Frequency content of pulse shapes

Data signal PSD

- Power Spectral Density
  - Governed by the Fourier Transform

$$s(t) \Leftrightarrow S(f)$$

  - Spectral representation of a communication signal $\left|S(f)\right|^2$

- Digital signal
  - Symbol duration T_s $\Leftrightarrow$ baud rate R_s
  - Pulse shape $p(t)$

Pulse shapes – two extremes

Square pulses

- Easily generated
- Spectrally inefficient
- Time limited

Sinc pulses

- More complex to generate
- “ideally” spectrally efficient
- Band limited

Pulse shapes – two extremes

Square pulses

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- Spectrally inefficient
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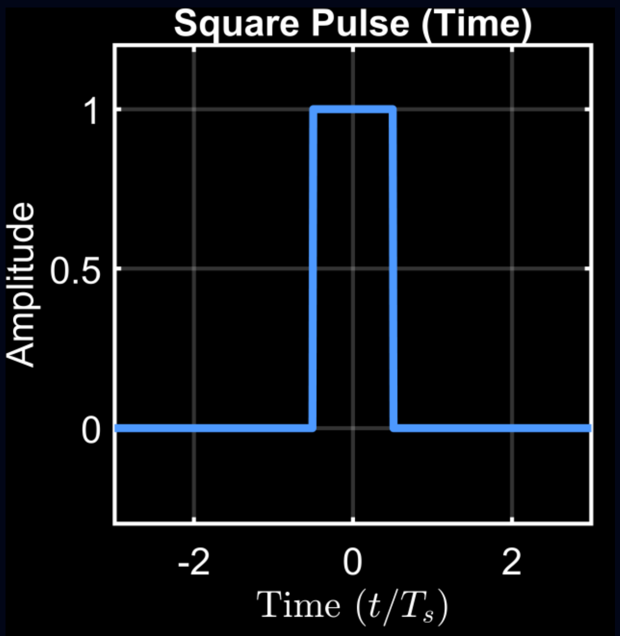

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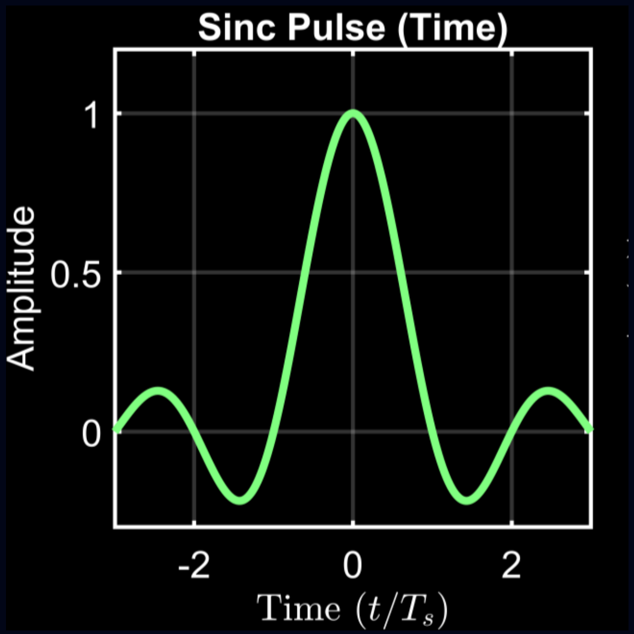

Pulse shapes – two extremes

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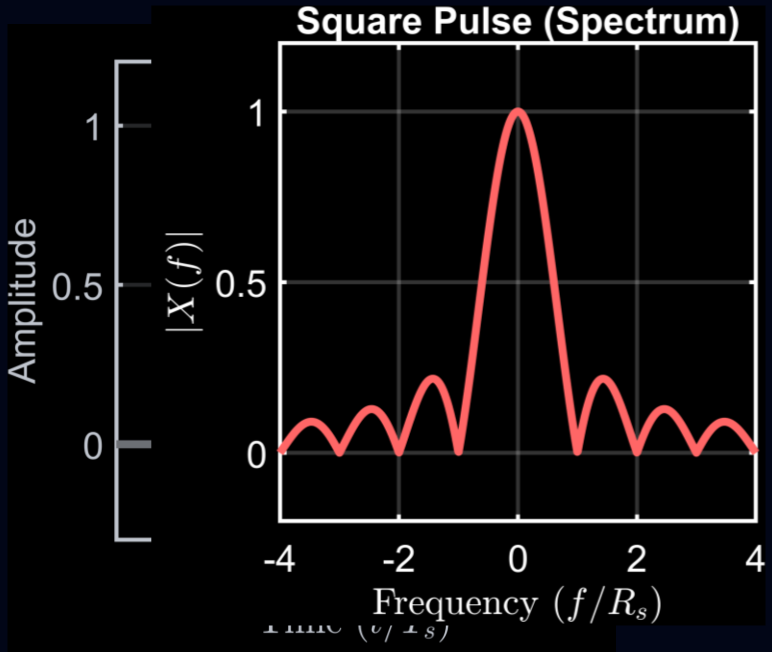
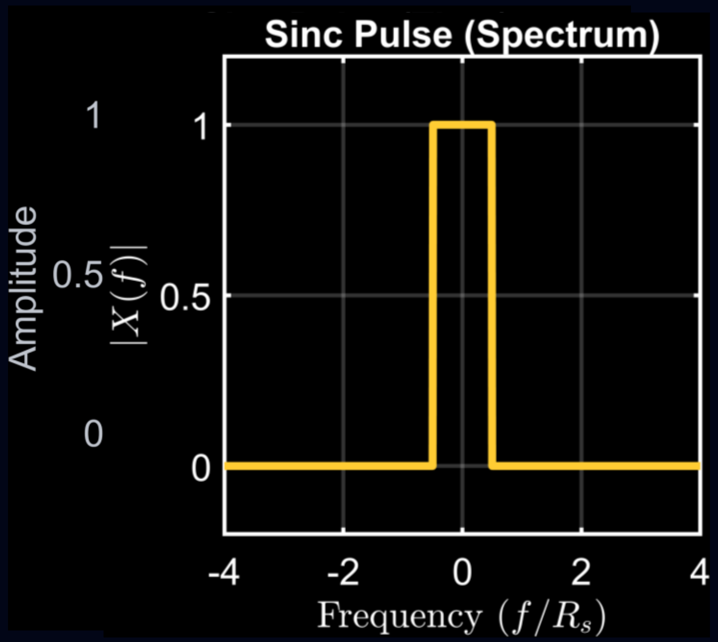




Practical considerations (TX)

Square pulses

- HP pattern generator

Sinc pulses

- Raised cosine more popular than Sinc
- Fixed filter possible
- Programmable versions also
    - arbitrary waveform generator
    - digital to analog converter
- Not available in teaching lab

Practical considerations

Square pulses

- HP pattern generator
- Data D and Data Bar $\overline{D}$ outputs
- NRZ non return to zero
- Frequency range
  - 100 Mb/s to 3 Gb/s

Focus our discussion on square pulses

Baud rate sweep

Bandwidth limited channel

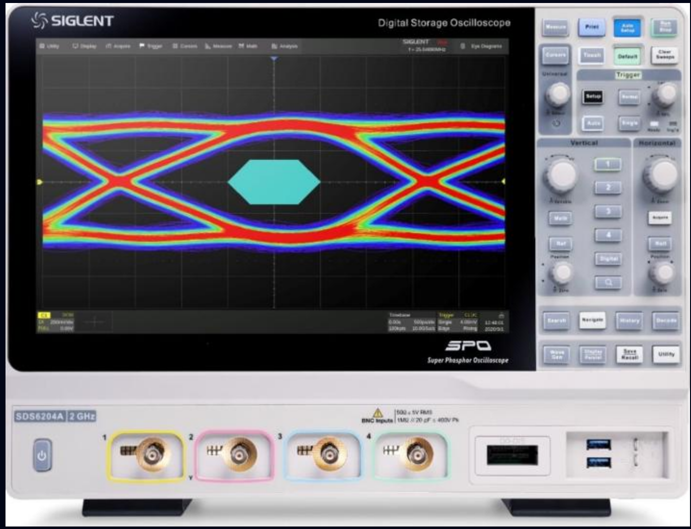
- Physical components
  - Impossible to have infinite bandwidth
  - Systems exhibit low pass filtering
  - Channel frequency response $H(f)$

- If signal bandwidth exceeds system bandwidth
  - Distortion
  - Pulse spreading
  - Intersymbol interference

Practical considerations (RX)

- Experimental setup
  - Real time oscilloscope
    - Captures data
    - Saves to file
  - Offline digital signal processing
    - Mimic any receiver
    - Same algorithms, but no longer real time

Practical considerations

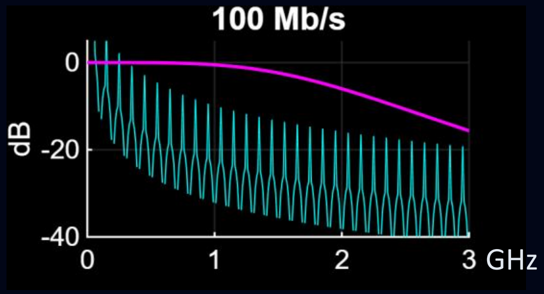


- Hardware we use
  - Siglent SKS6104A
  - RF bandwidth of 2 GHz
  - Sampling rate of 5 Gsa/s

Transmitter vs. Receiver $H(f)$

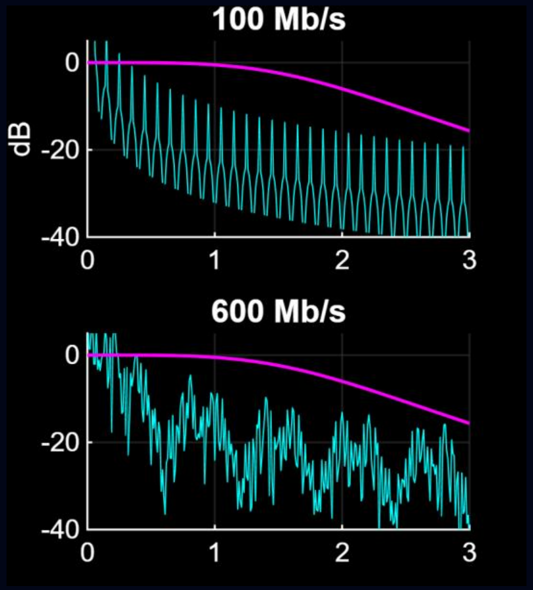
- RTO 2 GHz

- PRBS variable



Transmitter vs. Receiver $H(f)$

- RTO 2 GHz
- PRBS variable



Transmitter vs. Receiver $H(f)$

- RTO 2 GHz
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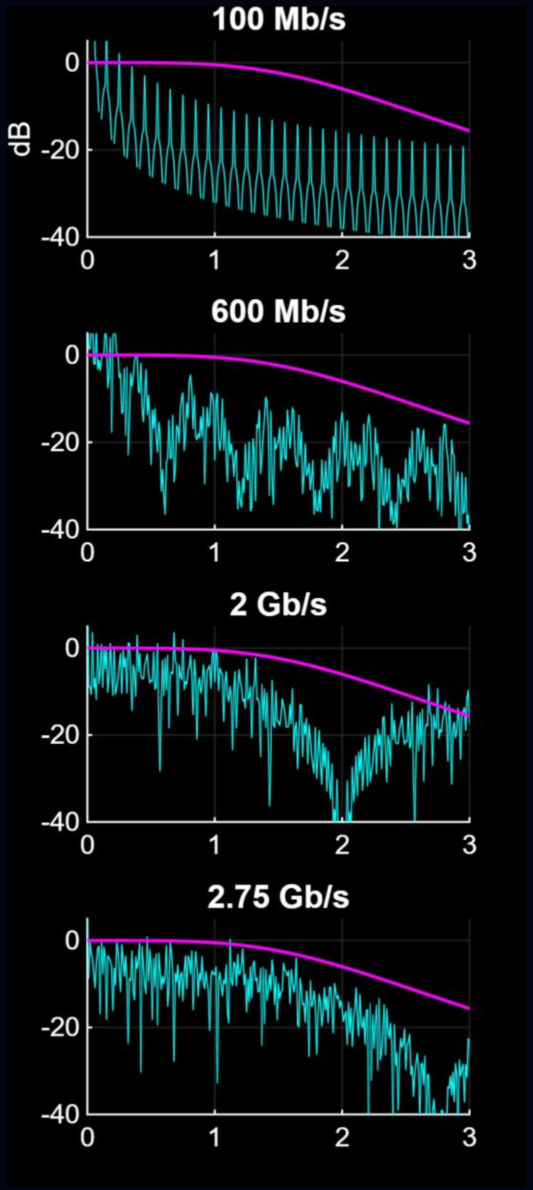
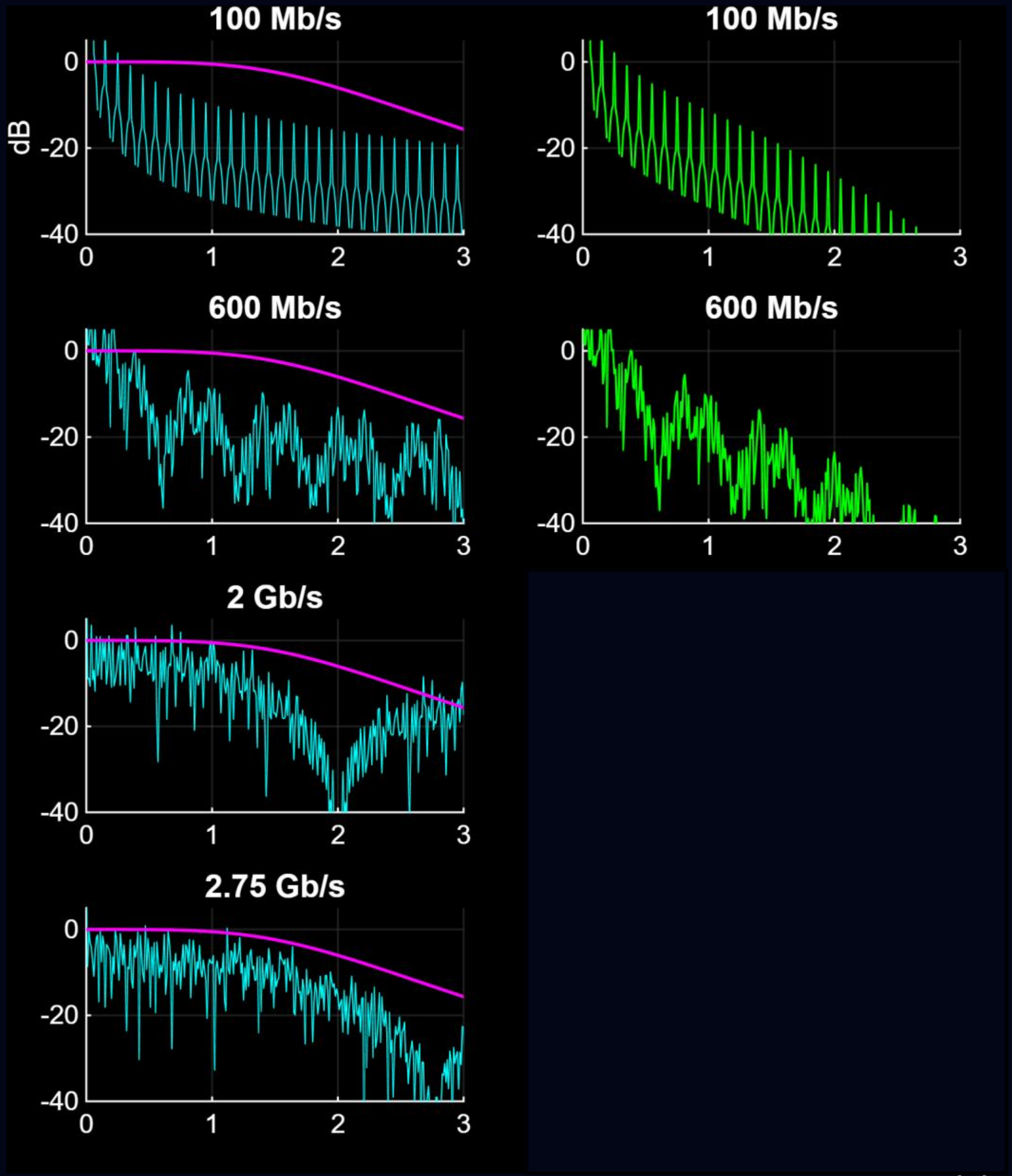
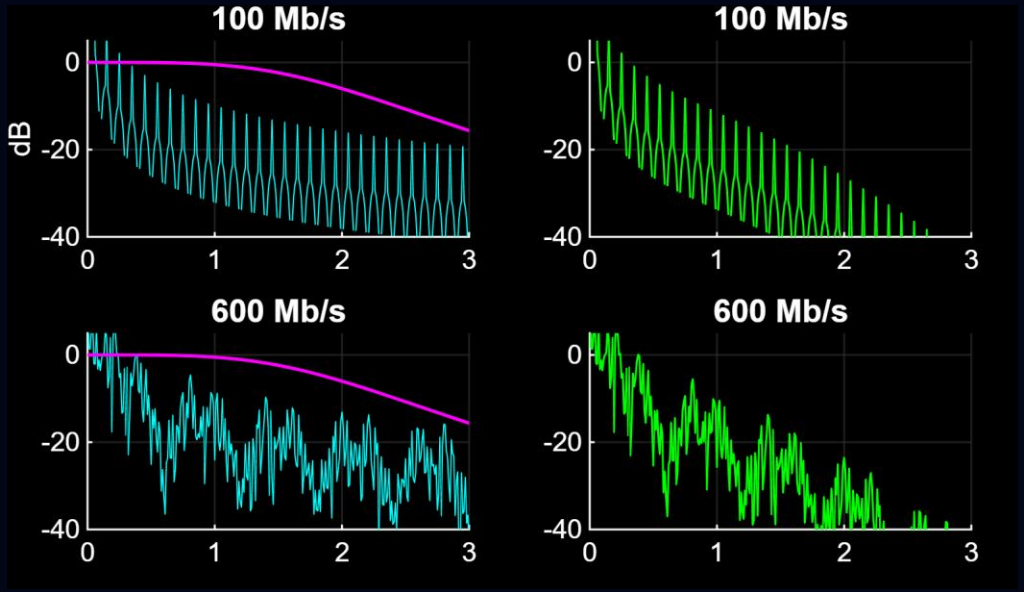


