/N
  - example for 1st+3rd / 1st+3rd+5th / 1st+3rd+5th+7th harmonic:



Rectangular waveform

- because of this, signals can take up relatively wide frequency span
  - sensitive on the quality of the transmission chain (phase and amplitude frequency characteristic); signals can be distorted when the amplitude and phase of the transmission differs for individual signal components
  - because of this (among other reasons) designers always try to limit the higher frequency components of the signal (pulse shaping, …)



Rise time vs. Bandwidth

- frequency domain bandwidth (-3dB) needed for certain rise time tr can be estimated using this formula:

$$f_{-3dB} = \frac{0{,}35}{t_r}$$

- total rise time of a series of transmission elements can be calculated as a square root of a sum of individual squared rise times
  - this is useful for example for determining the total rise time of a combination of an oscilloscope and a probe

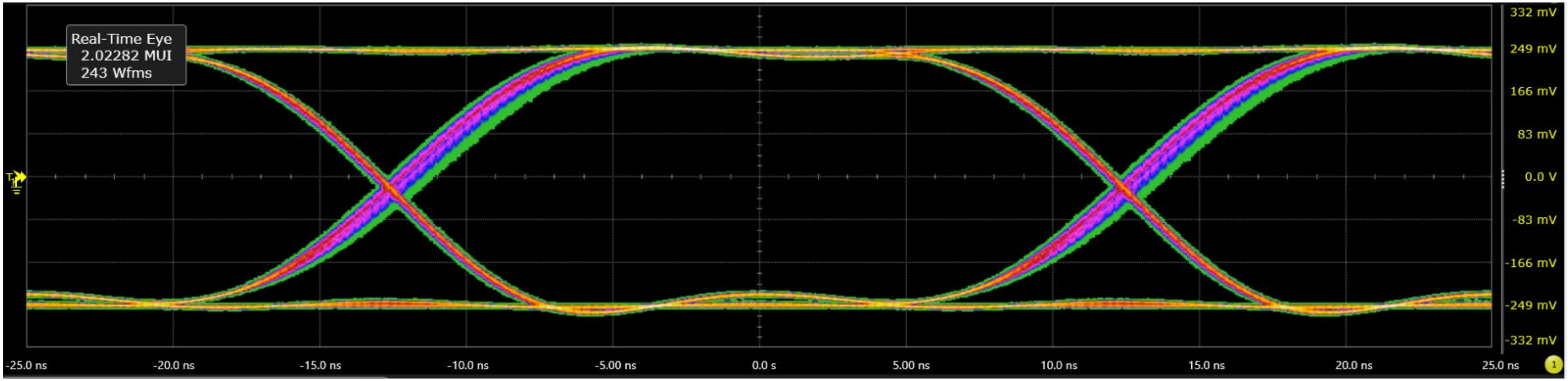
$$t_{r\_total} = \sqrt{t_{r1}^2 + t_{r2}^2 + \ldots + t_{rN}^2}$$

  - example for „Fast Ethernet“ 100BASE-TX – oscilloscope (BW 1 GHz) + probe (BW 500 MHz); for the shortest allowed edge time (3 ns):

$$t_{r\_total} = \sqrt{3^2 + 0{,}35^2 + 0{,}7^2} = 3{,}1ns$$

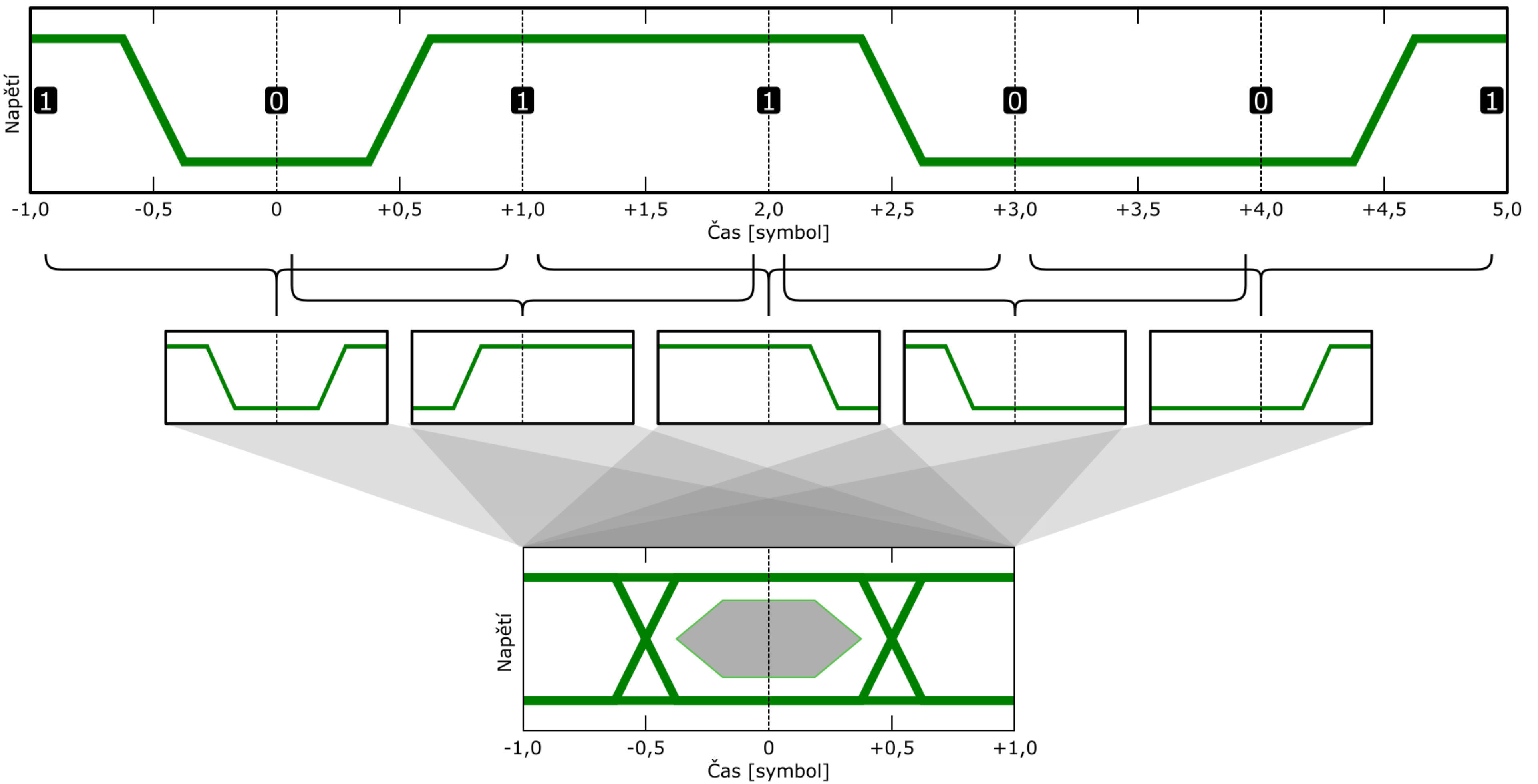
Eye diagram

- the eye diagram can be used as a useful tool for evaluating the quality of digital signals
  - it is created by stacking many waveforms of a signal on top of each other
  - it displays all the possible transitions within some signal (rising/falling edges as well as transitions between multiple levels in the case of a multi-level signal)
  - it typically displays two symbols of the signal ("center" of one symbol and +- ½)