Filtering effect

- RTO 2 GHz
- PRBS variable



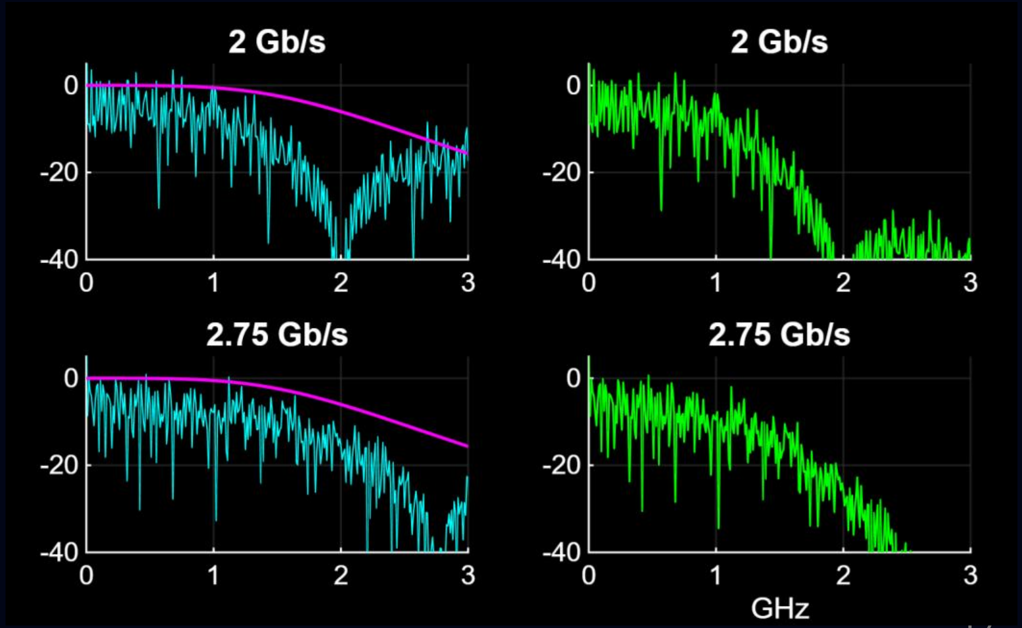
Filtering effect



no visible distortion in frequency domain

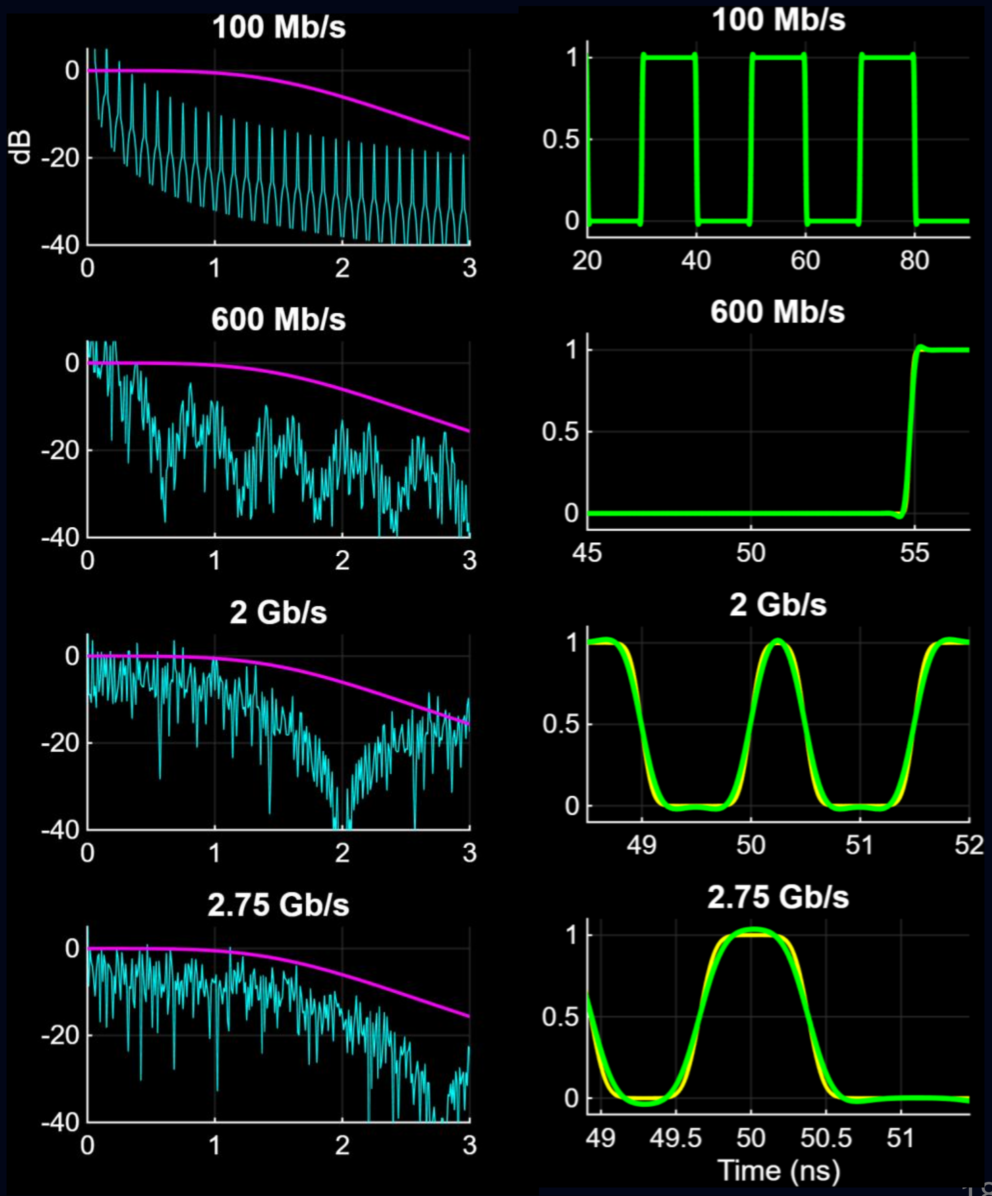
Filtering effect

distortion as more signal energy is
above 2 GHz



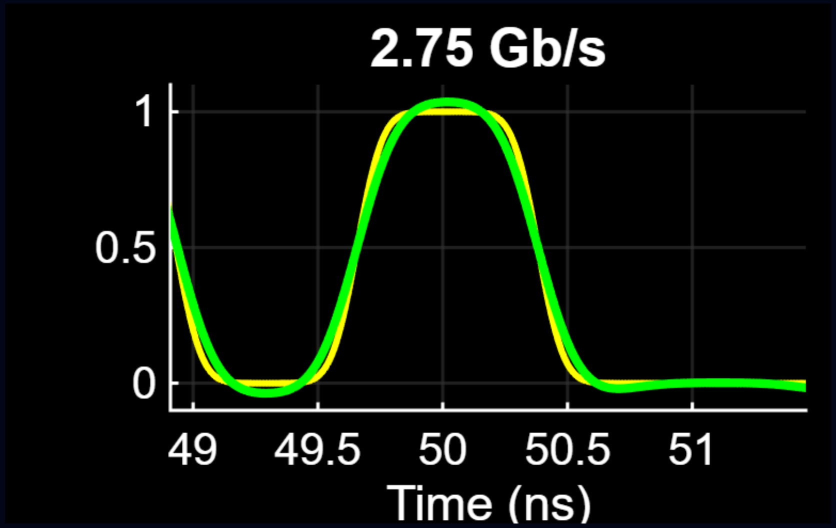
Filtering effect

time pulses get
more rounded (TX)
and
more distorted (RX)



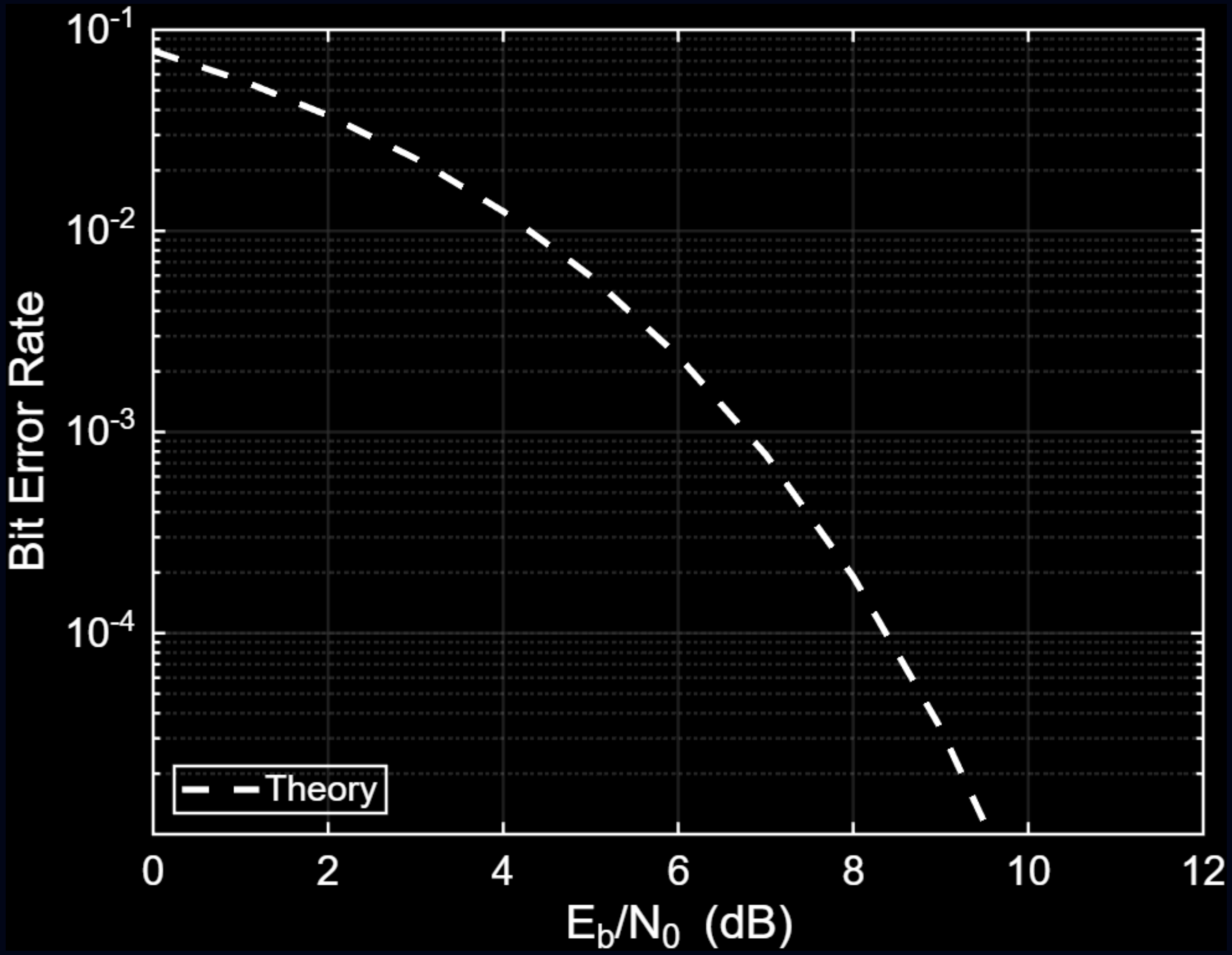
Filtering effect

eye diagrams very different

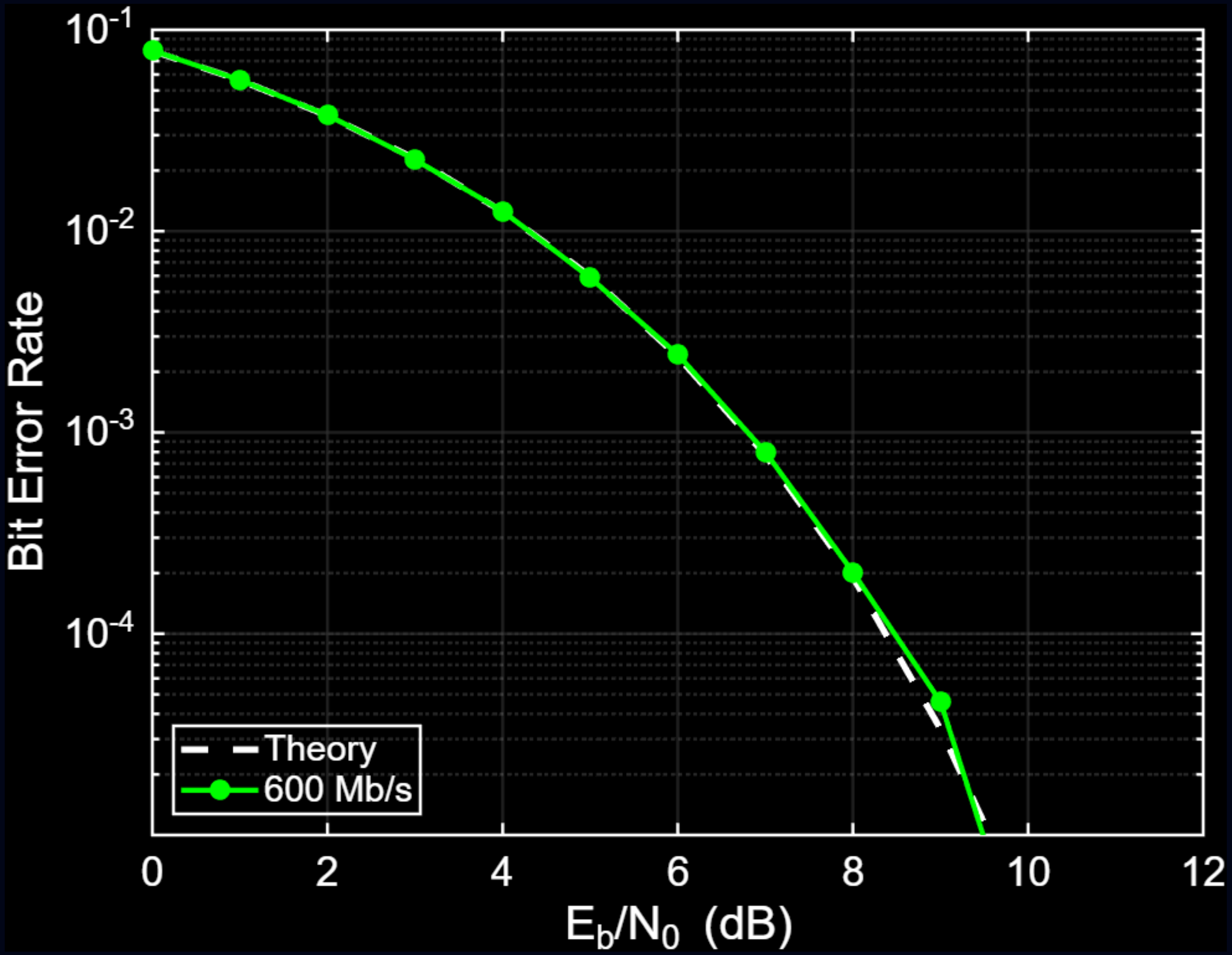


Penalty from Bandwidth Limitation

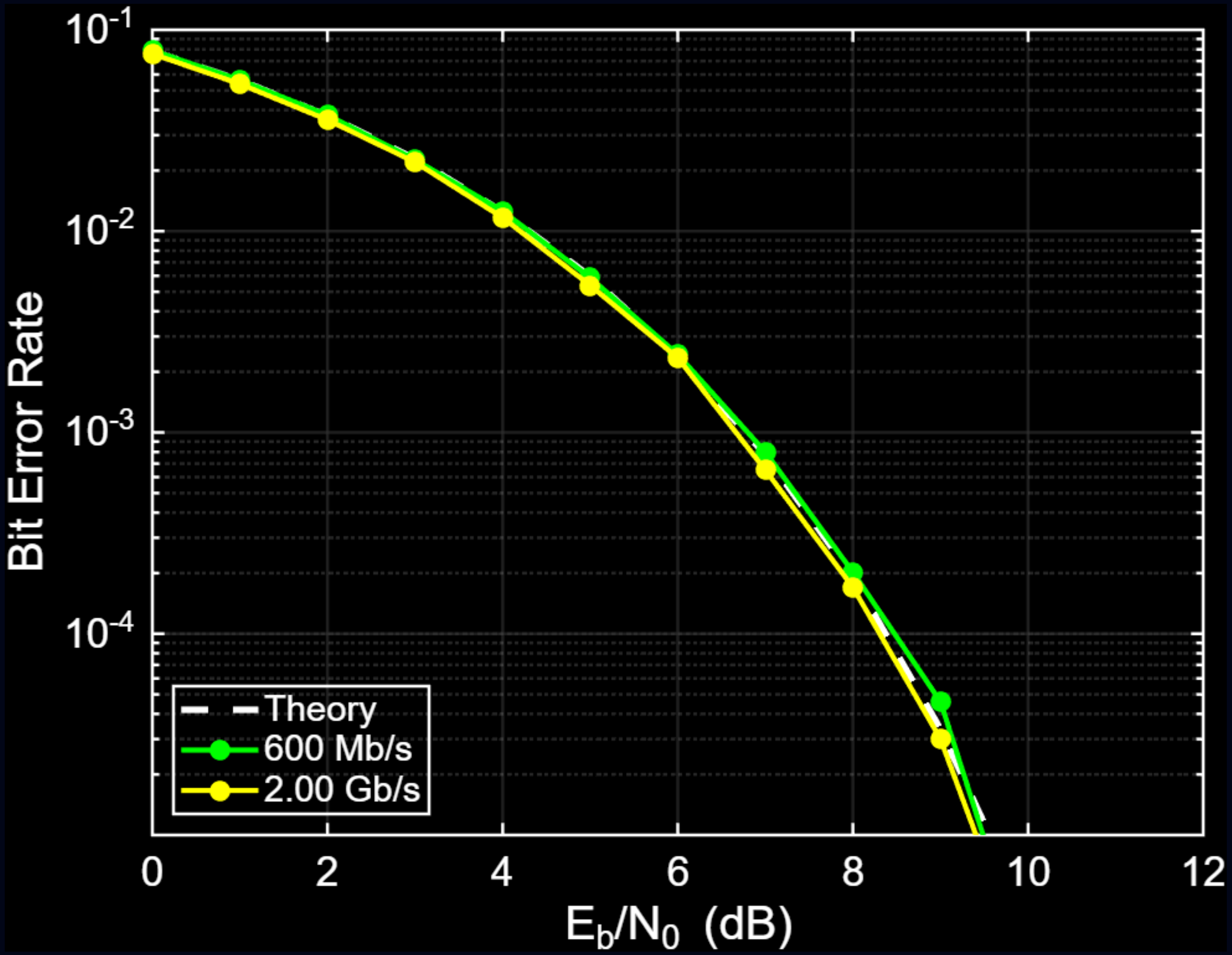
What happens to BER?