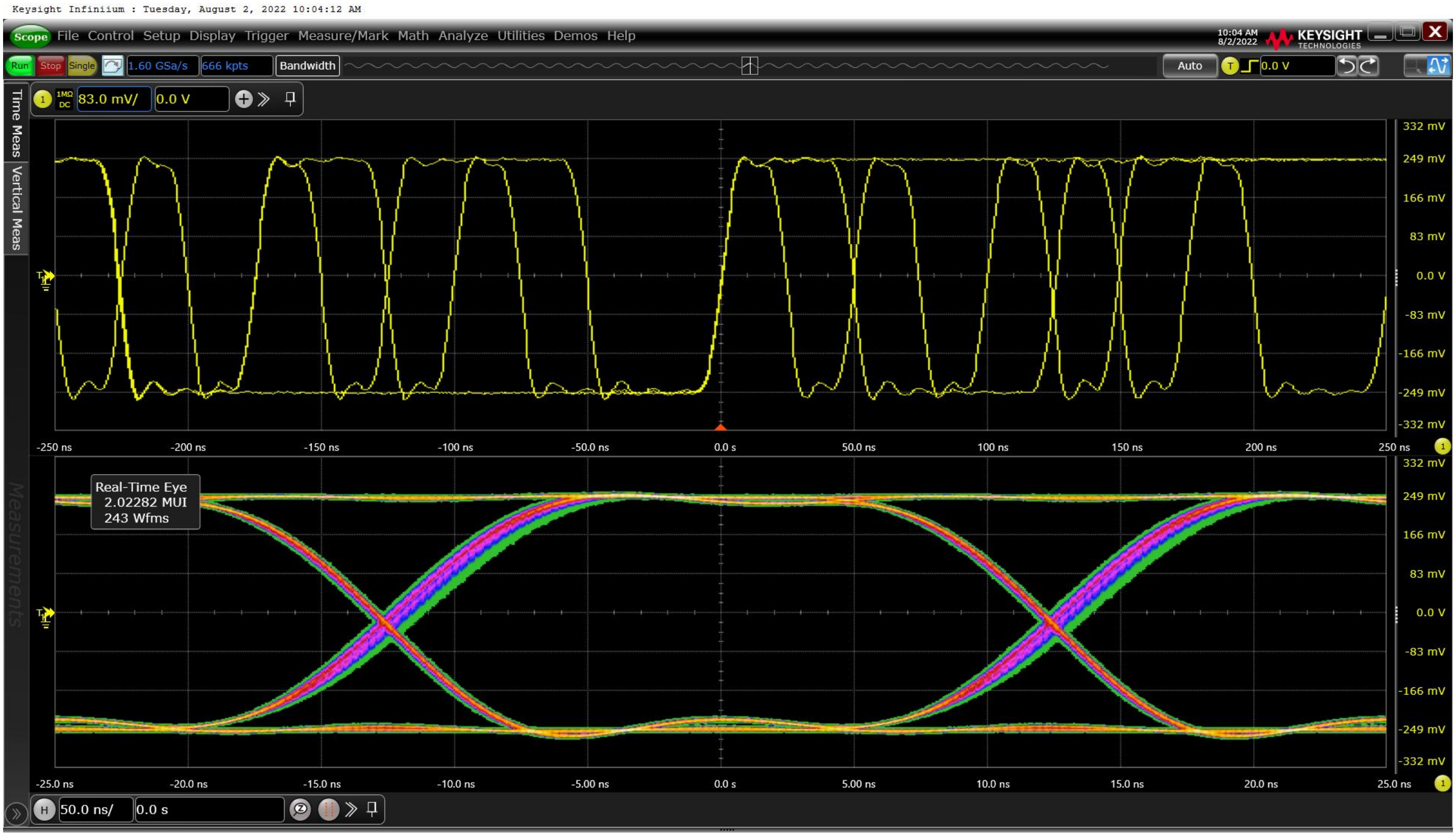
Eye diagram

- creation of the „eye“:



Eye diagram

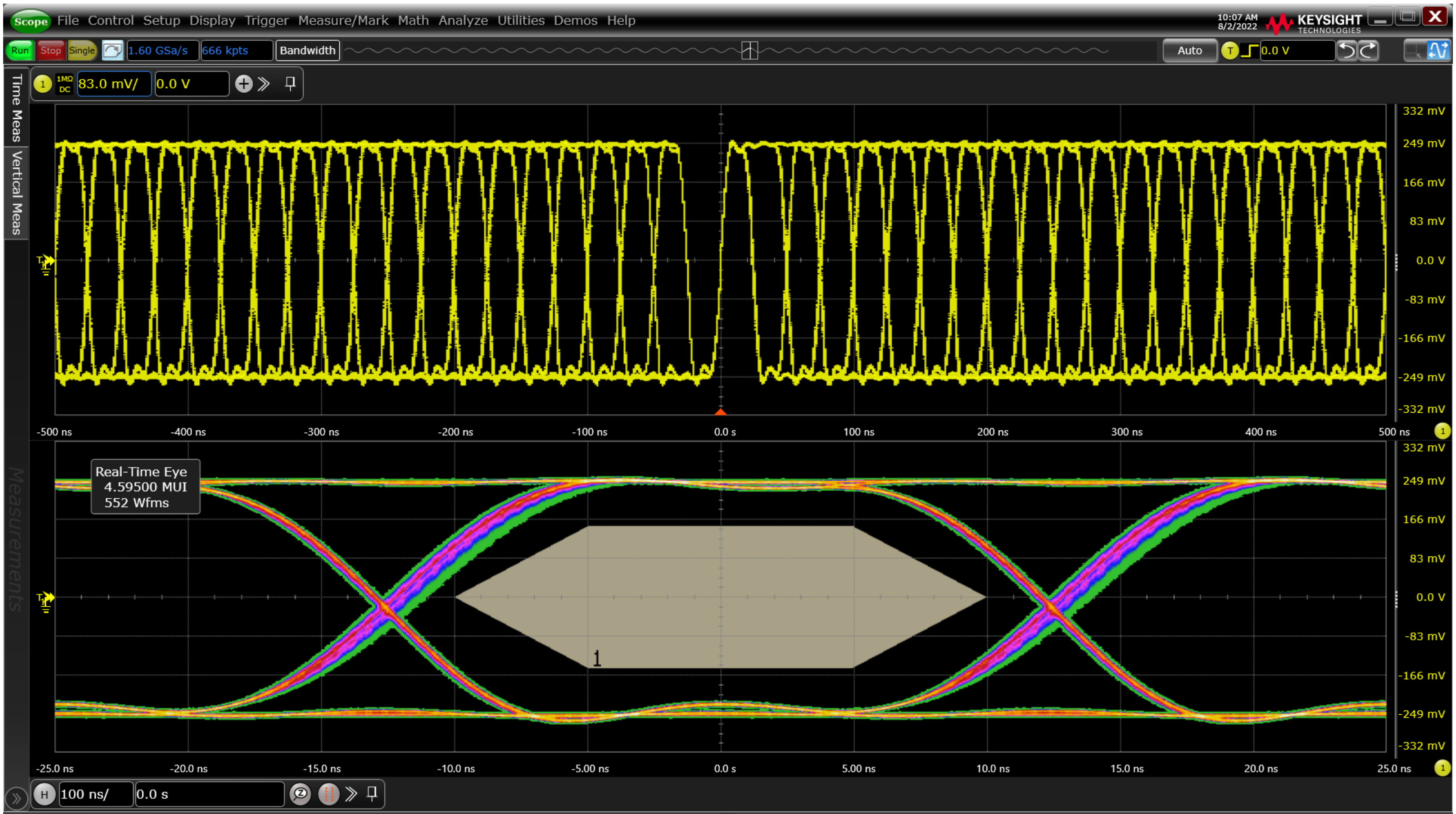
- creation of the „eye“:



Eye diagram

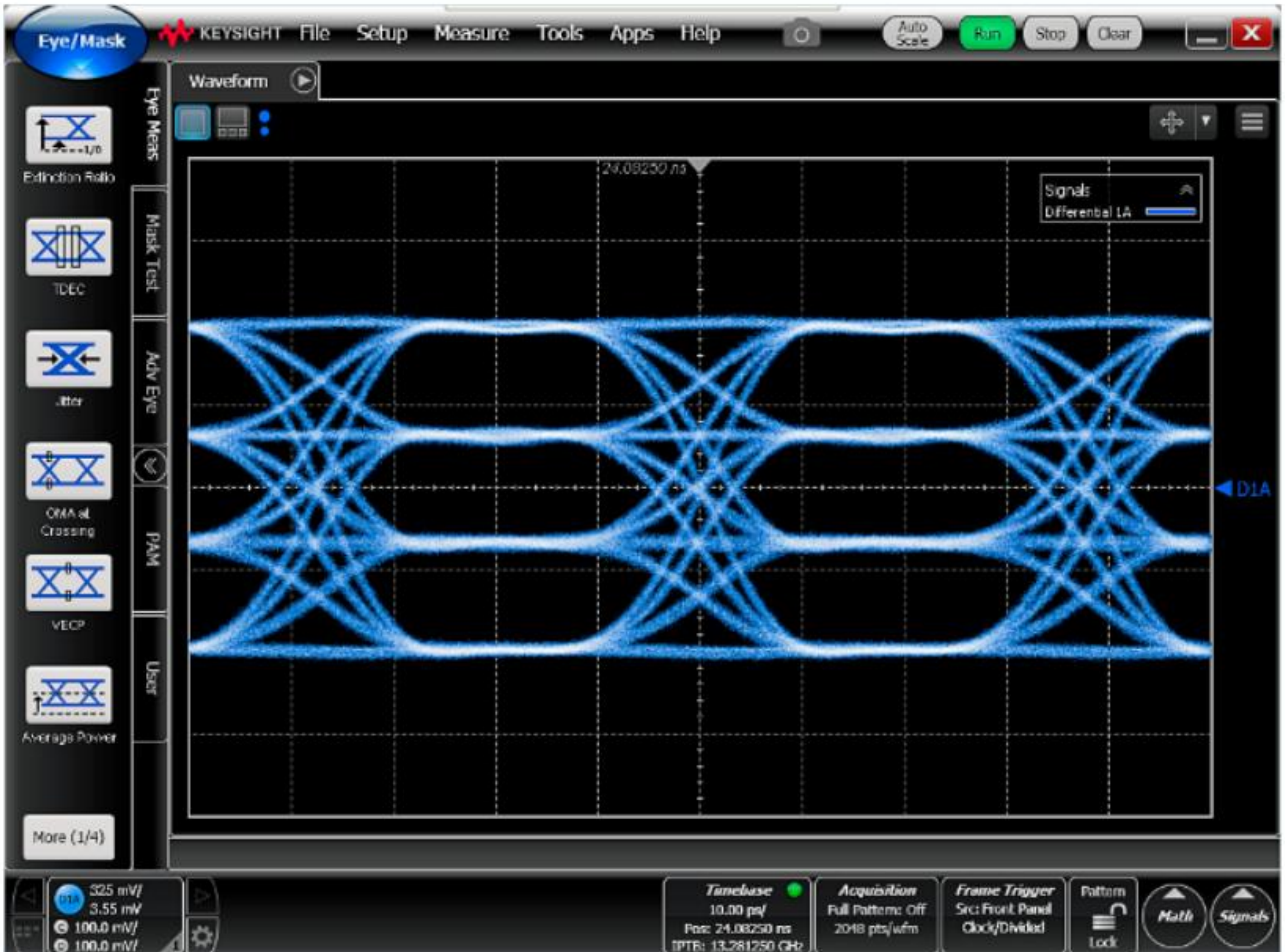
- the eye diagram is often used in combination with a mask that marks the area of desired "minimum opening" of the eye for a given technology:

Keysight Infiniium : Tuesday, August 2, 2022 10:08:00 AM



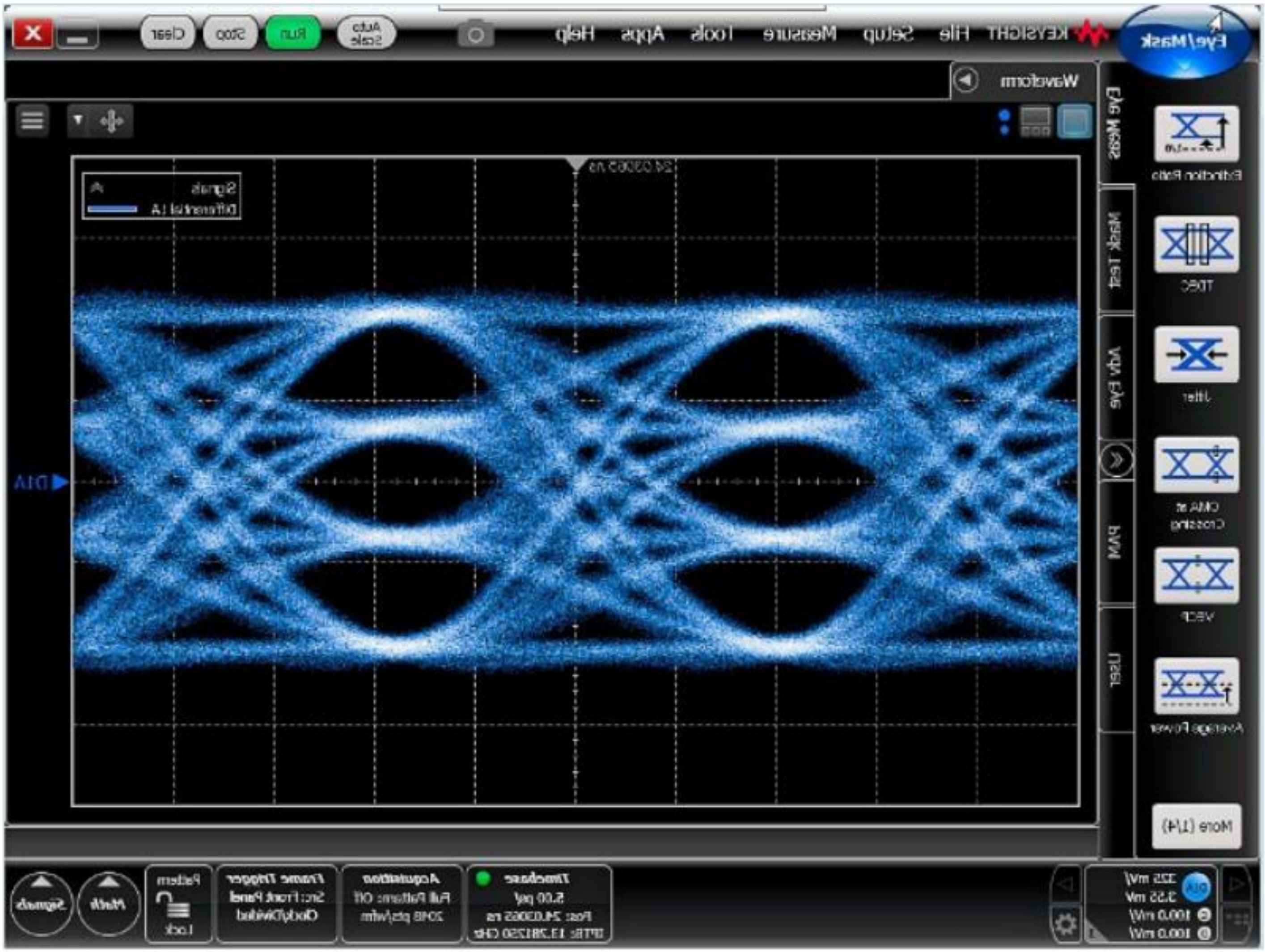
Eye diagram

- „slower“ (26,5625 Gbaud) PAM4 signal:



Eye diagram

- „faster“ (53,125 Gbaud) PAM4 signal:

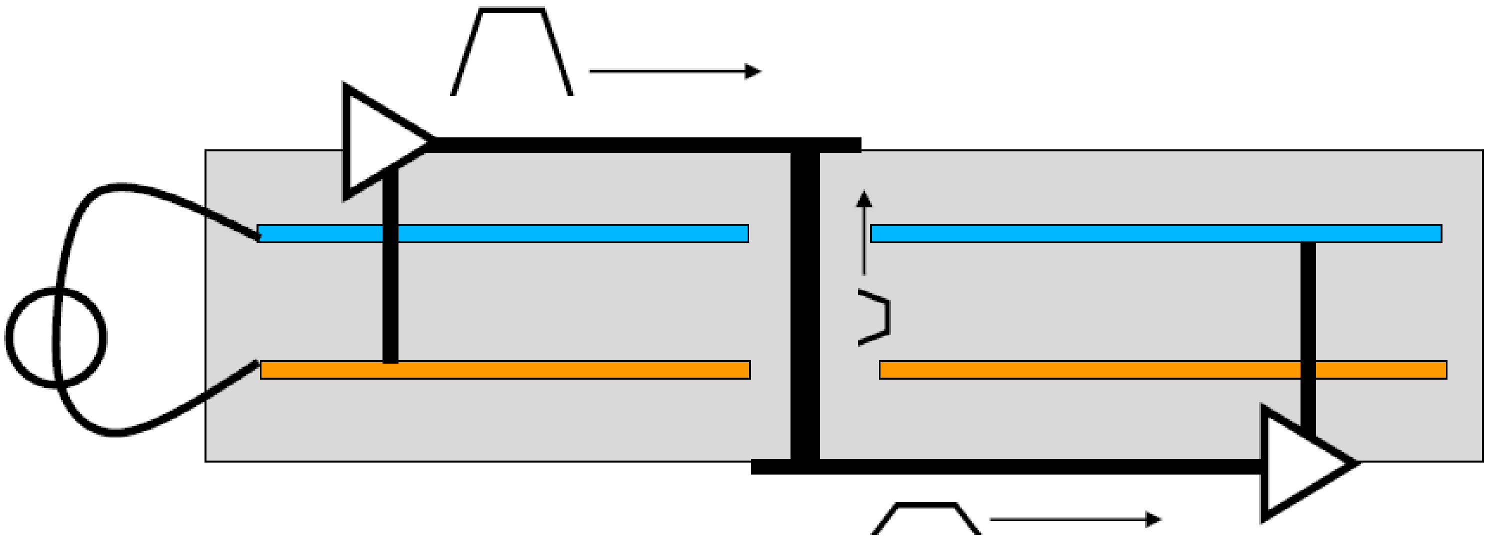


„Clock recovery“

- for correct signal reception, the receiver must be time-synchronized with the transmitter
  - as the signal speeds increase, the exact timing becomes more important
- the clock signal can be transmitted separately parallel to the data...
- … or it can be derived from the data signal inside the receiver
  - → „clock recovery“
  - this approach has a number of advantages – no need for additional transmission line and precise time synchronization of "clock" and data; less jitter in the received signal, …
- „clock recovery“ is used by oscilloscopes:
  - it is hard (or impossible in most cases) to get to the separate clock signal
  - used for various measurements - jitter, phase noise, eye diagram, …

Signal distortion

- causes of signal distortion in digital circuits:
  - the transmission line itself – attenuation, mismatch (reflections), signal propagation speed, dispersion (for non-homogeneous lines)
  - interference and crosstalk - from neighboring transmission lines, from power circuits, from the external environment, ...

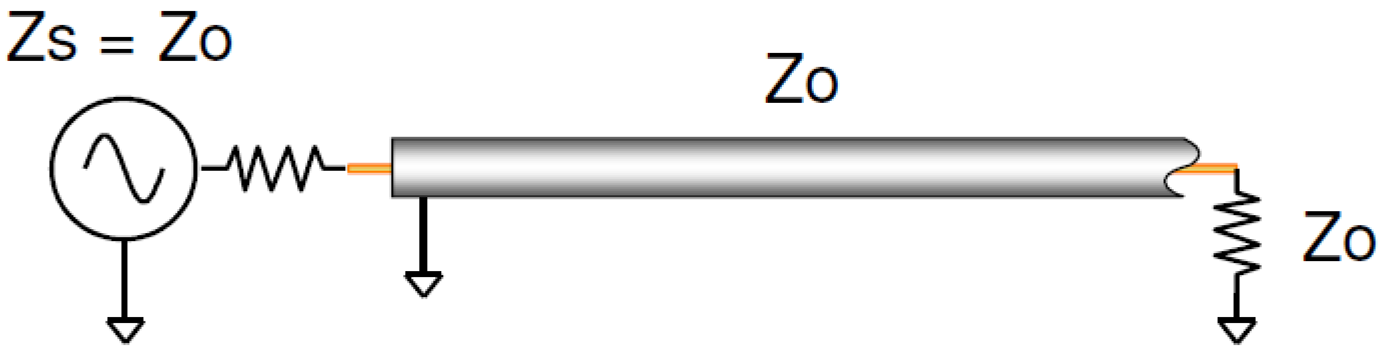


Transmission lines

- at low frequencies (~ $\lambda/10 >$ transfer distance), energy can be transfered using "two wires" (arbitrarily positioned)
  - voltage and current values not dependent on position along wires
- on higher frequencies (~ $\lambda/10 <$ transfer distance), special structures are needed for efficient power transfer
  - energy is transfered in form of traveling waves
  - values of voltage and current depend on the position and time
  - transmission line - two-conductor structure capable of supporting TEM mode
    - works from DC; velocity of propagation mostly not depending on frequency

Impedance matching

- characteristic impedance of the transmission line (Z_0)
  - defined as the voltage to current ratio of a traveling wave (no reflections) at a specific time and point on the line
  - depends on the geometry of the line and the materials used
  - impedance of differential lines – most often 100 Ω or 120 Ω
- impedance matching is the desirable condition where the impedances of the entire transmission chain are equal (source, line, load)
  - the result is the most efficient energy transfer without reflections

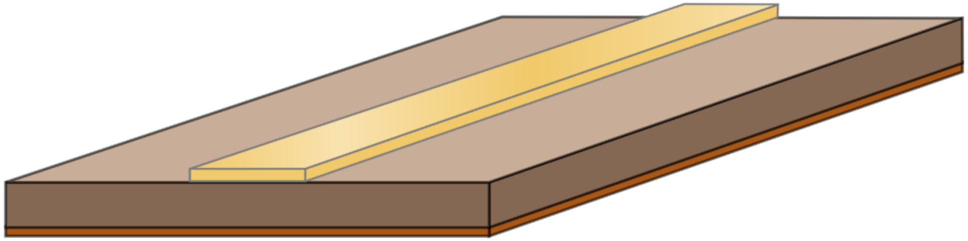


Transmission lines

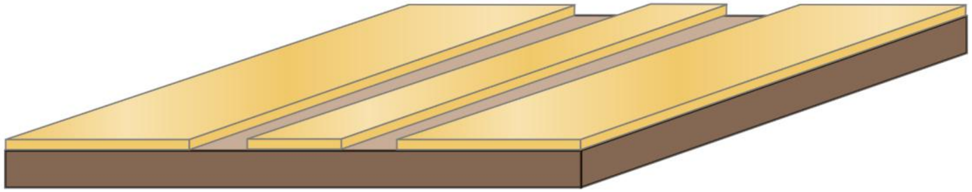
- modern digital circuits use various types of planar transmission lines:
  - microstrip, strip, coplanar, ... (and subvariants)
- compared to closed coaxial lines with homogeneous dielectric, these lines generally have worse properties
  - non-homogeneous dielectric (substrate and air) – dispersion
  - the line is open - it radiates to some extent and is prone to pick up interference from external sources
  - the PCB design is always the result of a trade-off between transmission line properties and available space
    - many other lines, their crossing; power circuits, …
    - a need to bring the signal to a given point with a certain delay
    - multi-layer PCBs – use of vias that can't have ideal properties

Transmission lines

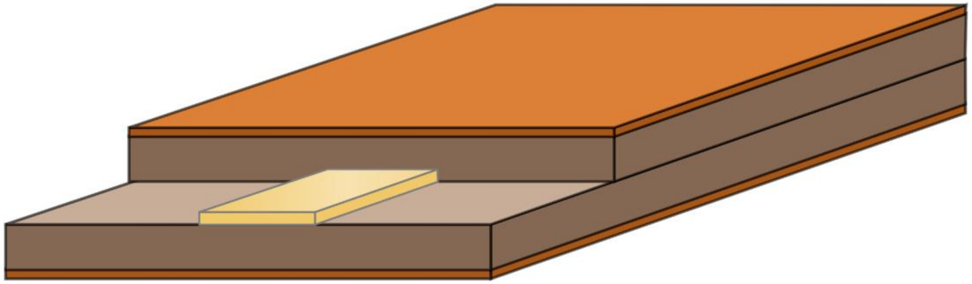
- microstrip line:



- coplanar waveguide:

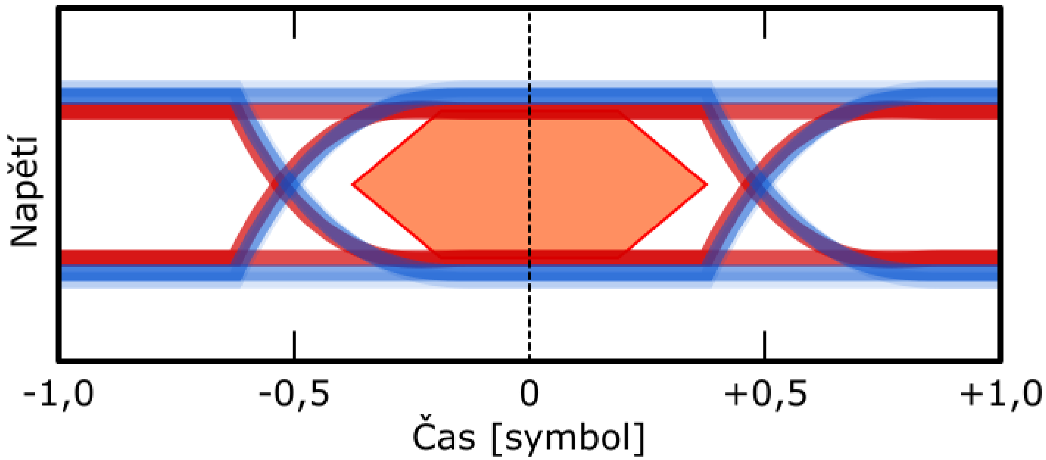


- stripline:



Transmission lines - properties

- attenuation – the decrease in signal level after passing through a line
  - attenuation increases with rising frequency (due to increasing losses in dielectrics)
  - if it is too large, the receiver may have trouble distinguishing signal levels
  - strong frequency dependence of the attenuation can cause distortion of the signal shape (attenuation of higher frequency components) - this can be solved to some extent by pre-distortion on the transmitter side



Transmission lines - properties

- line impedance; mismatch; reflections
  - reflections arise due to the mismatch between the main elements of the transmission chain (source, line, load) and also on all discontinuities on the transmission lines
    - bends, vias, minor production defects, inhomogeneities in the substrate material, ...
  - in addition to energy losses, reflections on the line cause other problems
    - interaction between the incident and reflected waves creates a standing wave
    - on the receiver side, depending on the frequency, a constructive or destructive addition of the forward and (repeatedly) reflected wave occurs
    - → the transmission characteristic is rippled in the frequency domain with a period inversely proportional to the distance between the discontinuities

Transmission lines - properties

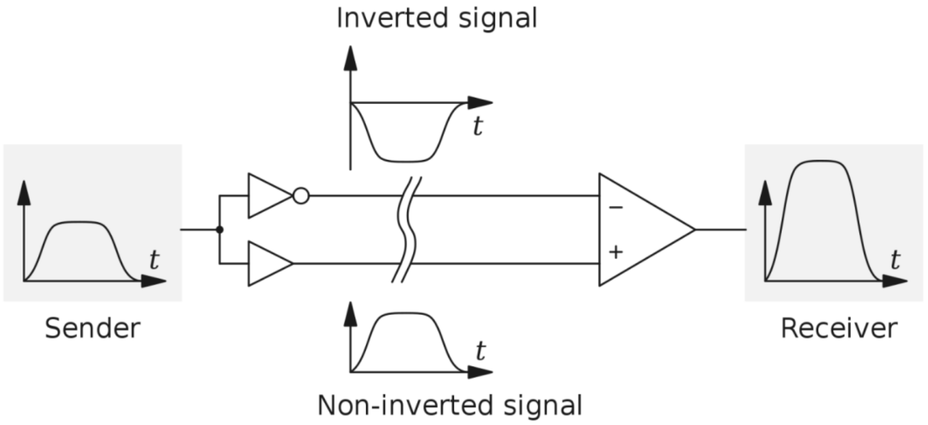
- transmission measurement example:

Transmission lines - properties

- dispersion – the speed of wave propagation changes depending on the signal frequency
  - can be a problem mainly with microstrip lines, where the effective permittivity increases with increasing frequency (more energy propagates through the dielectric substrate)
  - can lead to distortion of the transmitted signal
- electrical length – signal propagation time
  - might be important in cases where it is necessary to transmit time-synchronous signals over several parallel lines at the same time
    - for example, a data and clock signal or data split into multiple parallel lines

Differential signalling

- the transmission of signals over differential (symmetric) lines is used more and more in modern circuits; brings a number of advantages:
  - better immunity to interference and lower radiation
    - the wavelength of the interfering signal is typically significantly larger than the distance between the conductors of the symmetrical pair → the interference is coupled to both conductors in the same direction
  - less strict requirements on the quality of rf grounding → simpler design



Transmission lines - recommendations

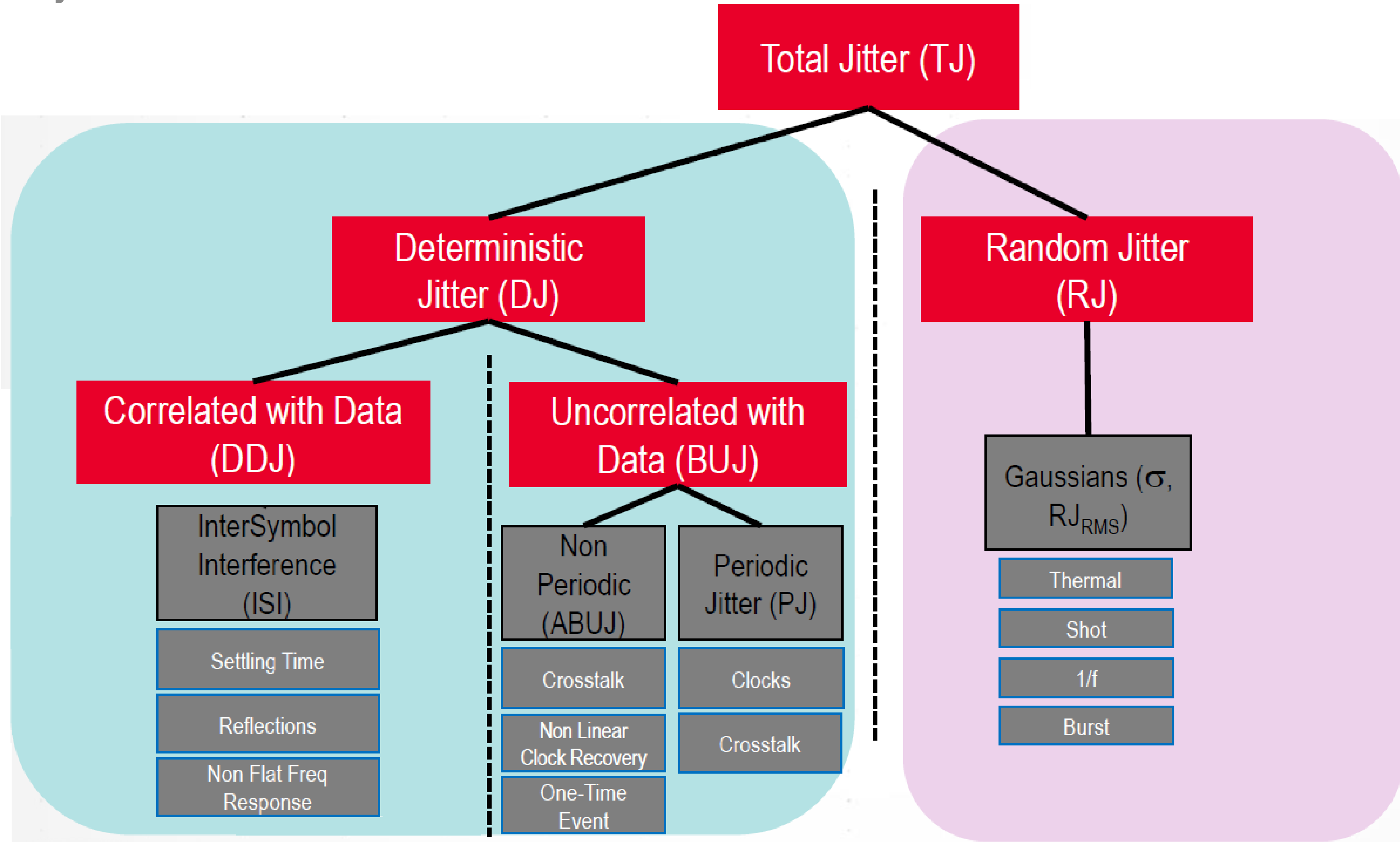
- careful line design - correct characteristic impedance
  - verification of the design and production accuracy on samples
  - source and load impedance
- transmission lines as short as possible
  - reduces the effect of ripple in the transmission characteristic
- optimalization of potentially problematic places
  - line bends, transitions between different types of lines, connections to connectors, ...
  - careful design of vias between PCB layers - different via designs can have very different properties
- in case of problems with high attenuation, a substrate with lower dielectric losses can be used or a wider line can be designed