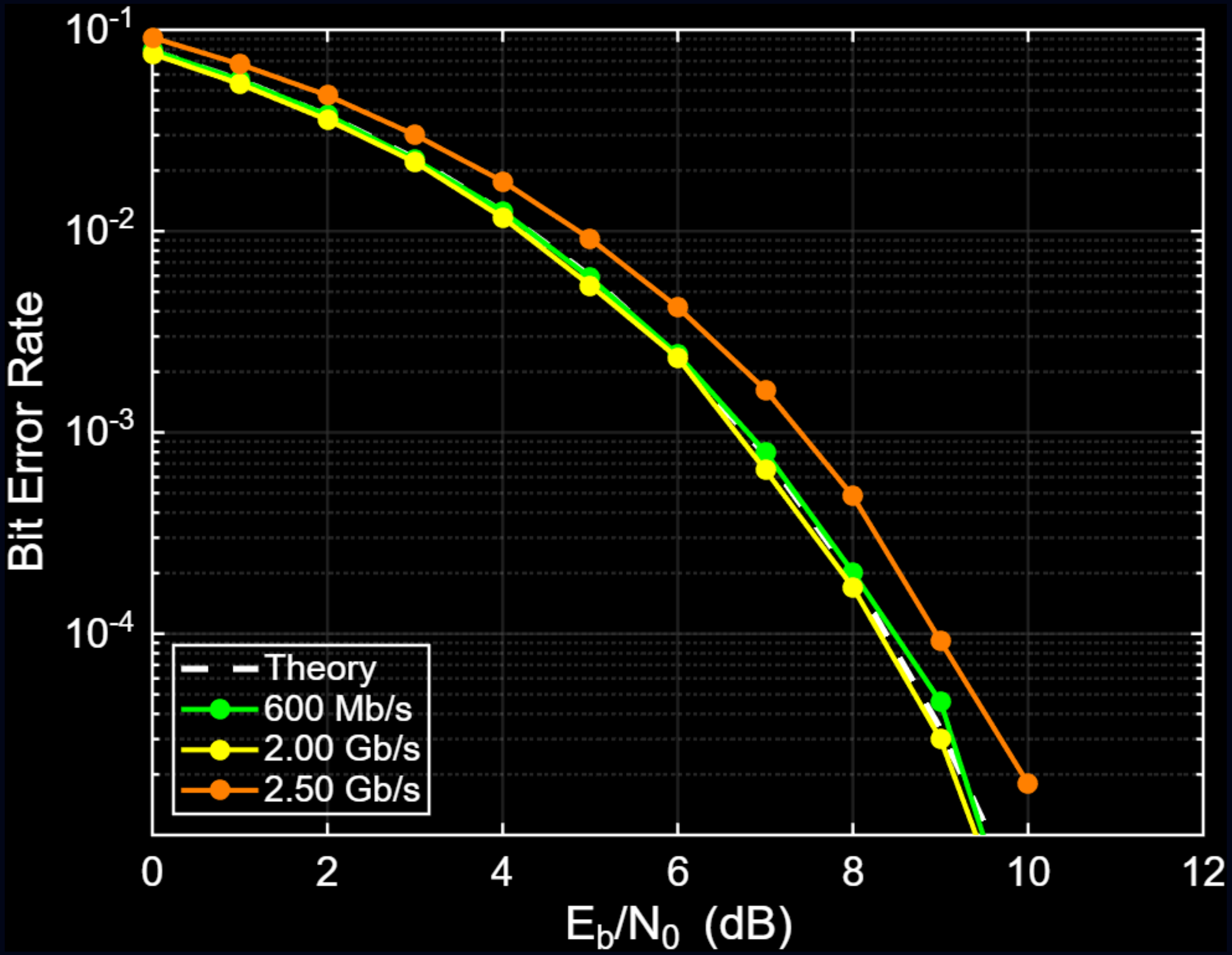
no impact at 600 Mb/s



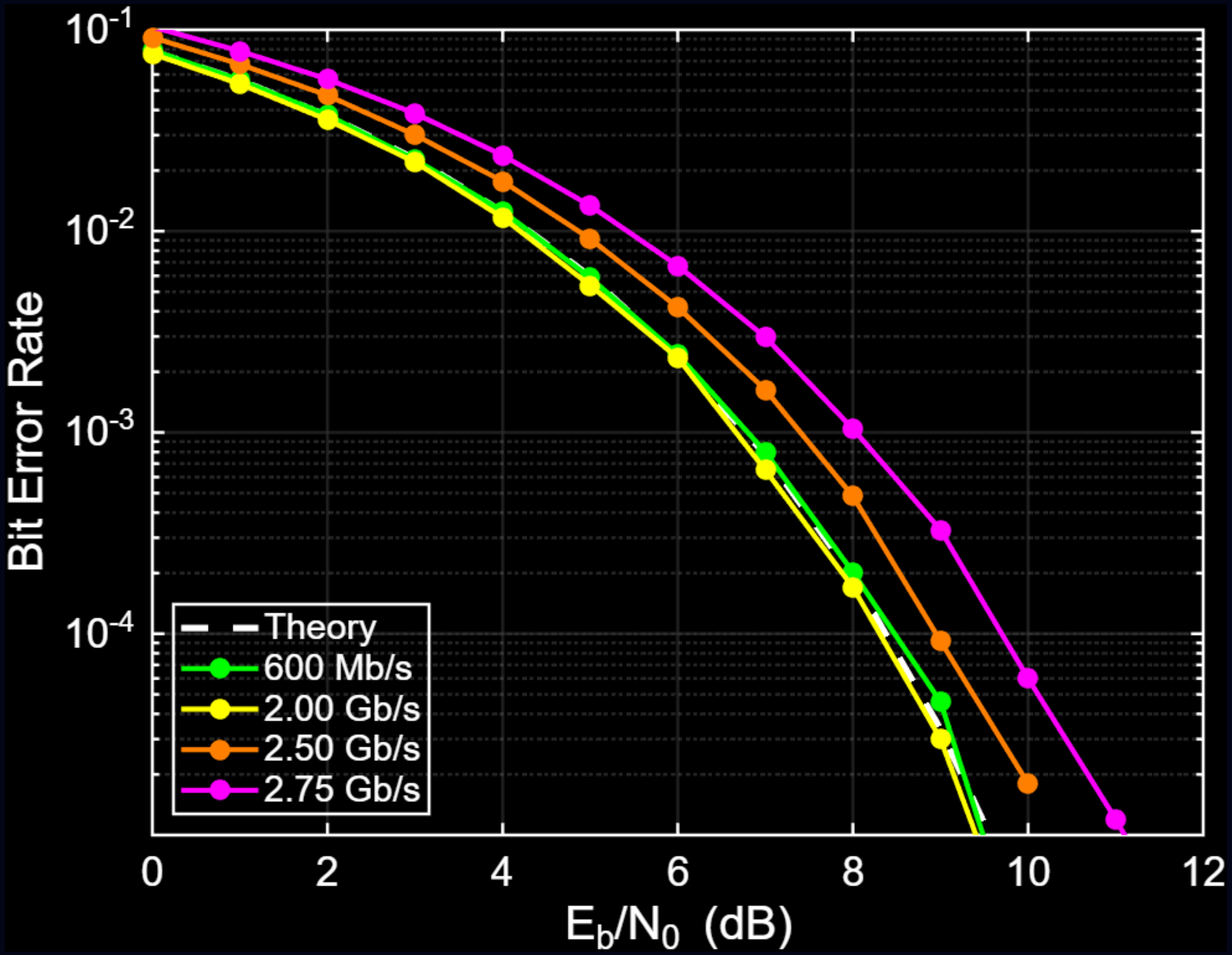
no impact at 2 Gb/s



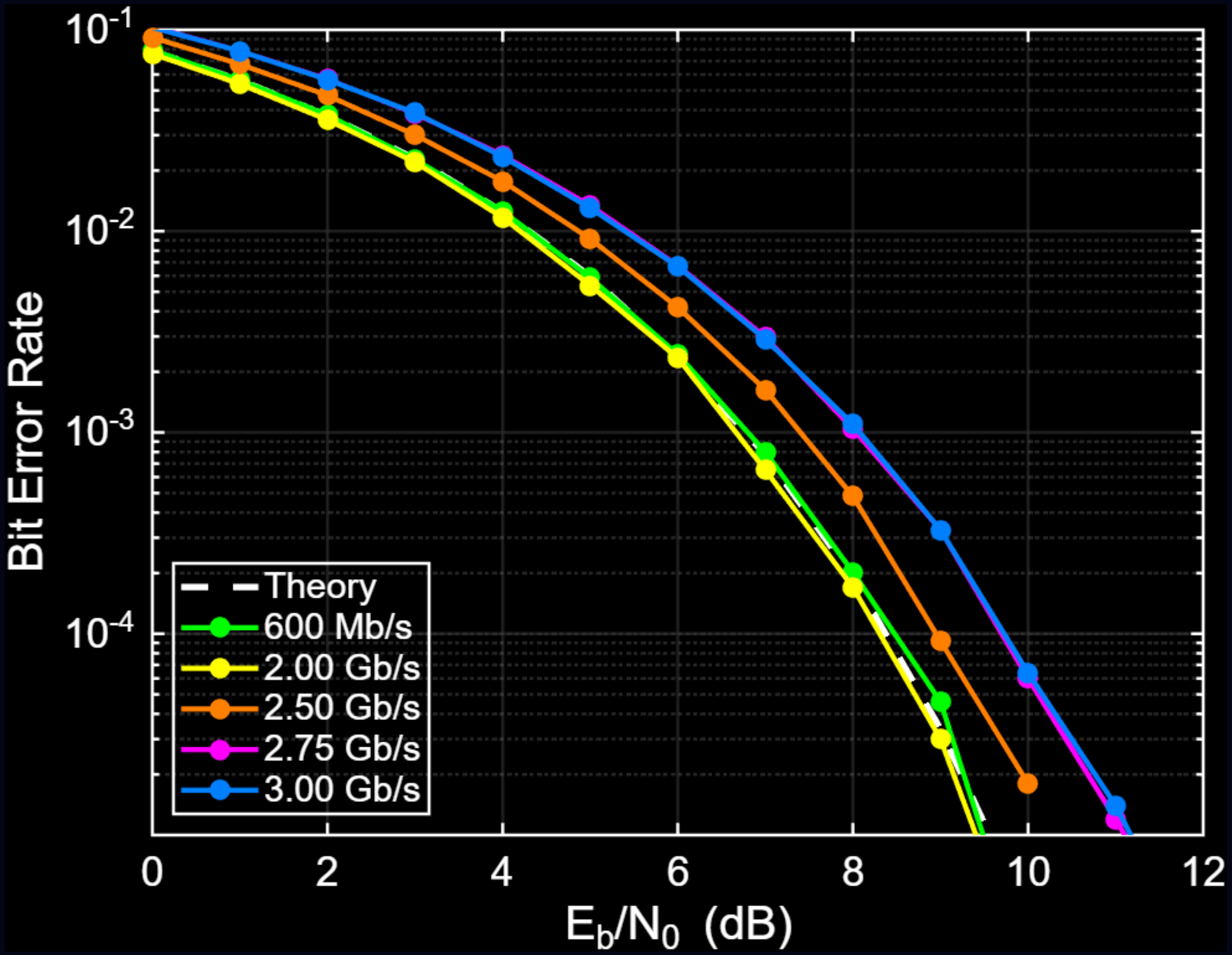
worse BER at 2.5 Gb/s



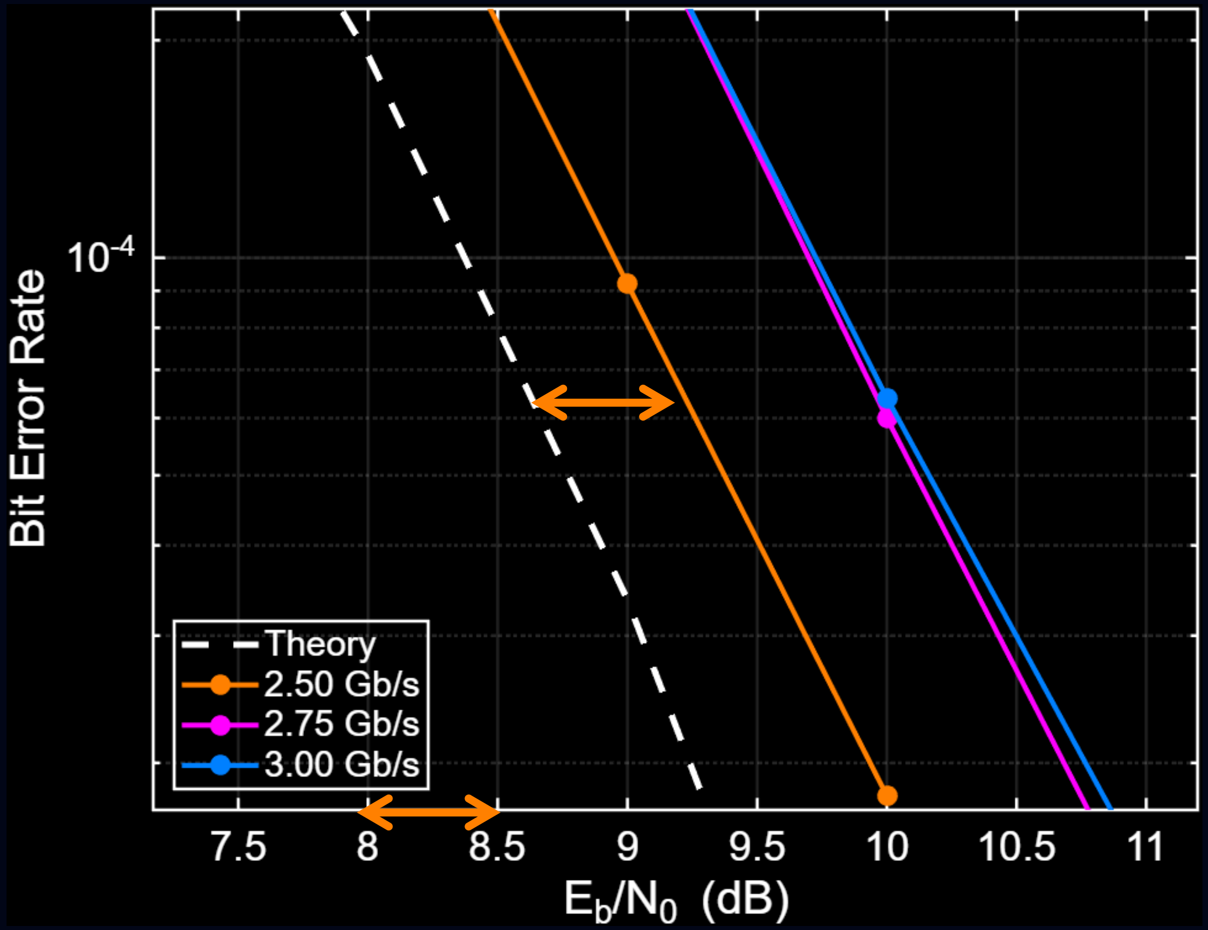
even worse BER at 2.75 Gb/s



saturated at 3 Gb/s

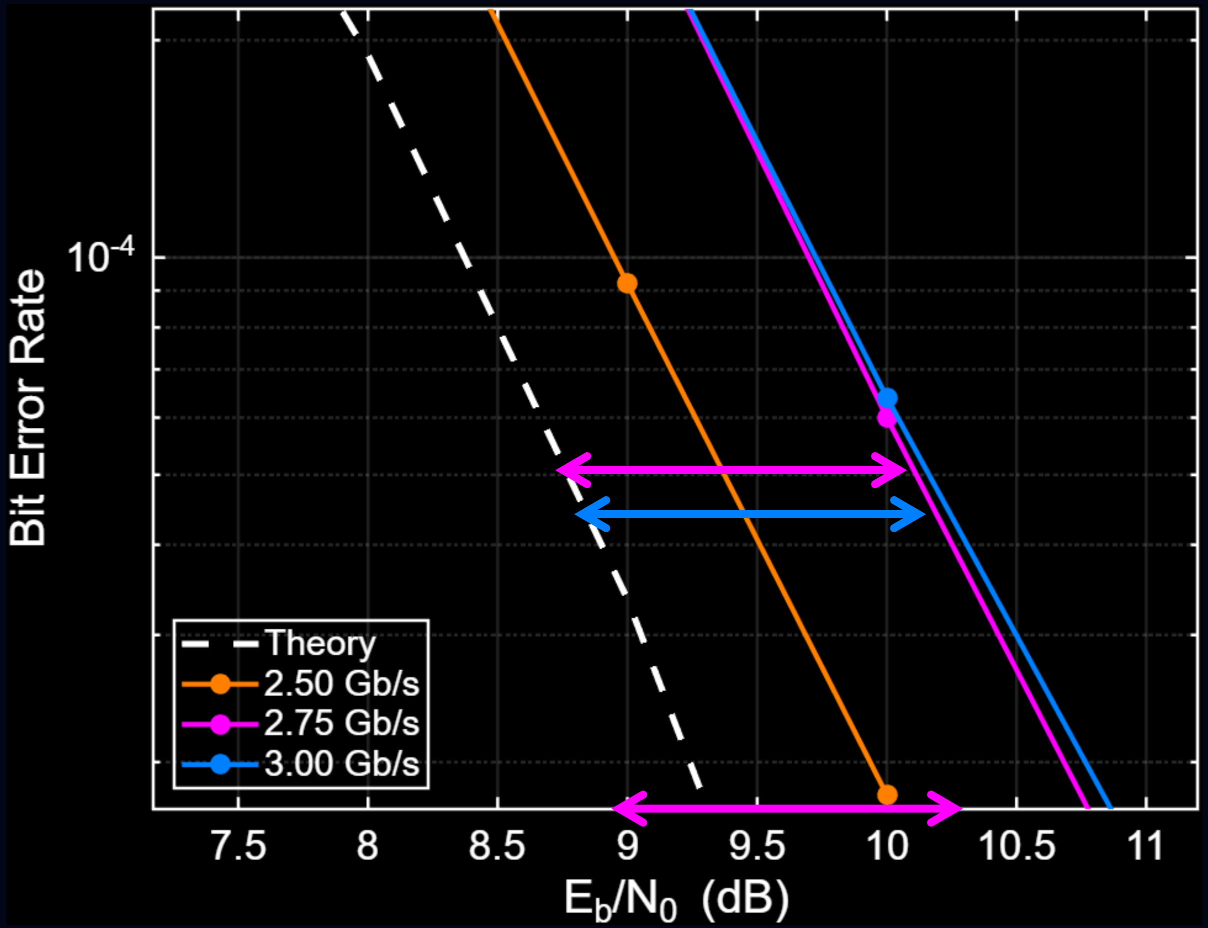


Implementation penalty



penalty 0.5 dB

Implementation penalty



penalty 1.25 dB

Bandwidth limitations

- Slowing down your transmission
  - Eliminates distortion
  - BER should follow theoretical curve
  - Good validation that system is well setup
- When hardware bandwidth is limited
  - Pulse shaping (if available)
    - Allows faster transmission
    - Very spectrally efficient
  - Equalization
    - Post processing DSP
    - Can overcome SNR penalty (at least some of the penalty)

Equivalent-time vs. Real-time Sampling Oscilloscopes

Two types of digital oscilloscopes

- Equivalent sampling
  - most common
  - least expensive
  - wider bandwidth affordable
  - digital version of original analog scope

- Real-time sampling
  - cost rises dramatically with bandwidth
  - required for offline processing

Two types of digital oscilloscopes

- Equivalent sampling
    - **Sampling oscilloscope**
      almost always equivalent time
    - DCA – digital communications analyzer
    - Sequential sampling

some marketing terms

- Real-time sampling
    - DSO – digital storage oscilloscope
    - Single-shot

Periodic vs. Data Signals

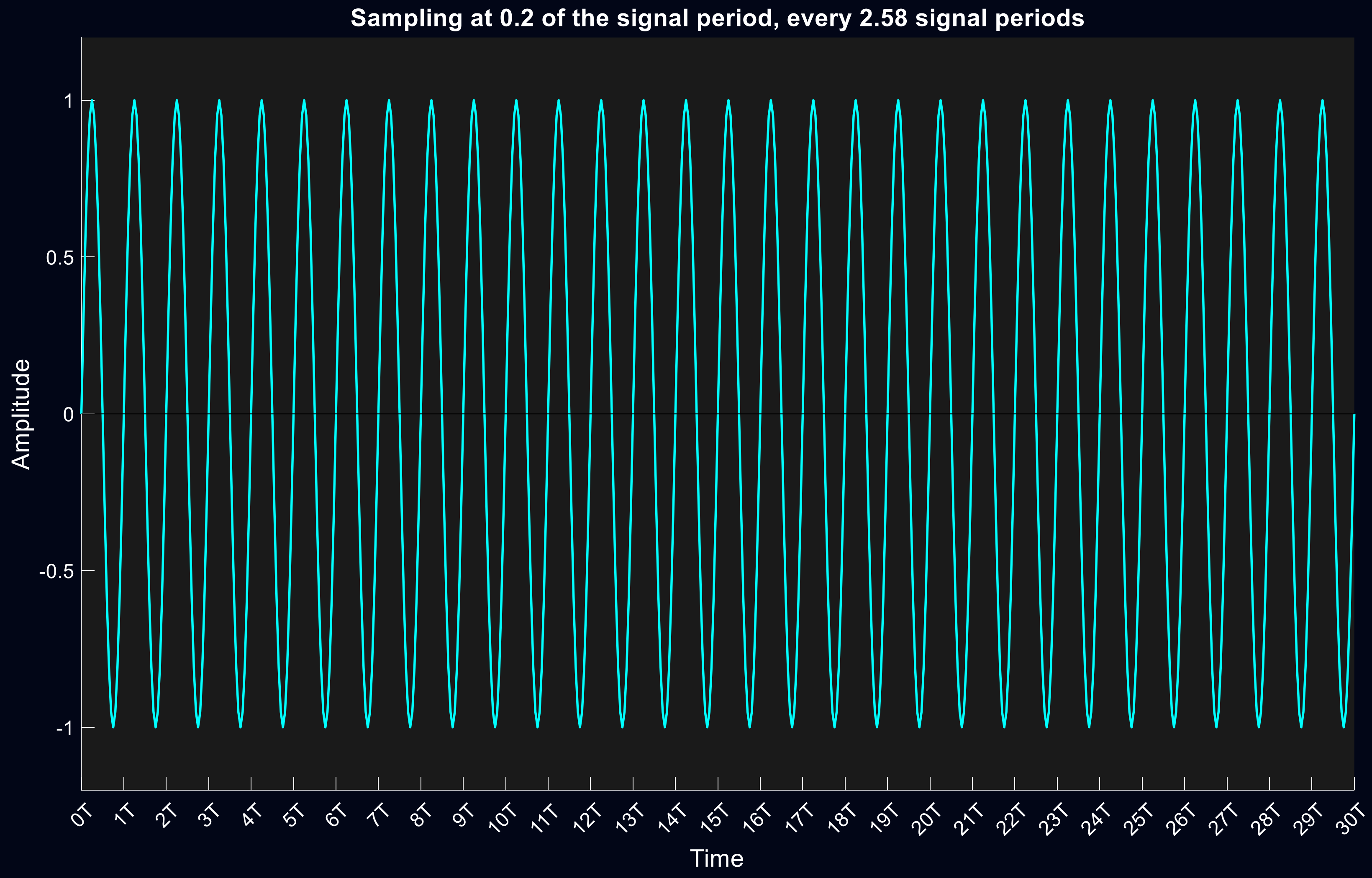
- Periodic
  - Unchanged from period to period
  - Sinusoids
  - Clock pulses

- Data Signals
  - Shape could be identical to periodic signals
  - Data does not shape
    - Change polarity (BPSK, QPSK)
    - Change amplitude (higher order modulation)