Interference and noise

- interference occurs in the entire transmission chain – transmitter, line, receiver
- total interference/noise can be divided into these categories:
  - random interference (noise) – cannot be predicted; thermal noise, …
  - deterministic interference:
    - related to transmitted data - intersymbol interference
    - unrelated to transmitted data – crosstalk, clock signals, interference from power circuits, random glitches, …
- noise manifests itself as "blurring" of the signal eye mainly in the vertical direction and partly also as jitter (in the time domain)

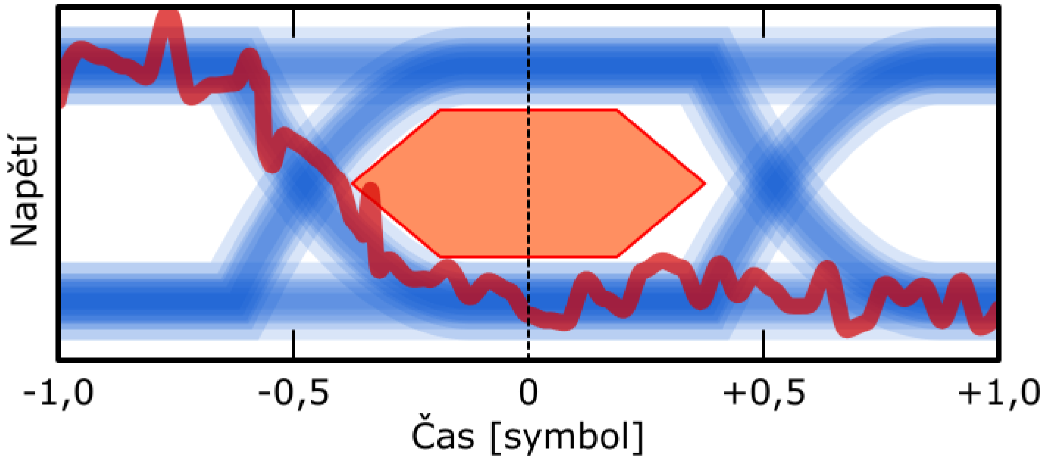
Interference and noise

- this same categorisation can be applied to jitter and interference/noise:

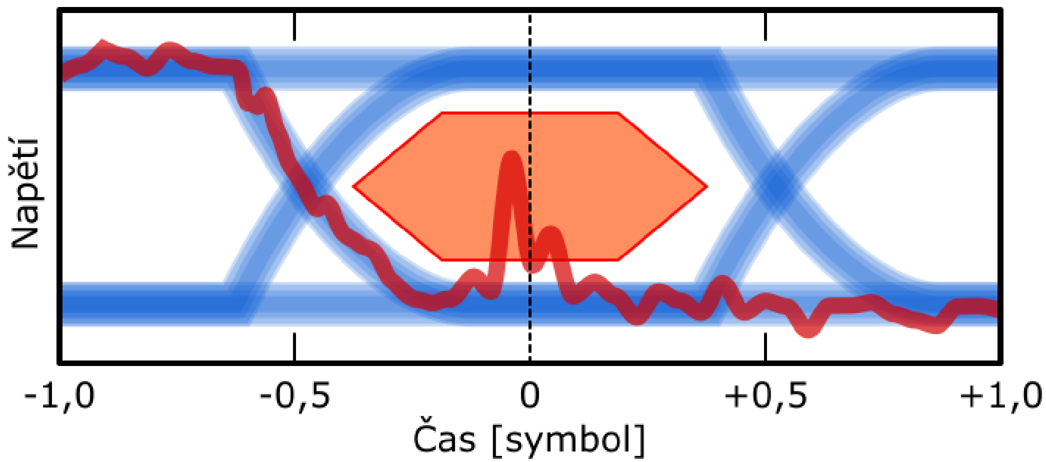


Interference and noise – eye diagram

- effect of random noise:
  - „eye“ closes from all sides (amplitude noise and jitter)

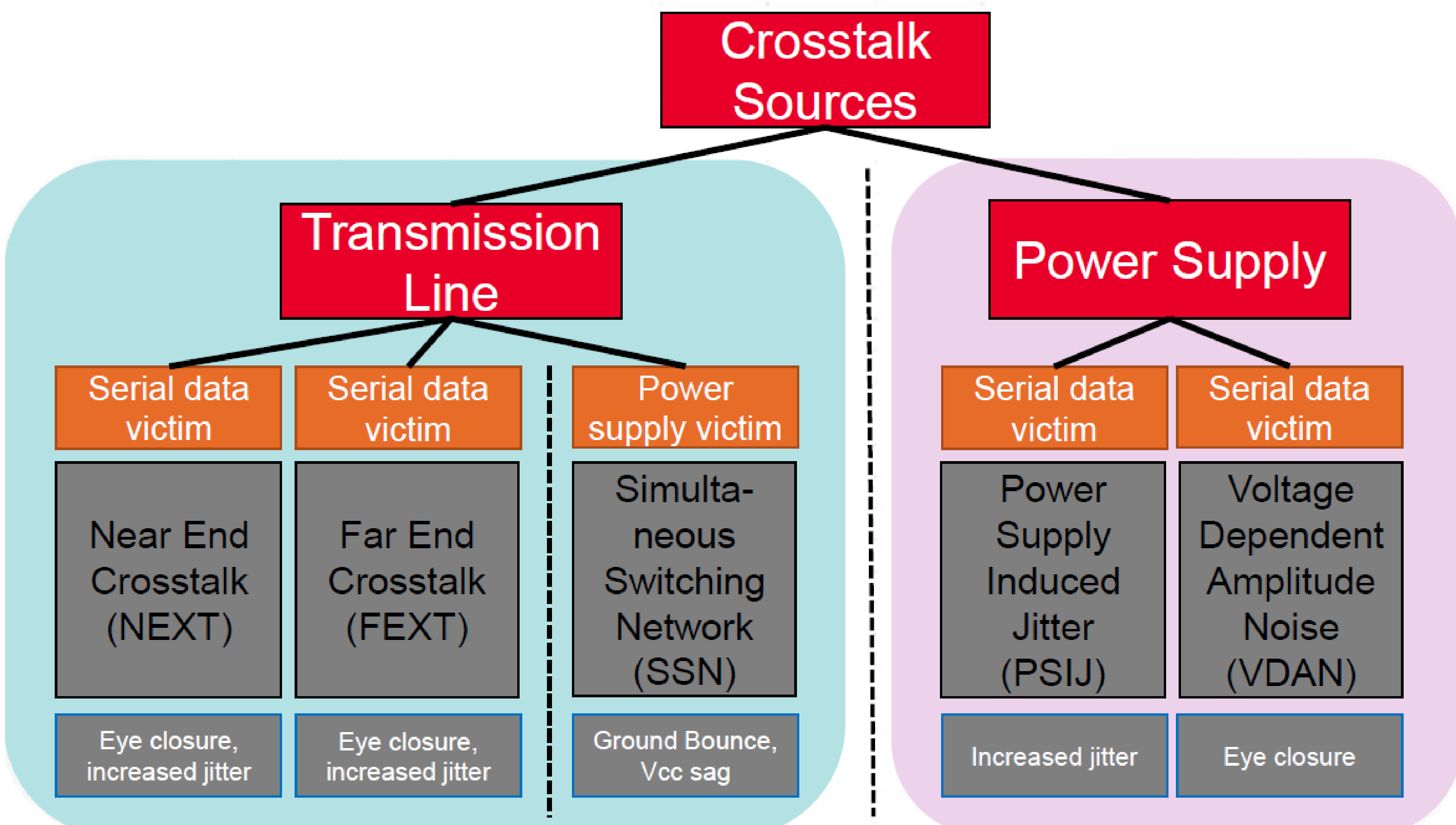


- „one-time“ events; glitches:
  - similar disturbances can make the correct symbol reception impossible
  - it is often hard to find the cause of such glitches