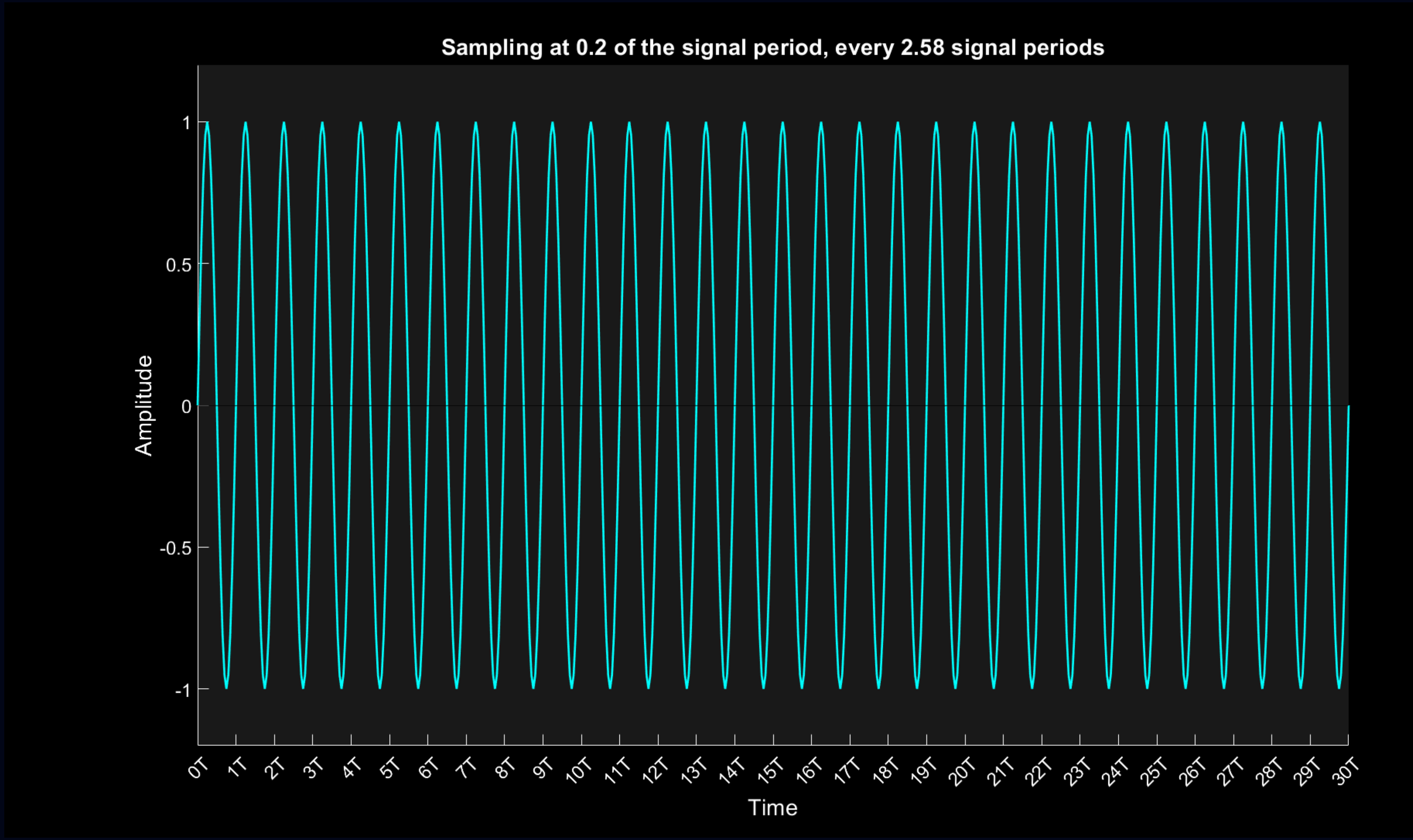
Equivalent-time Sampling Oscilloscopes

Periodic Signals

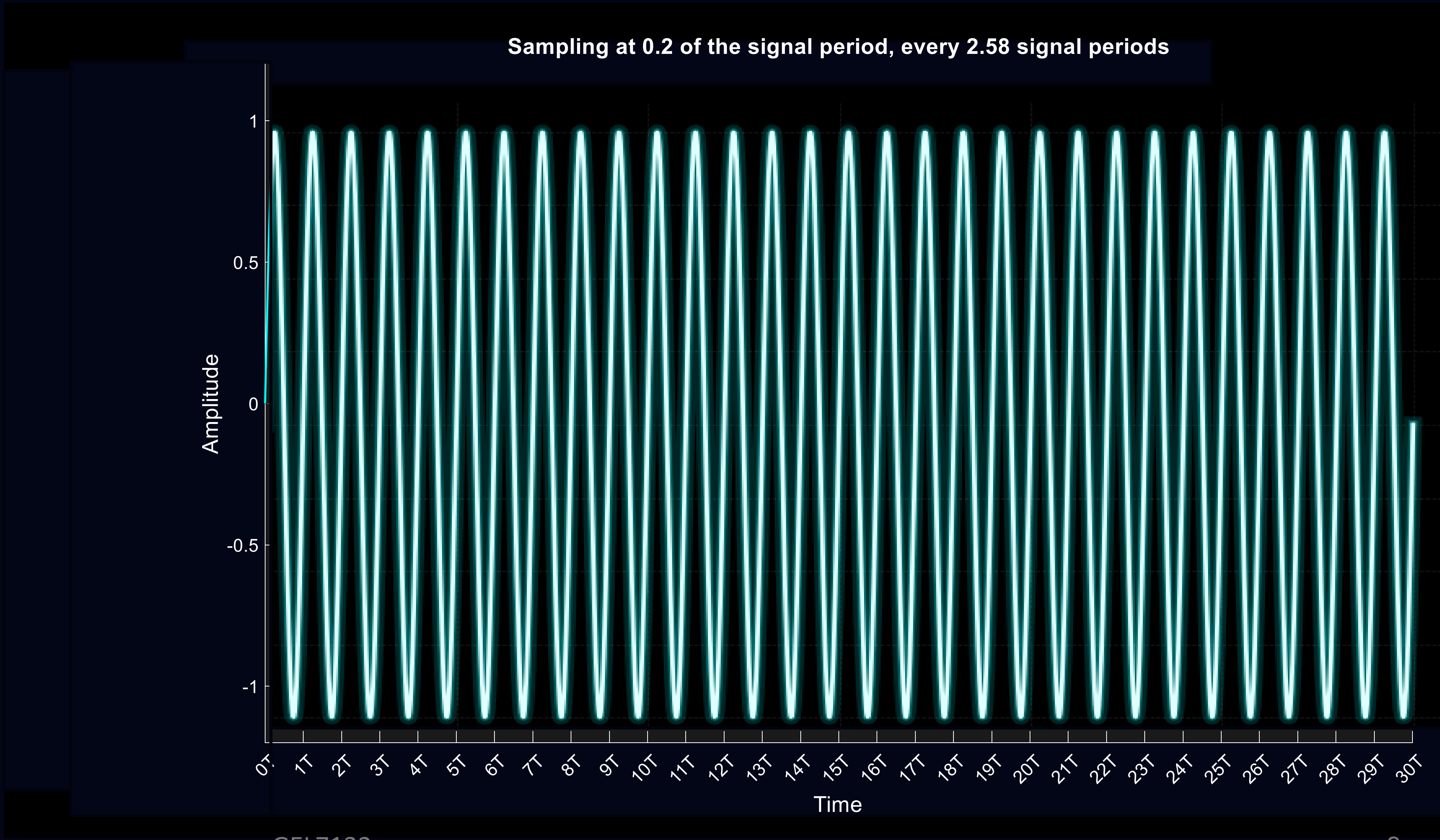
Period signal – sine tone



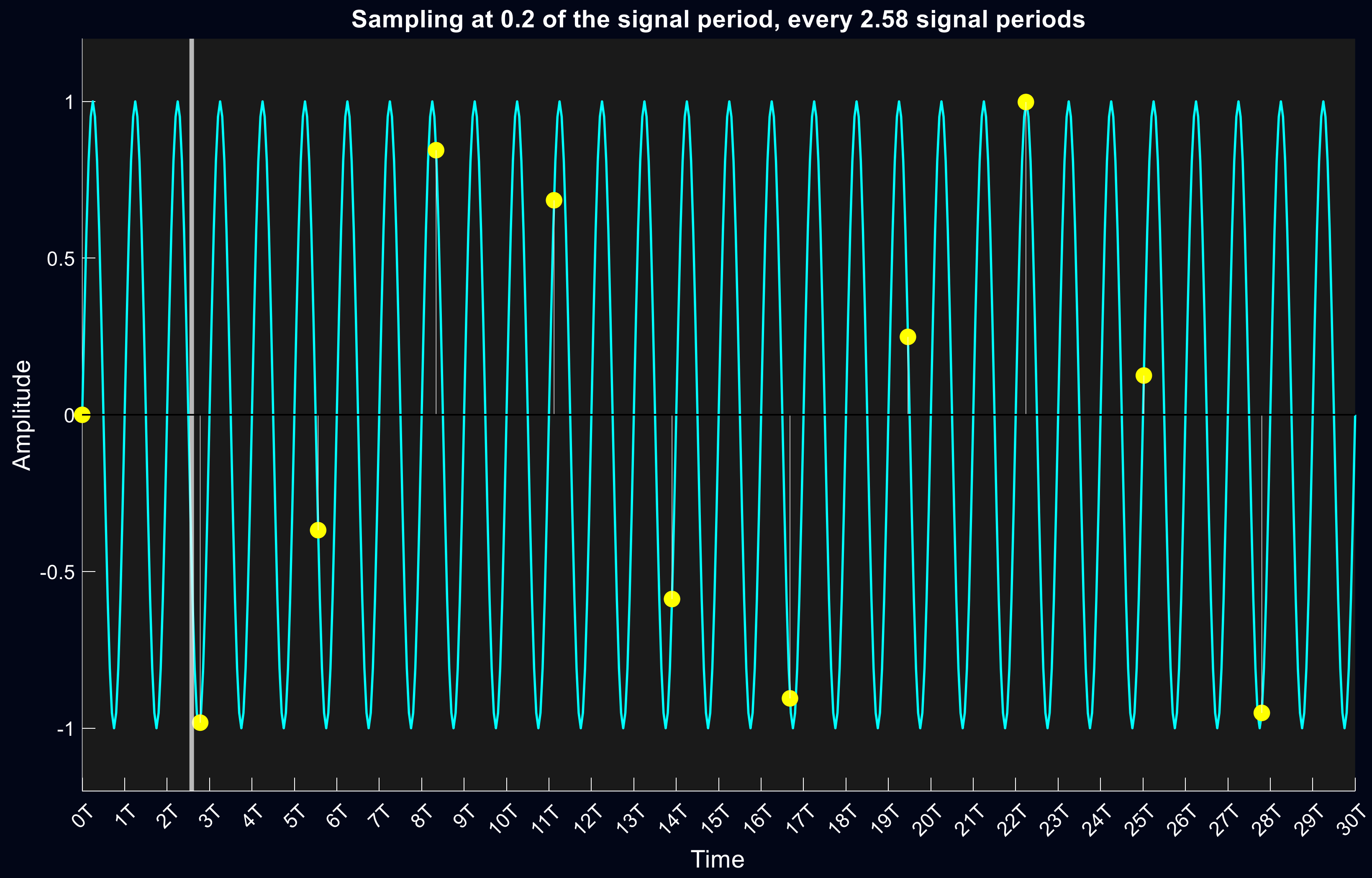
Sampling a periodic signal



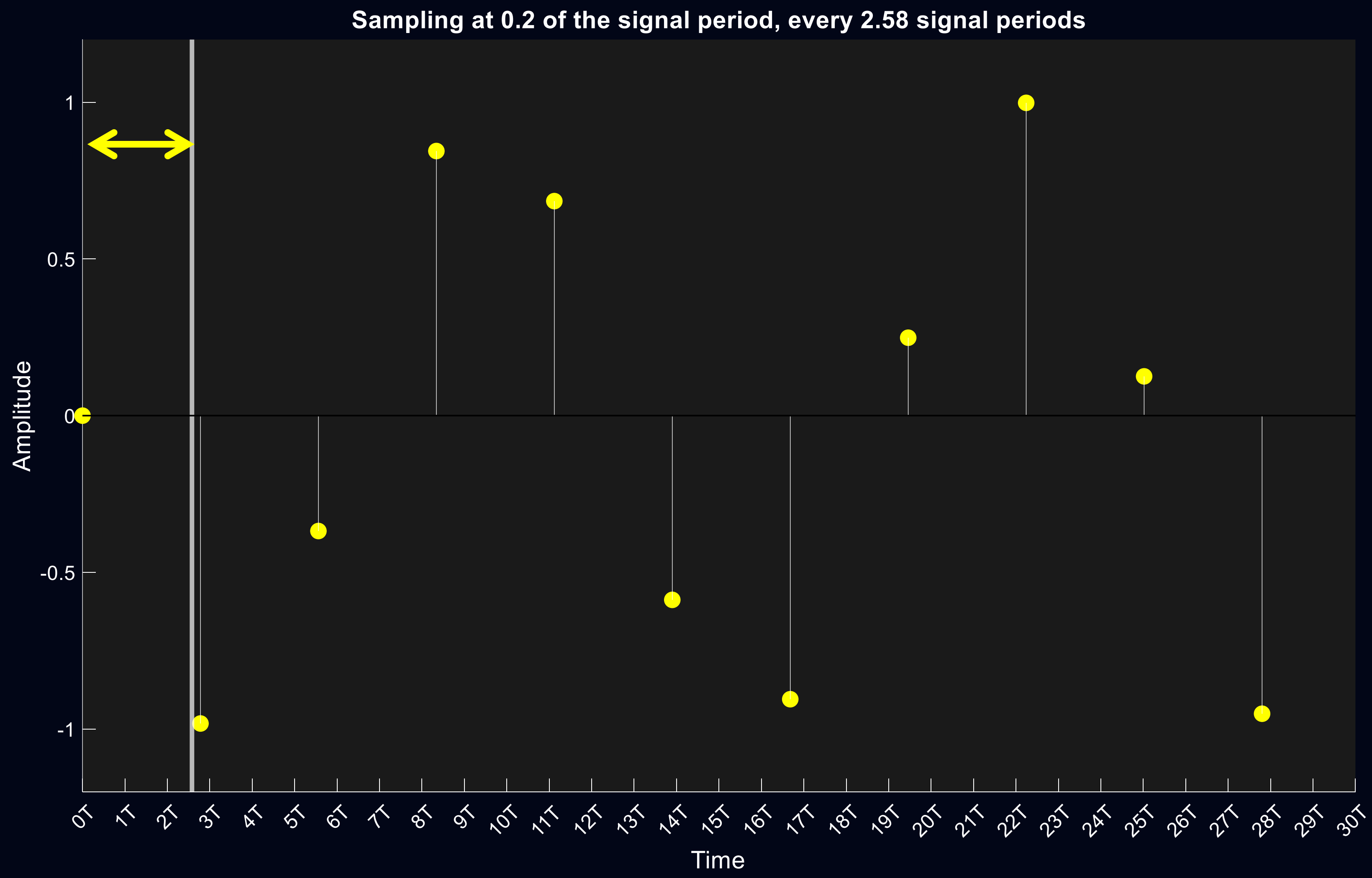
Sampling a periodic signal



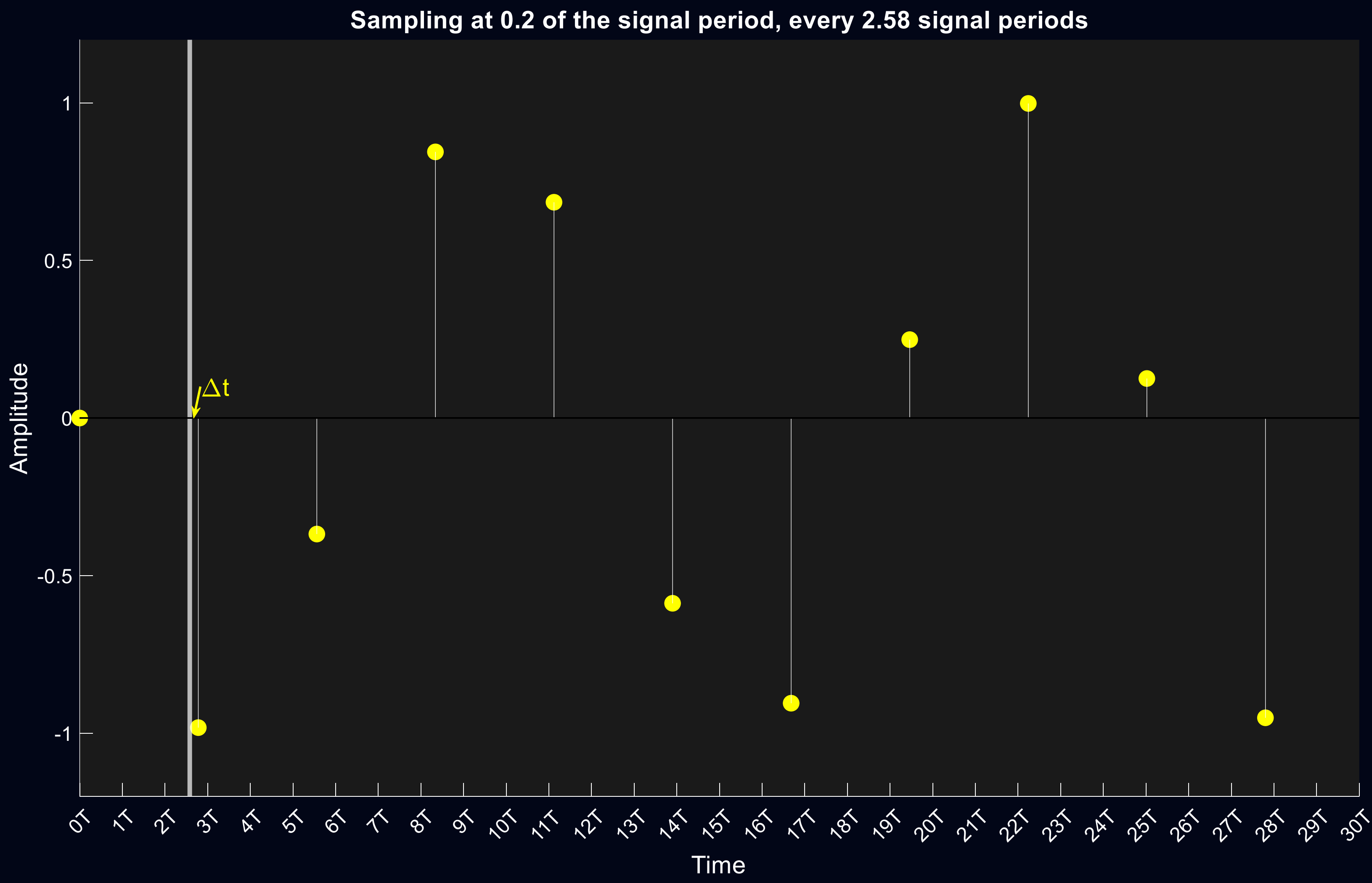
Sampling a periodic signal



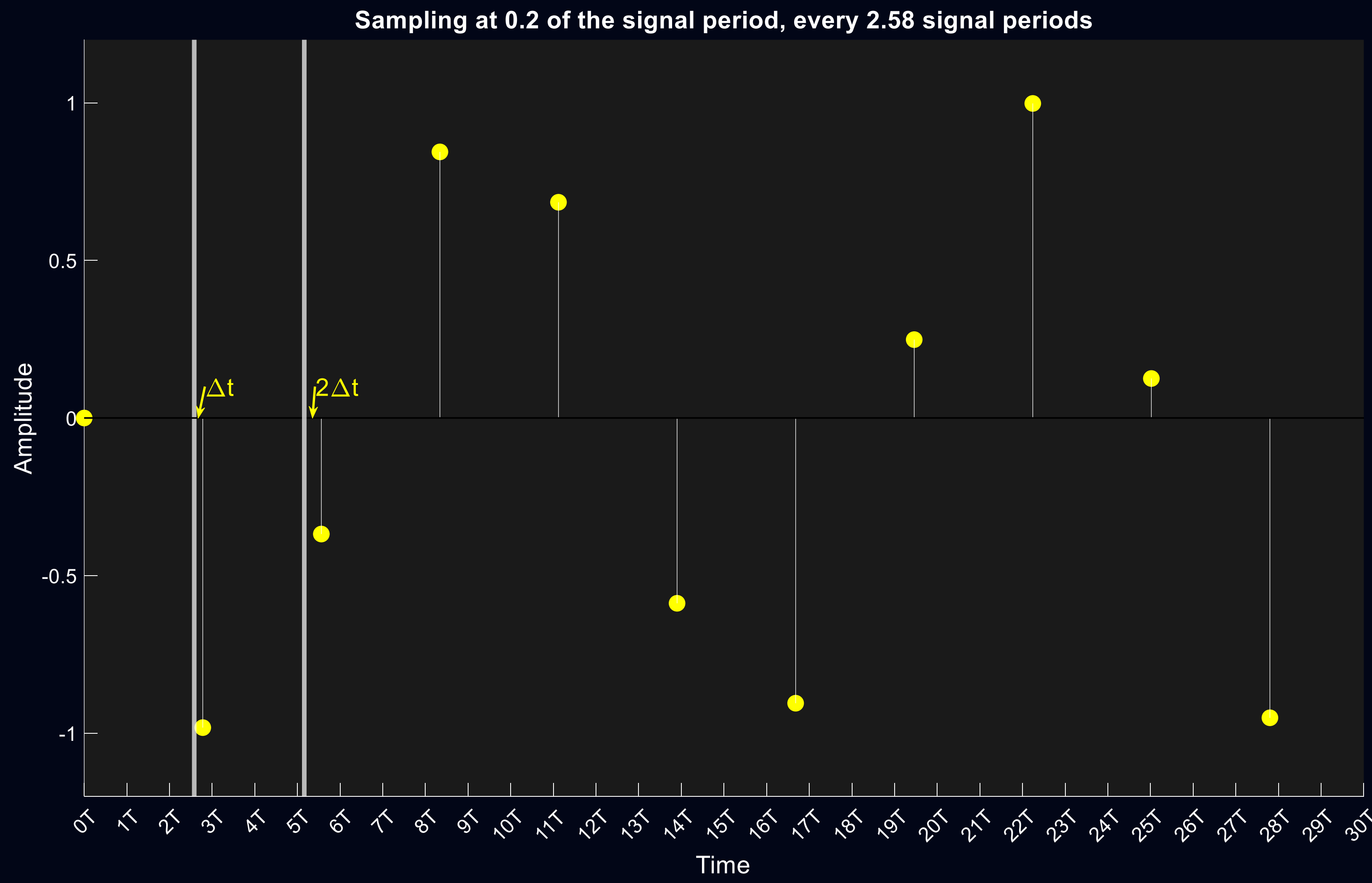
Re-arm time


Sampling at 0.2 of the signal period, every 2.58 signal periods
Amplitude
Time
1
0.5
0
-0.5
-1
0T 1T 2T 3T 4T 5T 6T 7T 8T 9T 10T 11T 12T 13T 14T 15T 16T 17T 18T 19T 20T 21T 22T 23T 24T 25T 26T 27T 28T 29T 30T

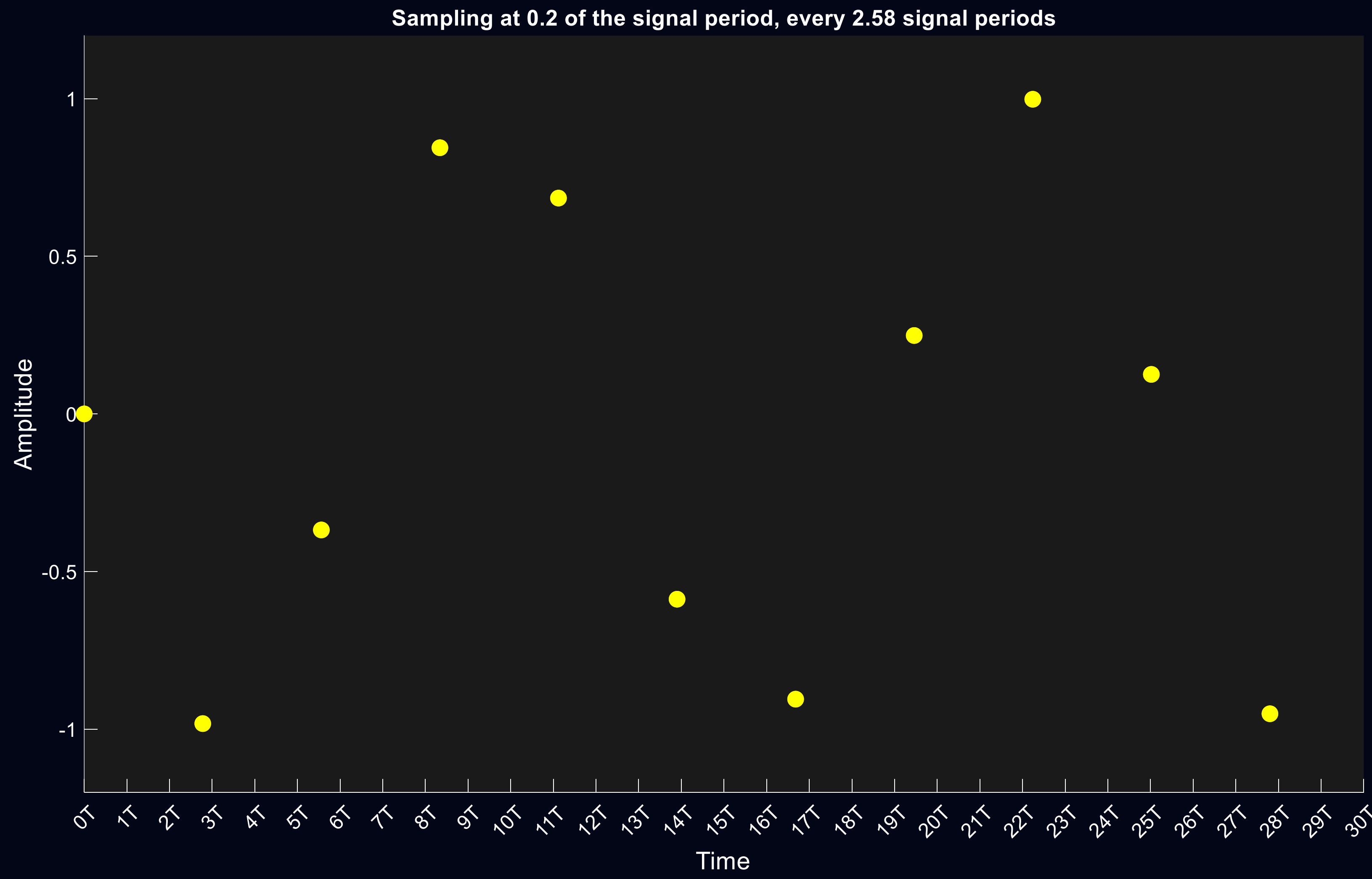
Sampling interval



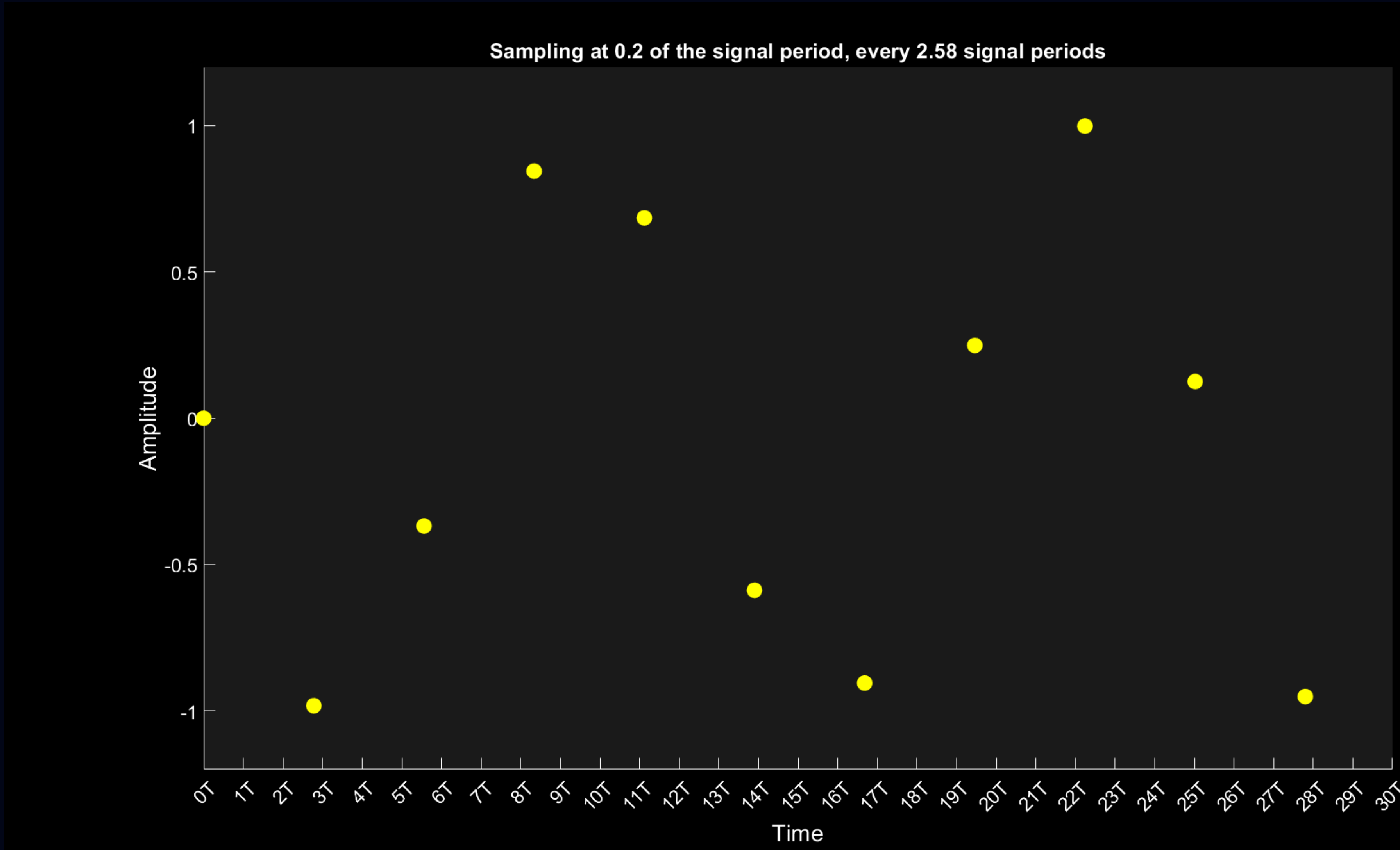
Sampling interval



Output


Sampling at 0.2 of the signal period, every 2.58 signal periods
Amplitude
1
0.5
0
-0.5
-1
0T
1T
2T
3T
4T
5T
6T
7T
8T
9T
10T
11T
12T
13T
14T
15T
16T
17T
18T
19T
20T
21T
22T
23T
24T
25T
26T
27T
28T
29T
30T
Time

Output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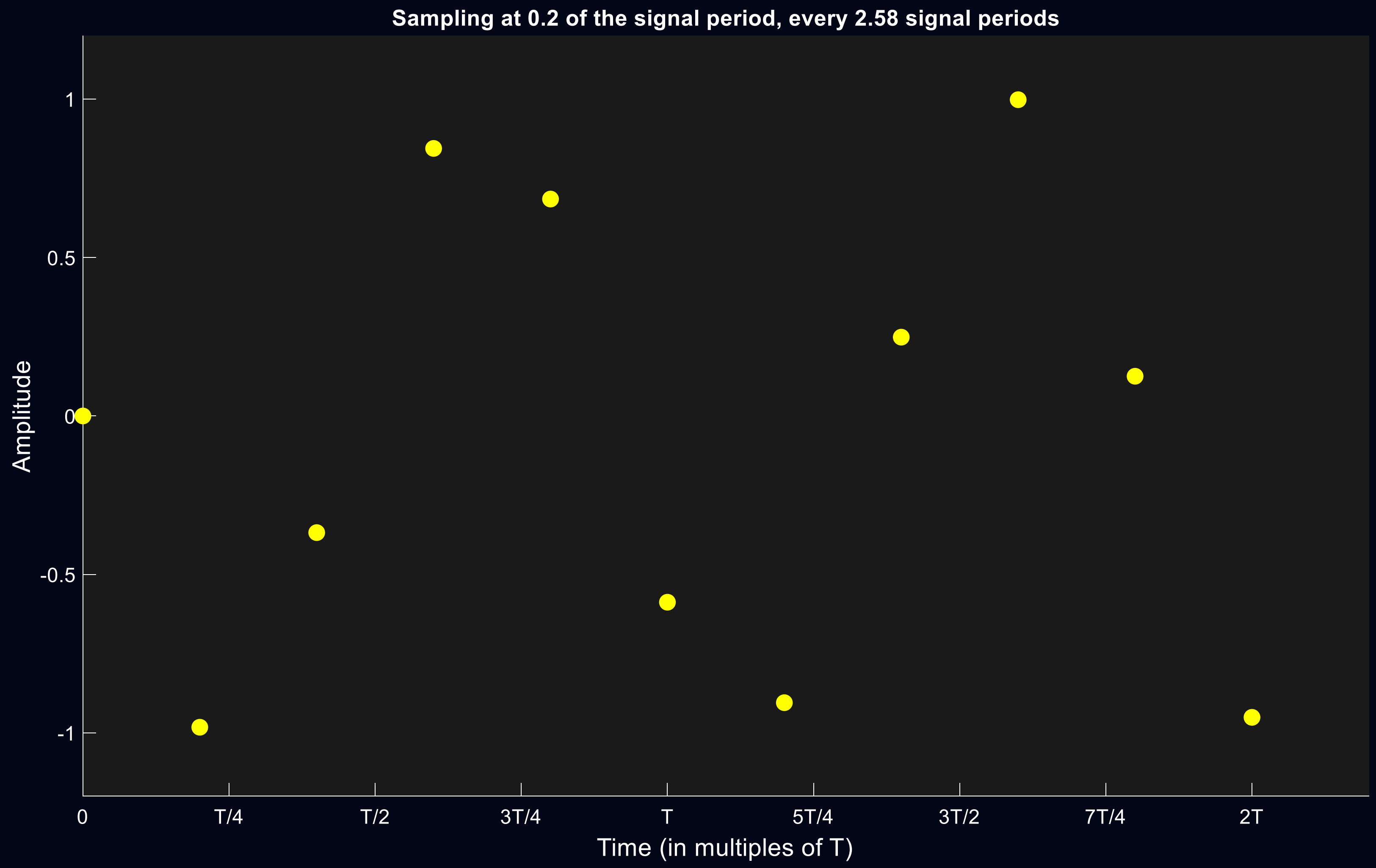
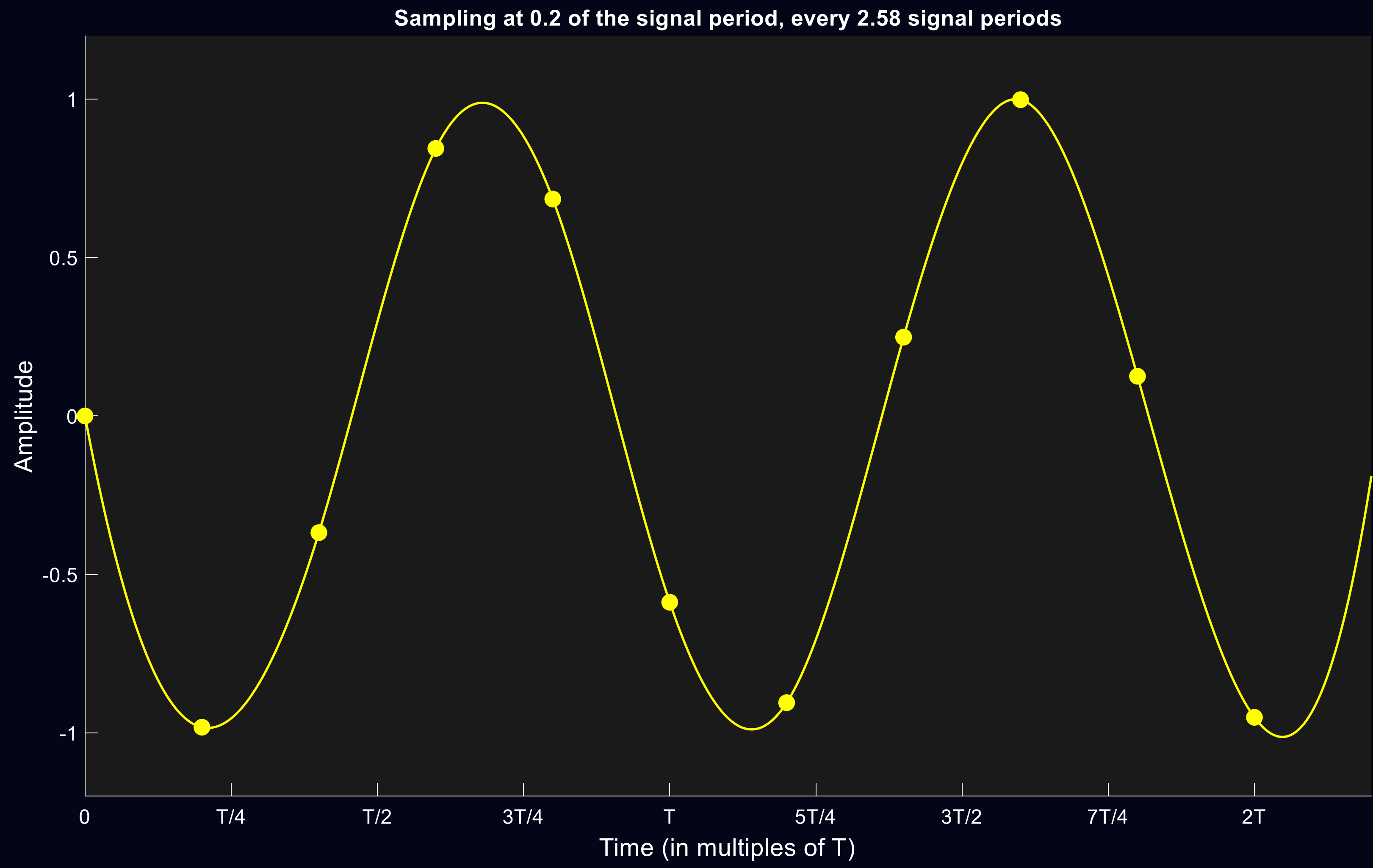
Amplitude
1
0.5
0
-0.5
-1
0T 1T 2T 3T 4T 5T 6T 7T 8T 9T 10T 11T 12T 13T 14T 15T 16T 17T 18T 19T 20T 21T 22T 23T 24T 25T 26T 27T 28T 29T 30T
Time

Output


Sampling at 0.2 of the signal period, every 2.58 signal periods
Amplitude
1
0.5
0
-0.5
-1
0
T/4
T/2
3T/4
T
5T/4
3T/2
7T/4
2T
Time (in multiples of T)

Output


Sampling at 0.2 of the signal period, every 2.58 signal periods
Amplitude
1
0.5
0
-0.5
-1
0
T/4
T/2
3T/4
T
5T/4
3T/2
7T/4
2T
Time (in multiples of T)