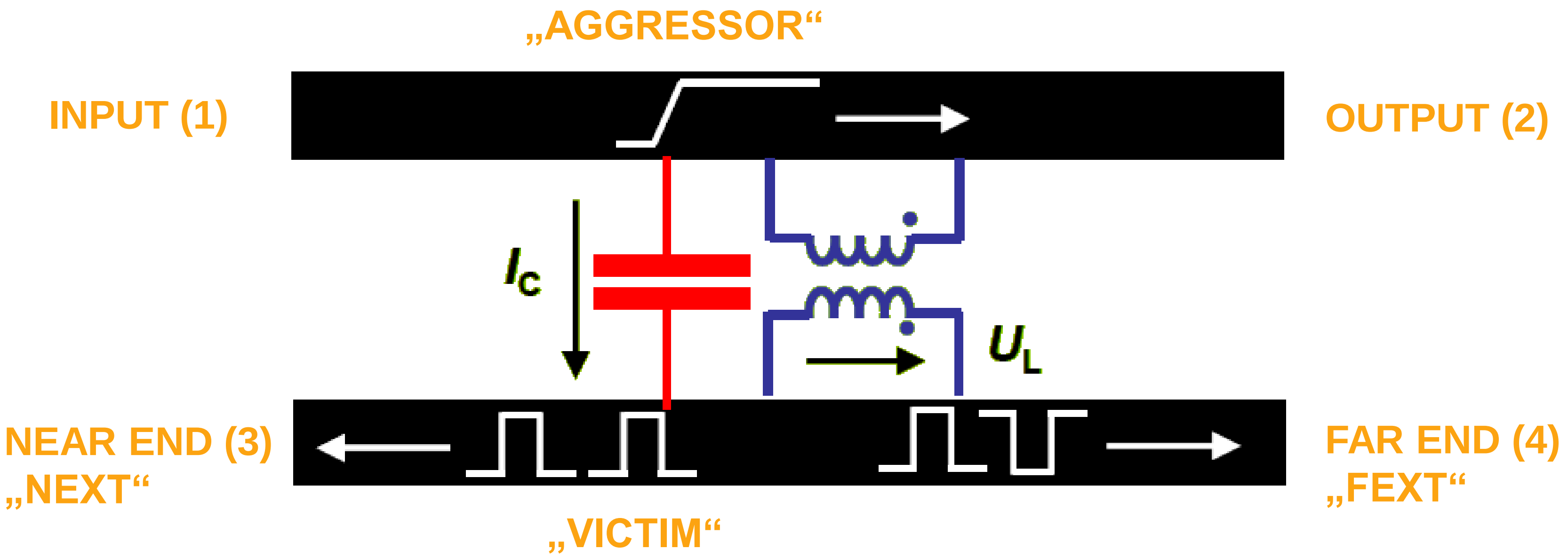
Crosstalk

- general categorisation of crosstalk:



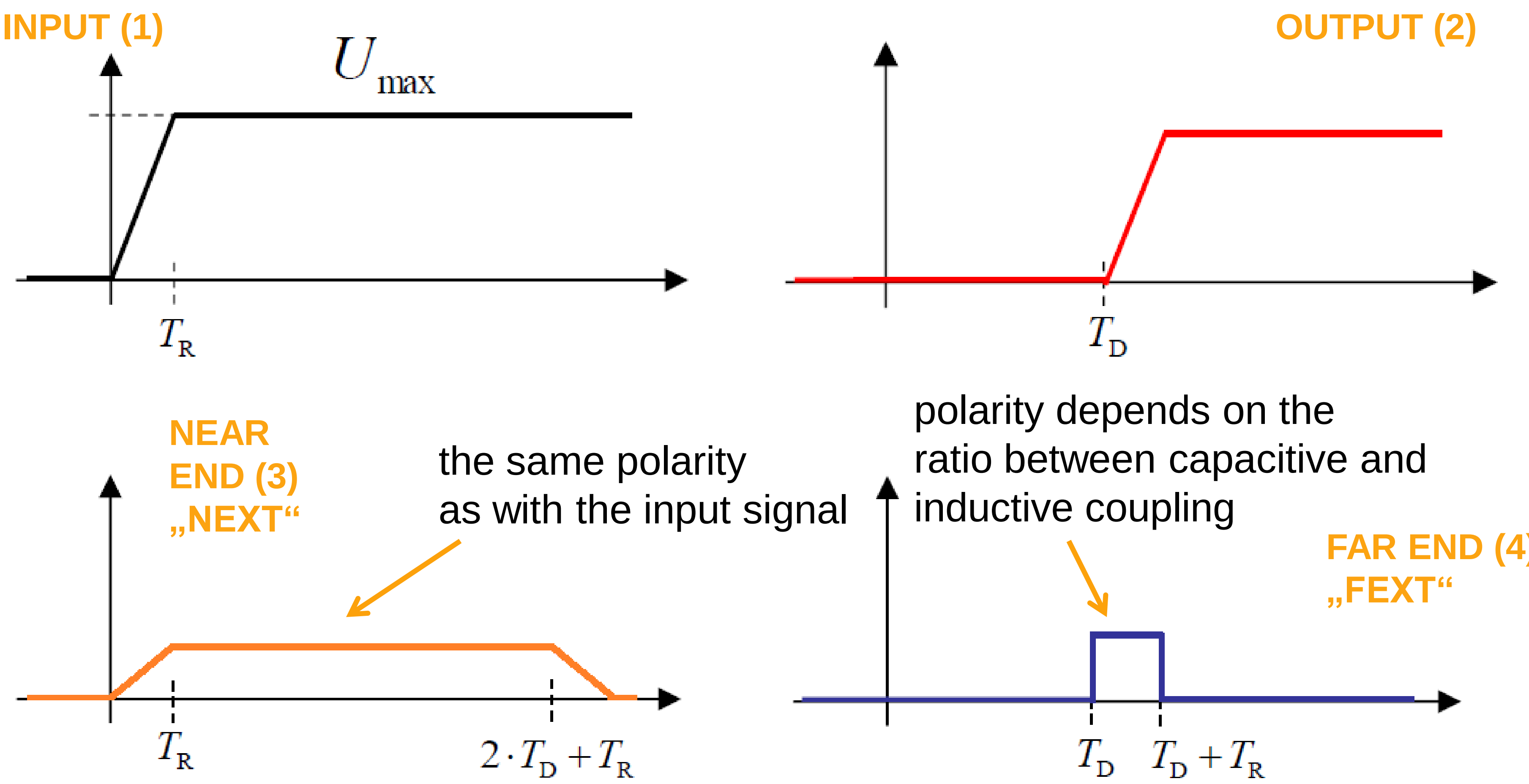
Crosstalk between signal lines

- crosstalk generally arises as a result of capacitive and inductive coupling between two lines ("aggressor" and "victim")
  - most common crosstalks - NEXT (from 1 to 3) and FEXT (from 1 to 4):



Crosstalk

- NEXT crosstalk duration is $2 \cdot T_D$ (2x signal transit time); „FEXT“ crosstalk duration corresponds with the rise time of the signal (T_R)