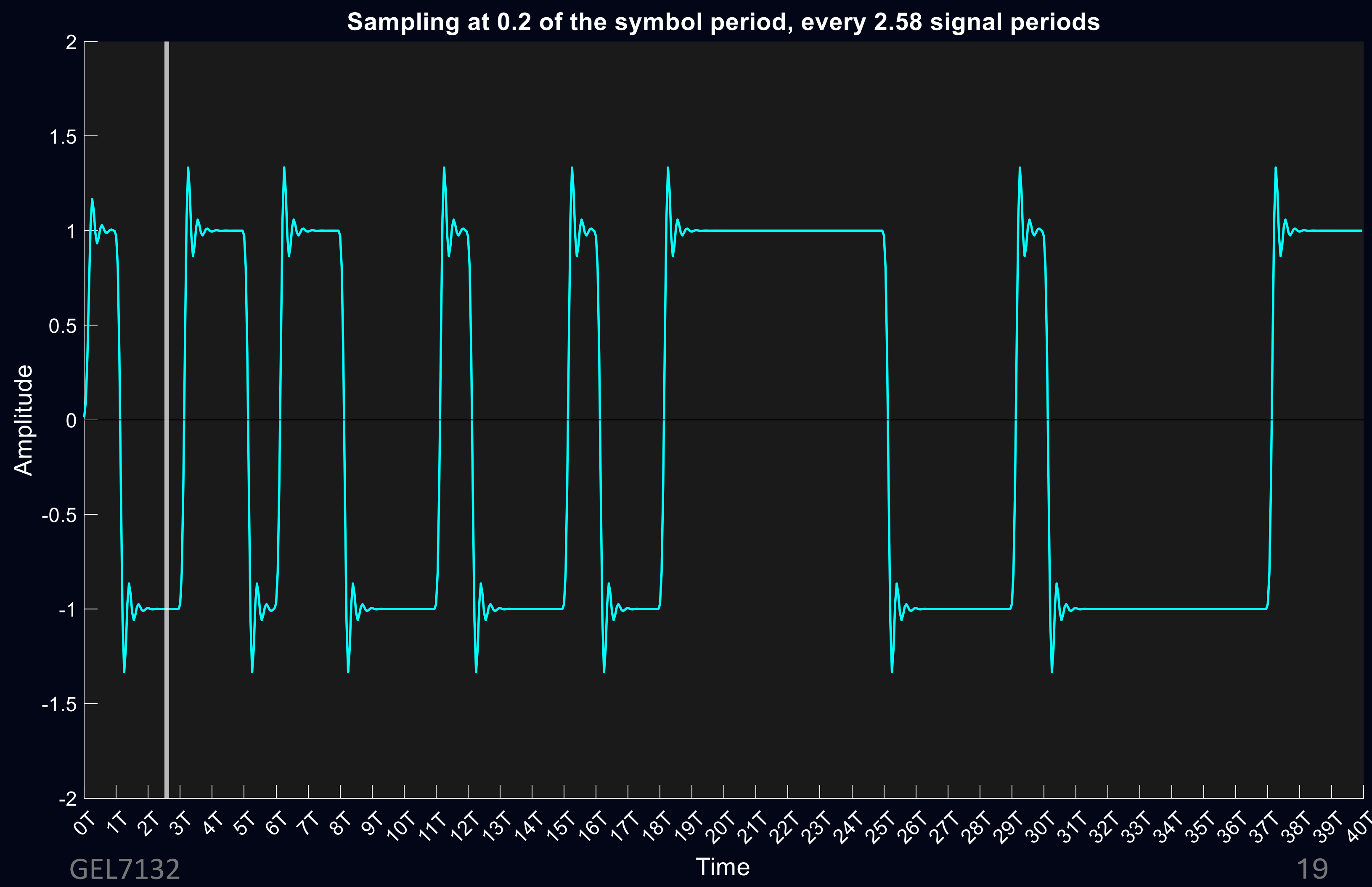
Periodic signals

- Works very well

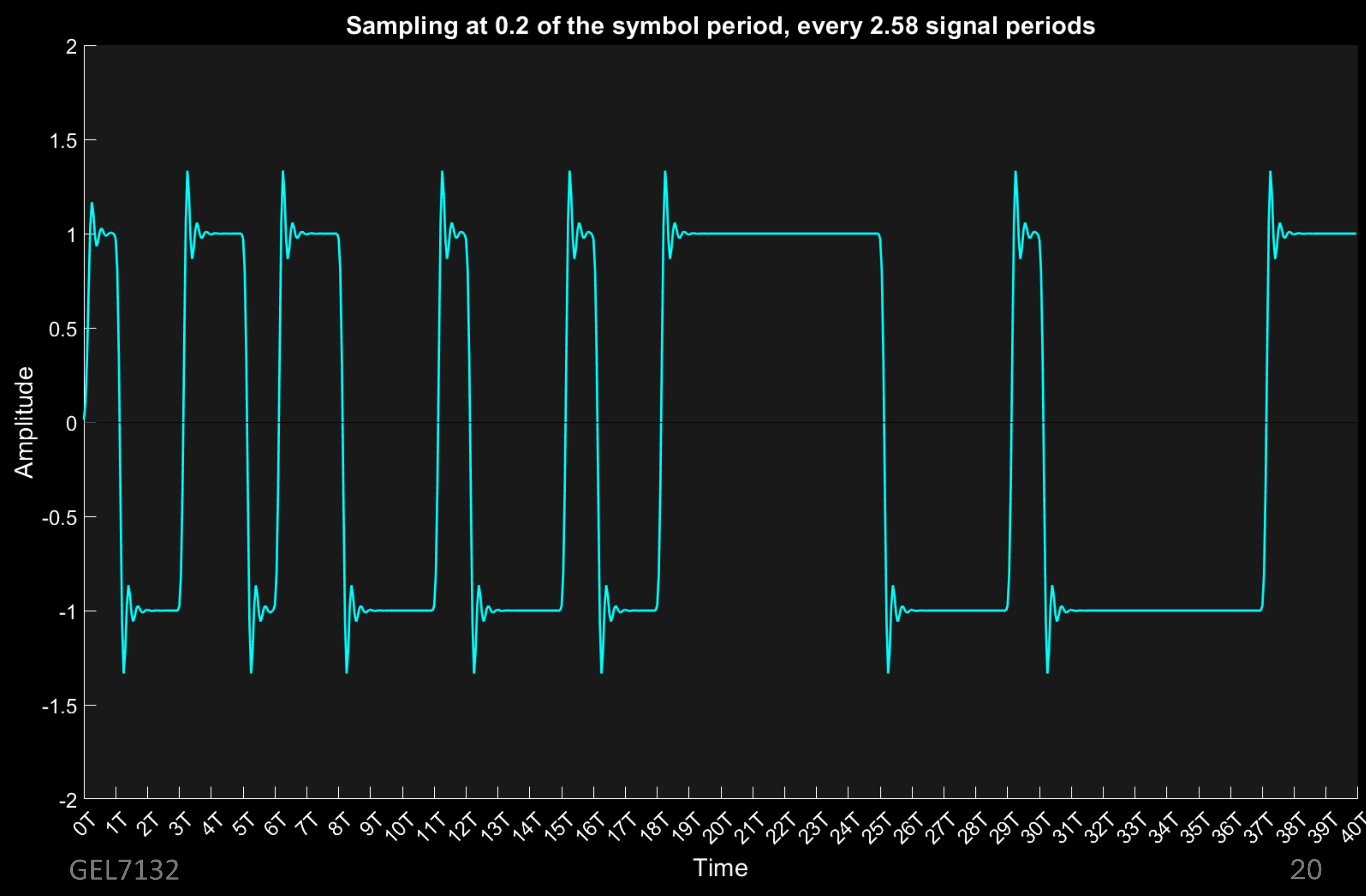
Equivalent-time Sampling Oscilloscopes

Data Signals

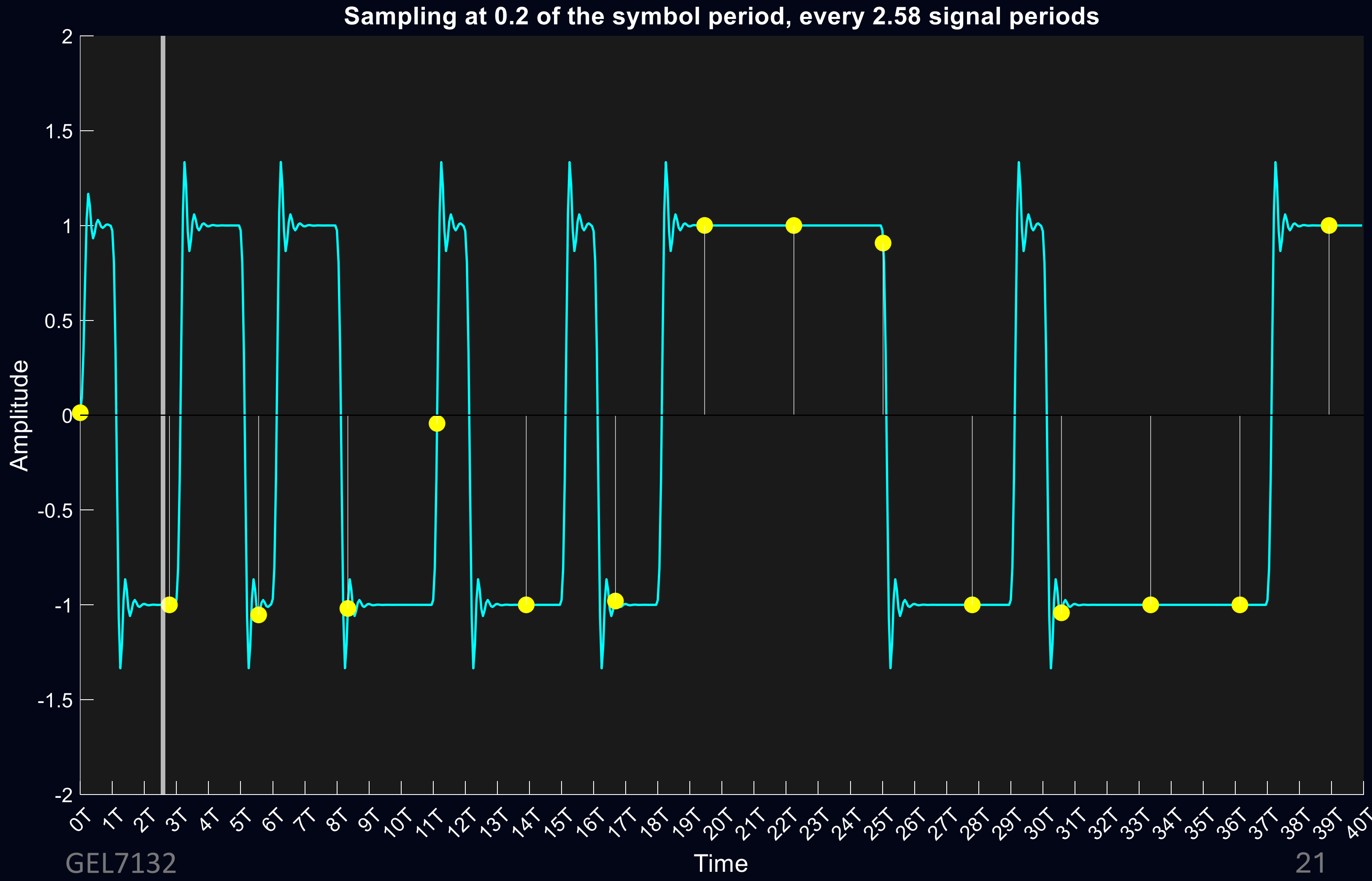
Sampling a data signal



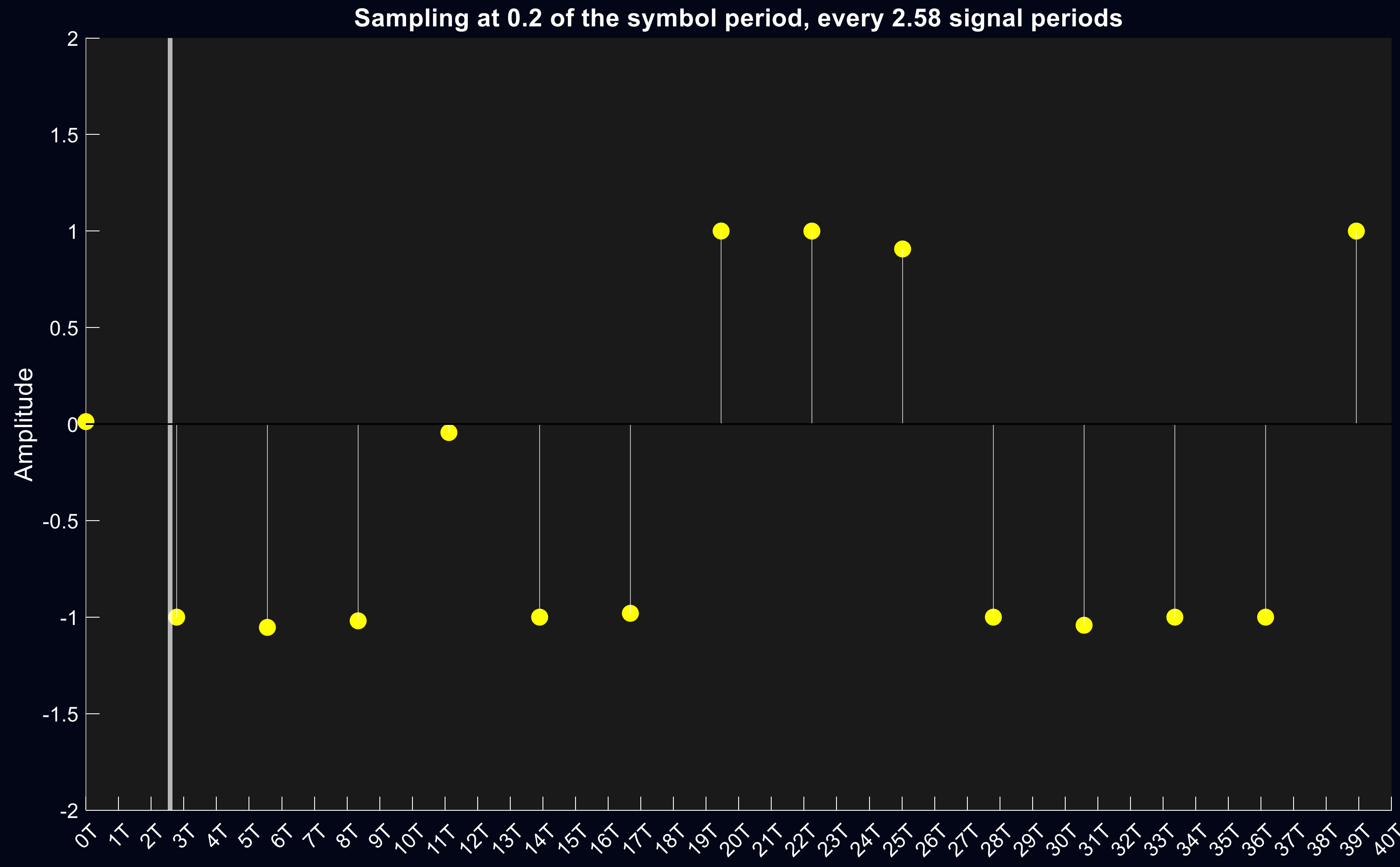
Sampling a data signal



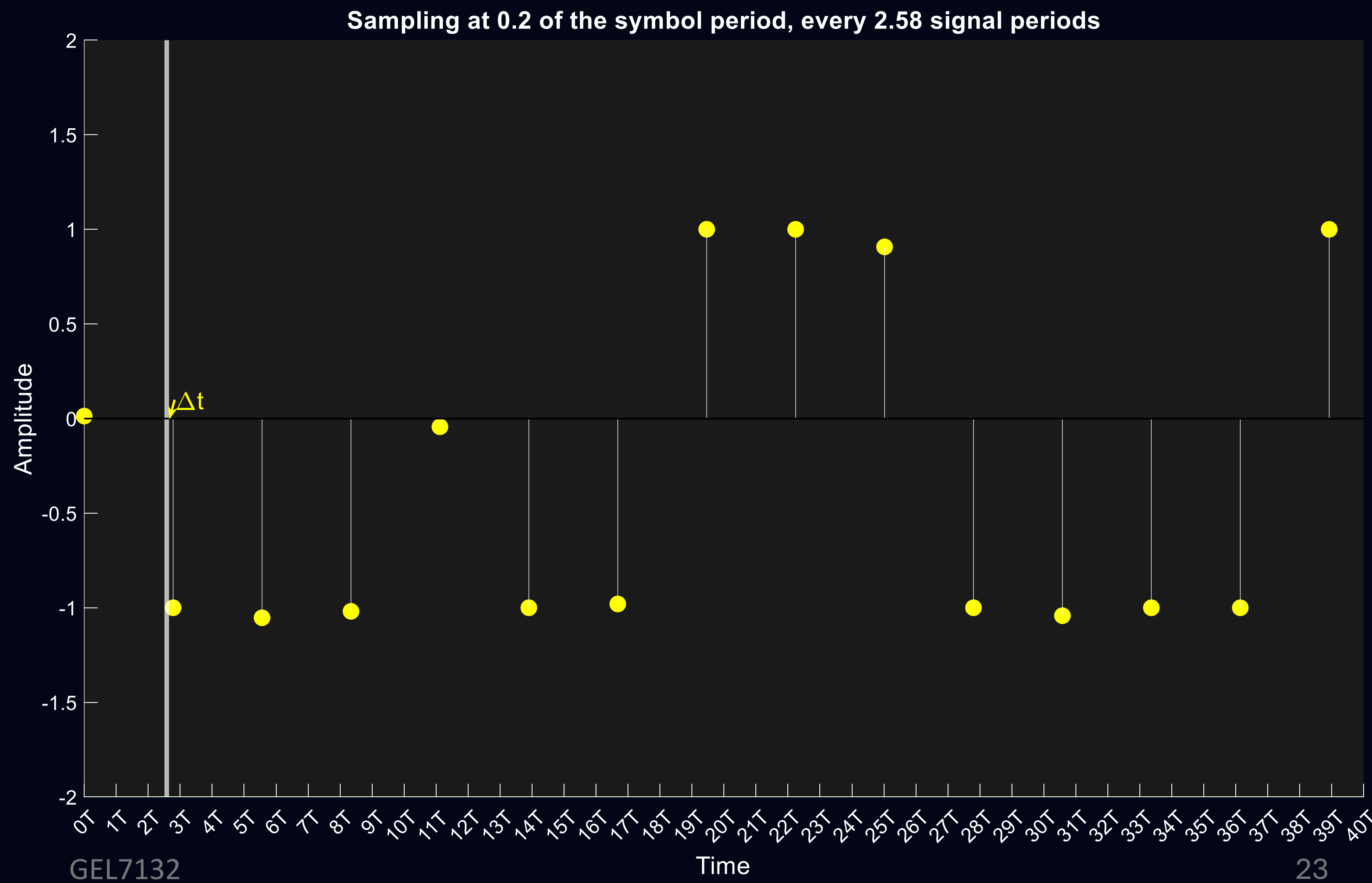
Sampling a data signal



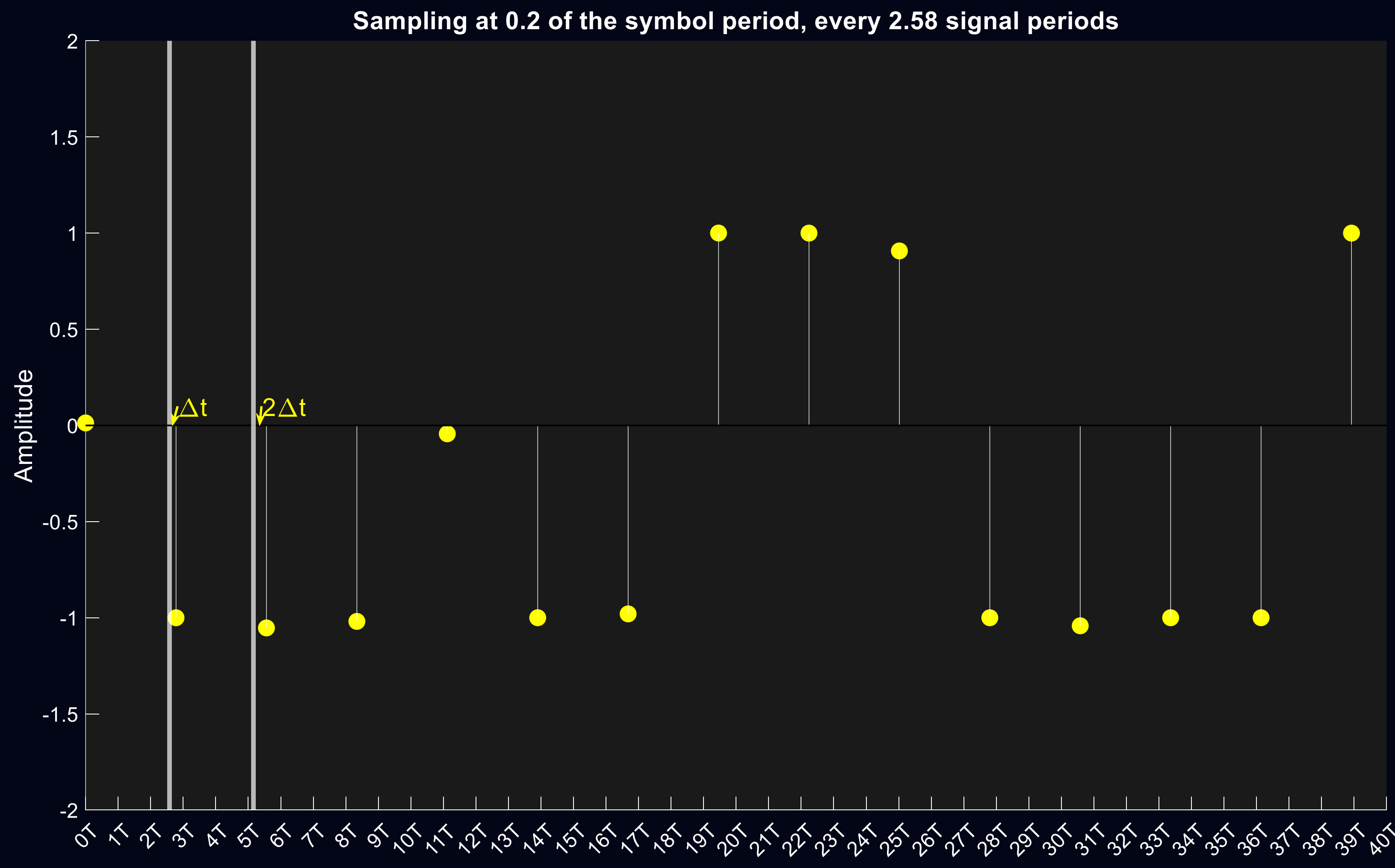
Sampling a data signal



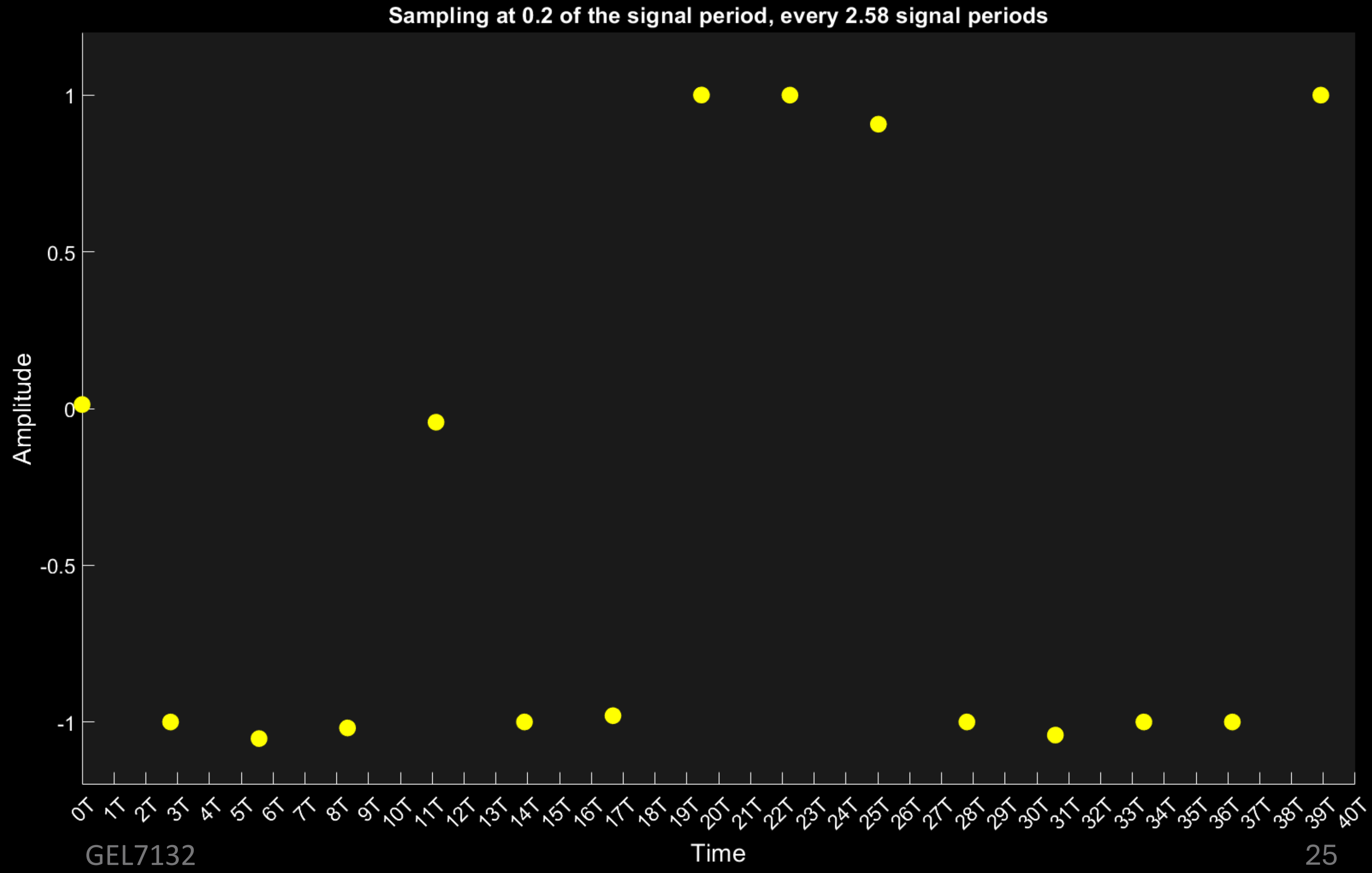
Sampling a data signal



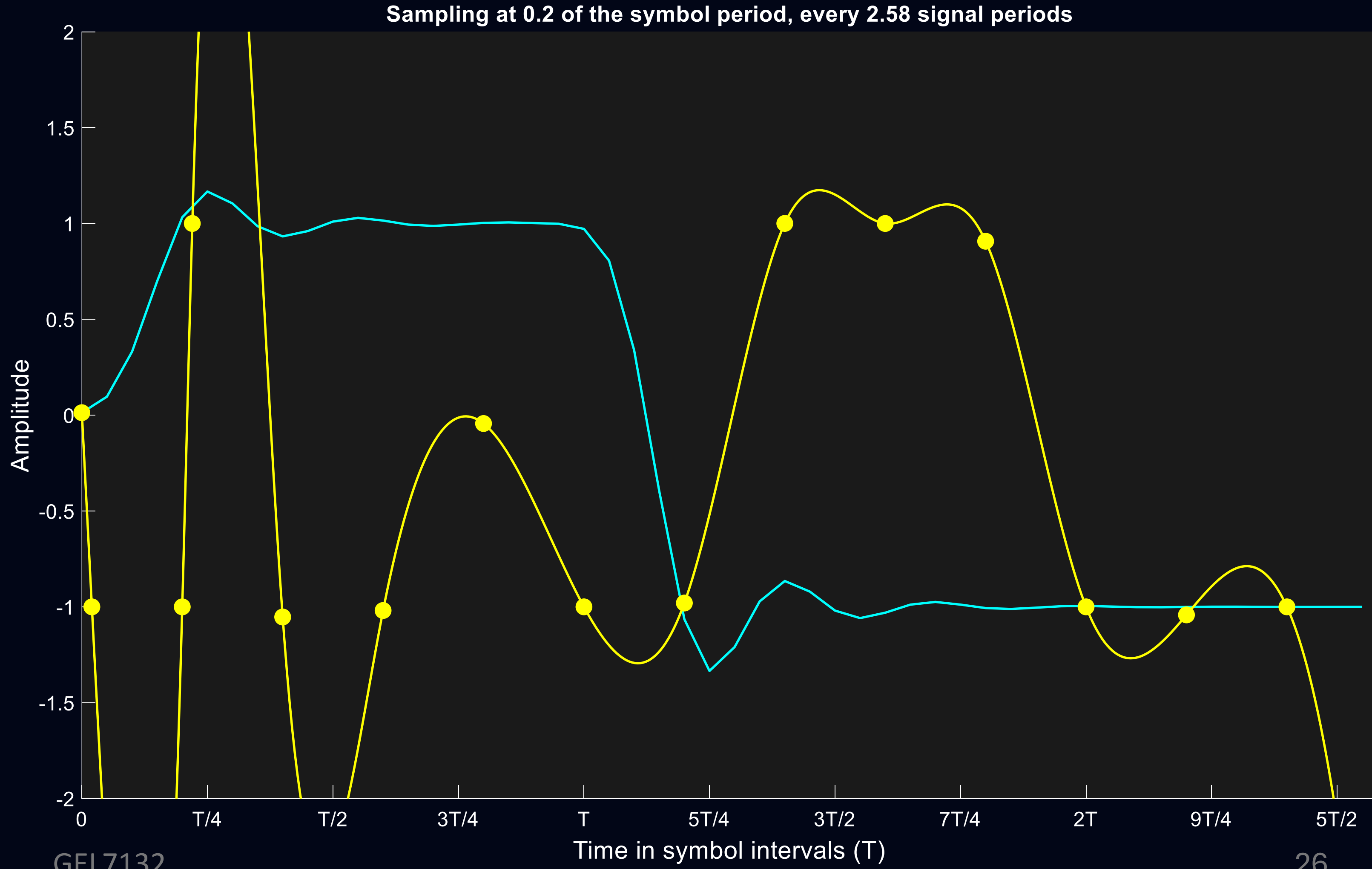
Sampling a data signal



Sampling a data signal



Sampling a data signal



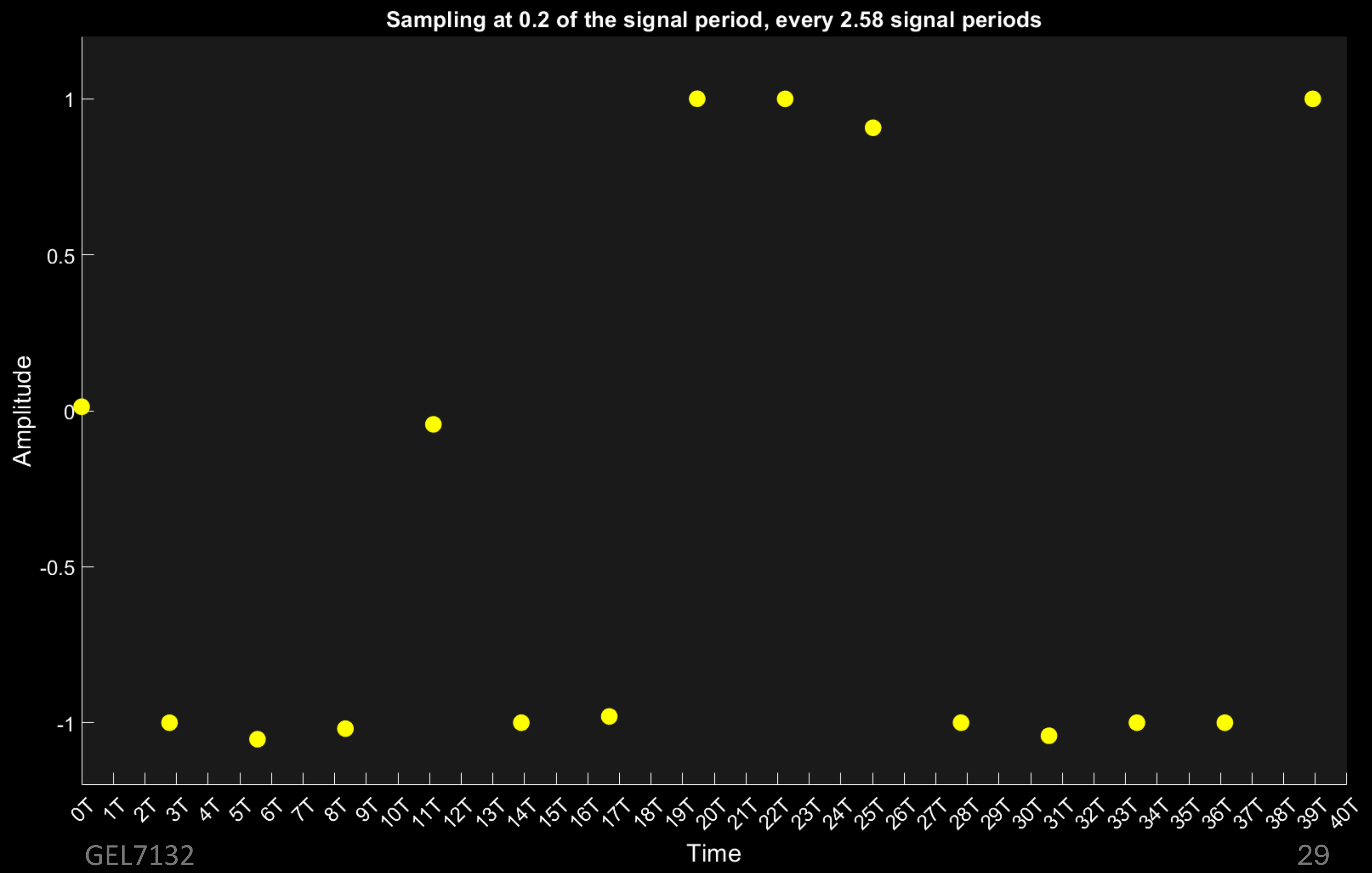
Data Signals

- Signal reconstruction is not possible