Crosstalk

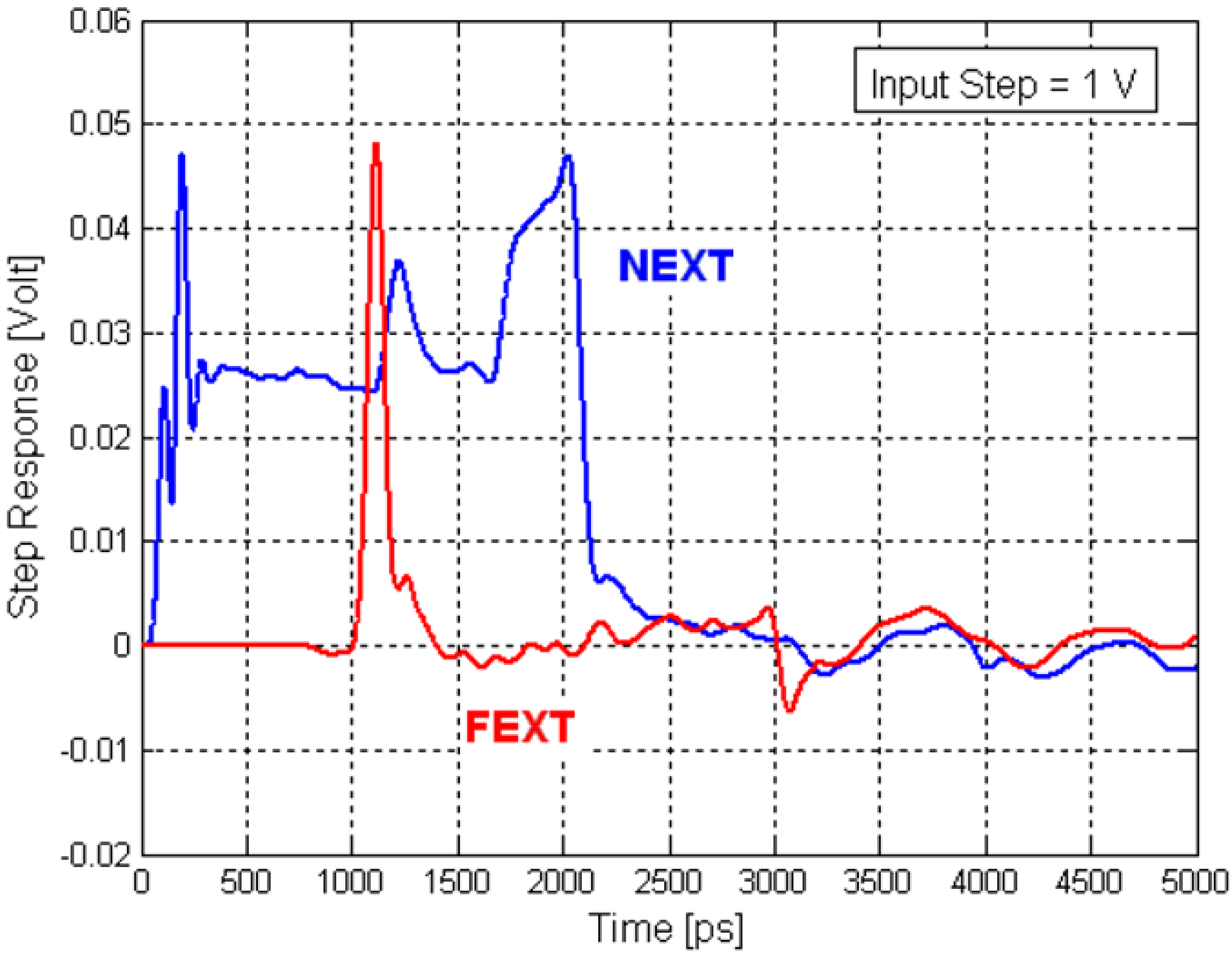
- total "NEXT" crosstalk is a sum of the effects of capacitive and inductive coupling; resulting "FEXT" crosstalk is a difference between capacitive and inductive coupling effects
  - the amplitude of FEXT crosstalk is directly proportional to the length of the line and inversely proportional to the rise time of the signal; can be large
  - approximate relations for calculating the amplitude of both crosstalks:

$$U_{NEXT\_\max} = \frac{k_C + k_L}{4} \cdot U_{INP\_\max}$$

$$U_{FEXT\_\max} = \frac{k_C - k_L}{2} \cdot \frac{T_D}{T_R} \cdot U_{INP\_\max}$$

Crosstalk

- crosstalk measurement example:

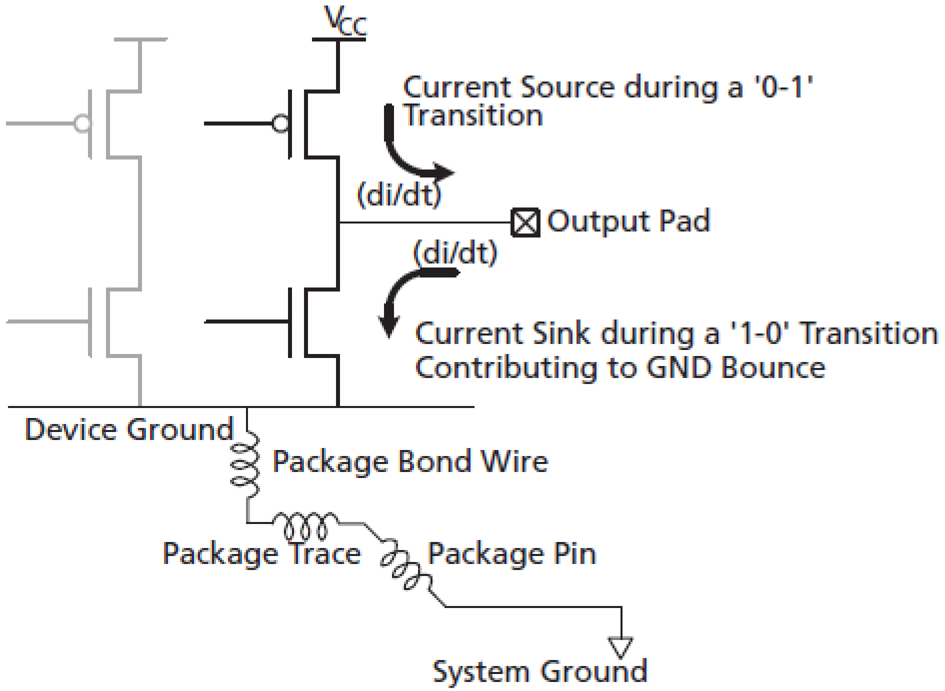


Crosstalk - recommendations

- increase the distance (separation) between transmission lines
- reduce the distance between the line and the ground
- reduce the coupling distance between two lines
- balance the effects of inductive and capacitive coupling (for FEXT crosstalk, the effects are subtracted)
- increase the signal rise time (again, this reduces the FEXT crosstalk)
- use differential signalling
    - eliminates (or largely suppresses) influence of various types of interference

Crosstalk – SSN

- „simultaneous switching noise“ – „ground bounce“ and „V_{CC} bounce“
  - interference that occurs on the power circuits as a result of the simultaneous switching of multiple signal outputs
  - the impulse current taken from the source and flowing to the signal ground can cause a drop in the supply voltage (V_{cc} bounce) or an increase in the ground level (ground bounce; more common)



Crosstalk – SSN

- example of SSN – the yellow trace shows the supply voltage ripple related to the edges of the clock signal (green trace)

Signal integrity measurements

- oscilloscope
  - displays signals in time domain; essential instrument for SI measurements
  - eye diagram – quick signal quality assessment, eye opening, mask test
  - analysis of jitter, crosstalk, phase noise, ...
  - certification ("compliance") measurements for many standards
- vector network analyzer (VNA)
  - primarily measures transmissions and reflections in the frequency domain (characterization of transmission lines, various components, ...)
  - VNA measurements are often necessary for compliance testing
  - modern VNAs are used for TDR measurements as well - conversion into the time domain using the inverse Fourier transformation

Signal integrity measurements

- TDR („Time domain Reflectometry“) oscilloscope
  - typically a sampling oscilloscope combined with a pulse or step generator
  - direct measurement of reflections and transmissions in the time domain (impulse response of the circuit)
- BERT (Bit Error Ratio Tester)
  - high-level testing of the transmission chain and receivers
  - signal ("pattern") generator - generates a known bit sequence that is sent to the tested transmission chain
    - the signal can be impaired intentionally (by adding jitter, parasitic signals, ...)
  - signal analyzer – receives the data sequence after passing through the signal path (or receiver) and compares it with the transmitted signal
  - the end result is the information about the error rate in almost real use conditions

Signal integrity measurements

- BERT (Bit Error Ratio Tester)