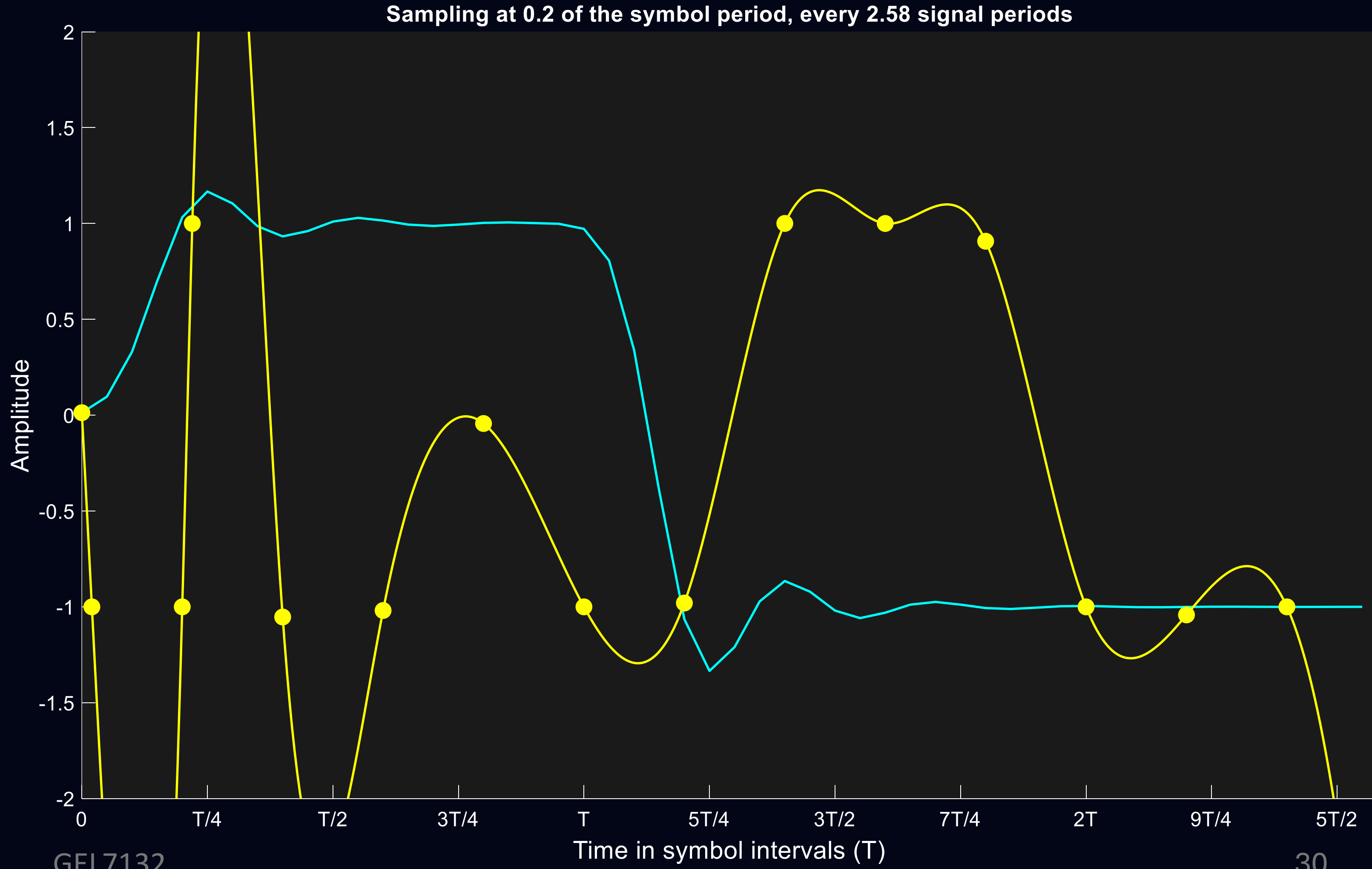
Equivalent-time Sampling Oscilloscopes

Data Signals – Eye Diagram

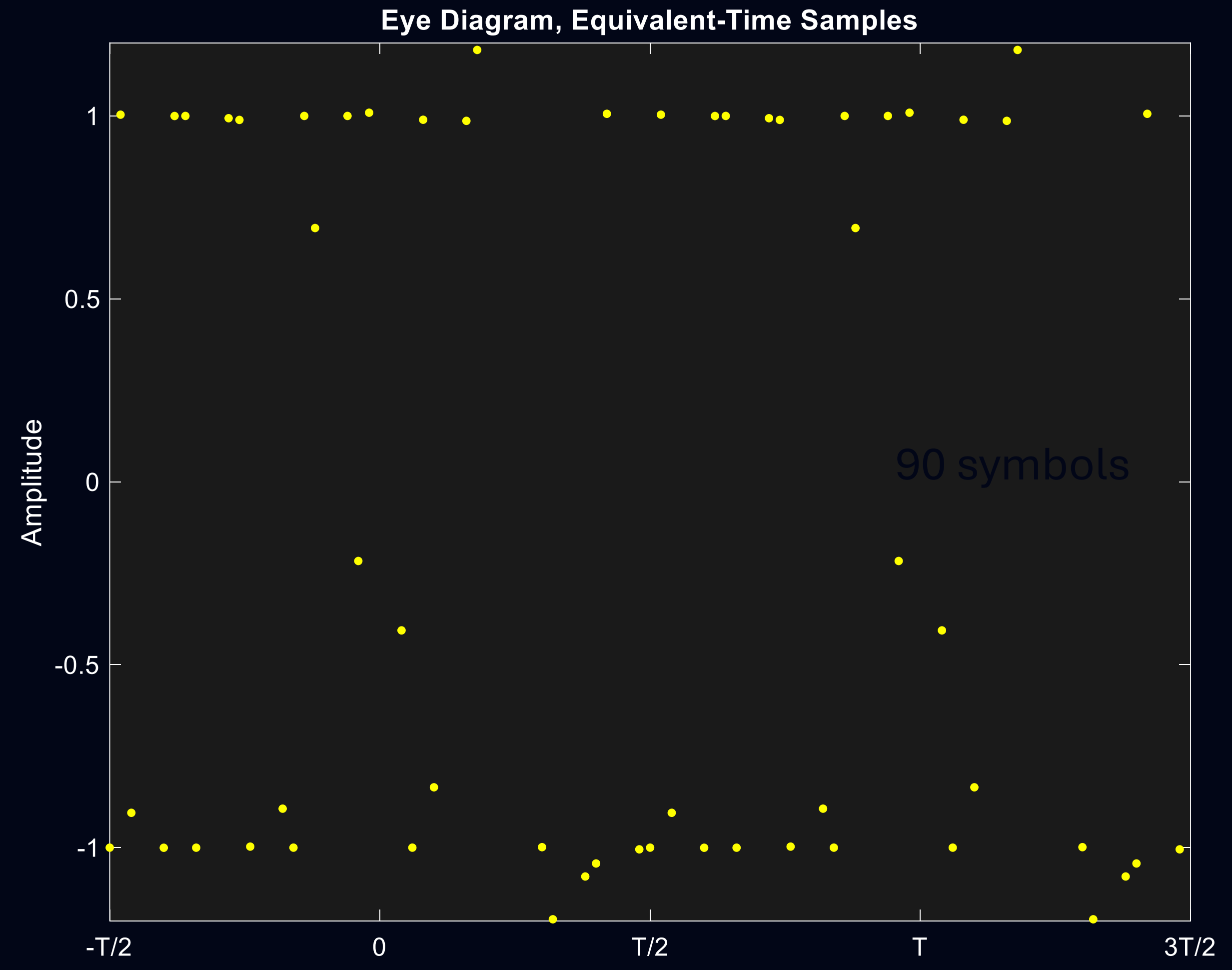
Sampling a data signal



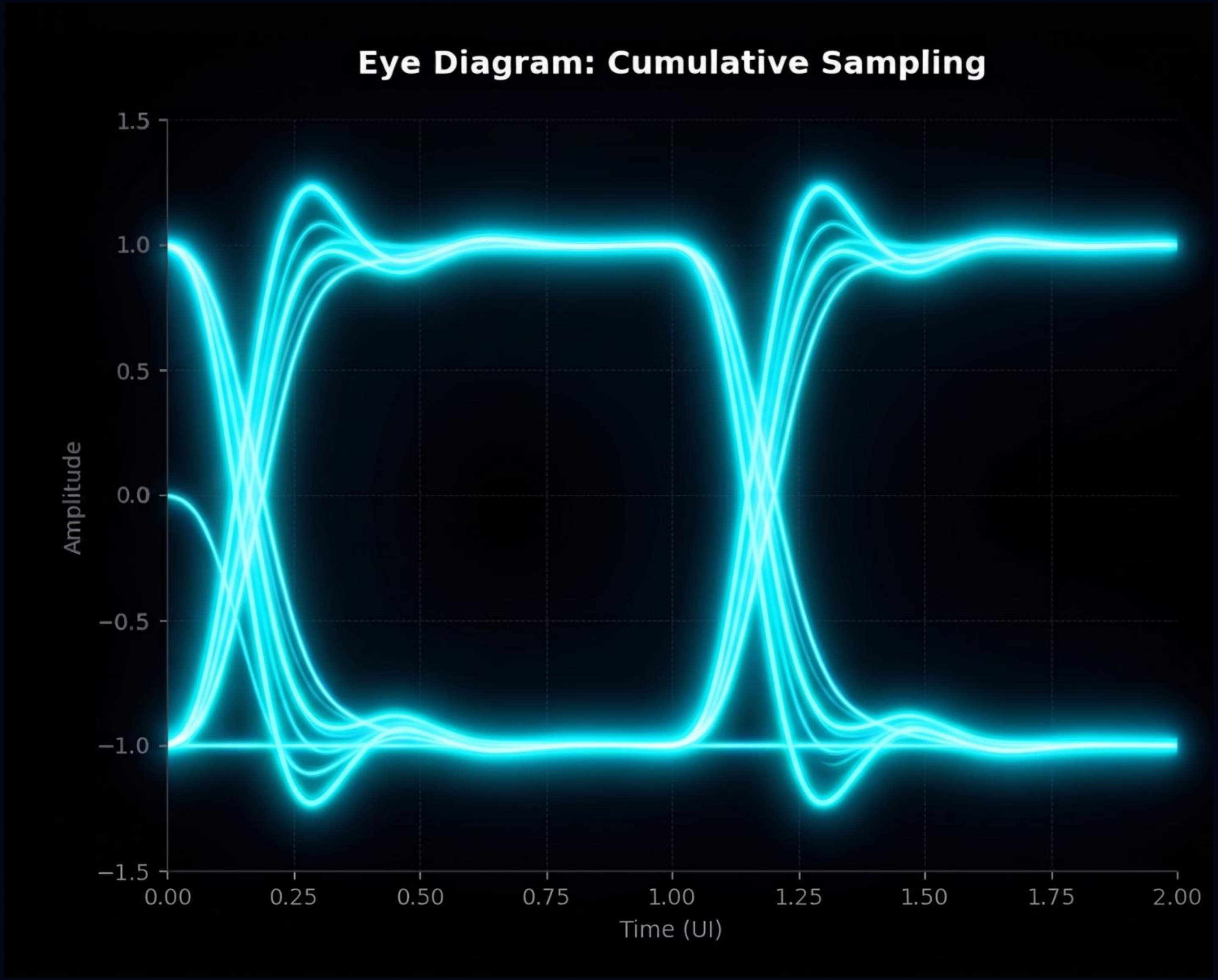
Spline fit was inappropriate



Same samples – eye diagram



Eye diagram



Eye Diagram: Cumulative Sampling
Amplitude
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
Time (UI)

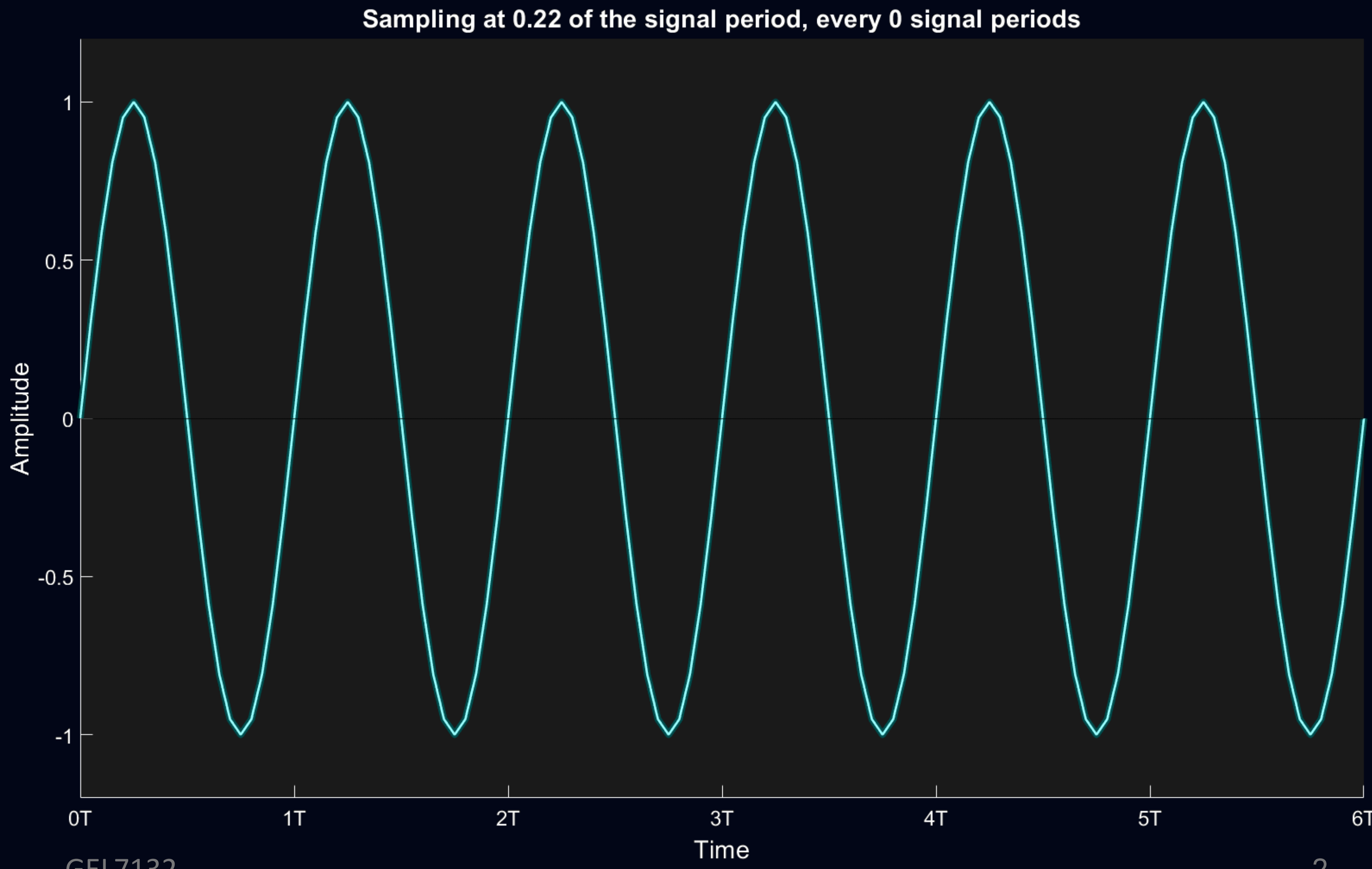
Functions available on Sampling Scope

- Cannot recover data !
- Signal integrity
  - Eye diagrams & for PAM4 TDECQ
  - Rise/fall time
  - Extinction ratio
- Signal analysis
  - Frequency content of a stable connection
  - Time domain reflectometry (with pulse source)
    - De-embedding, characterization, etc.

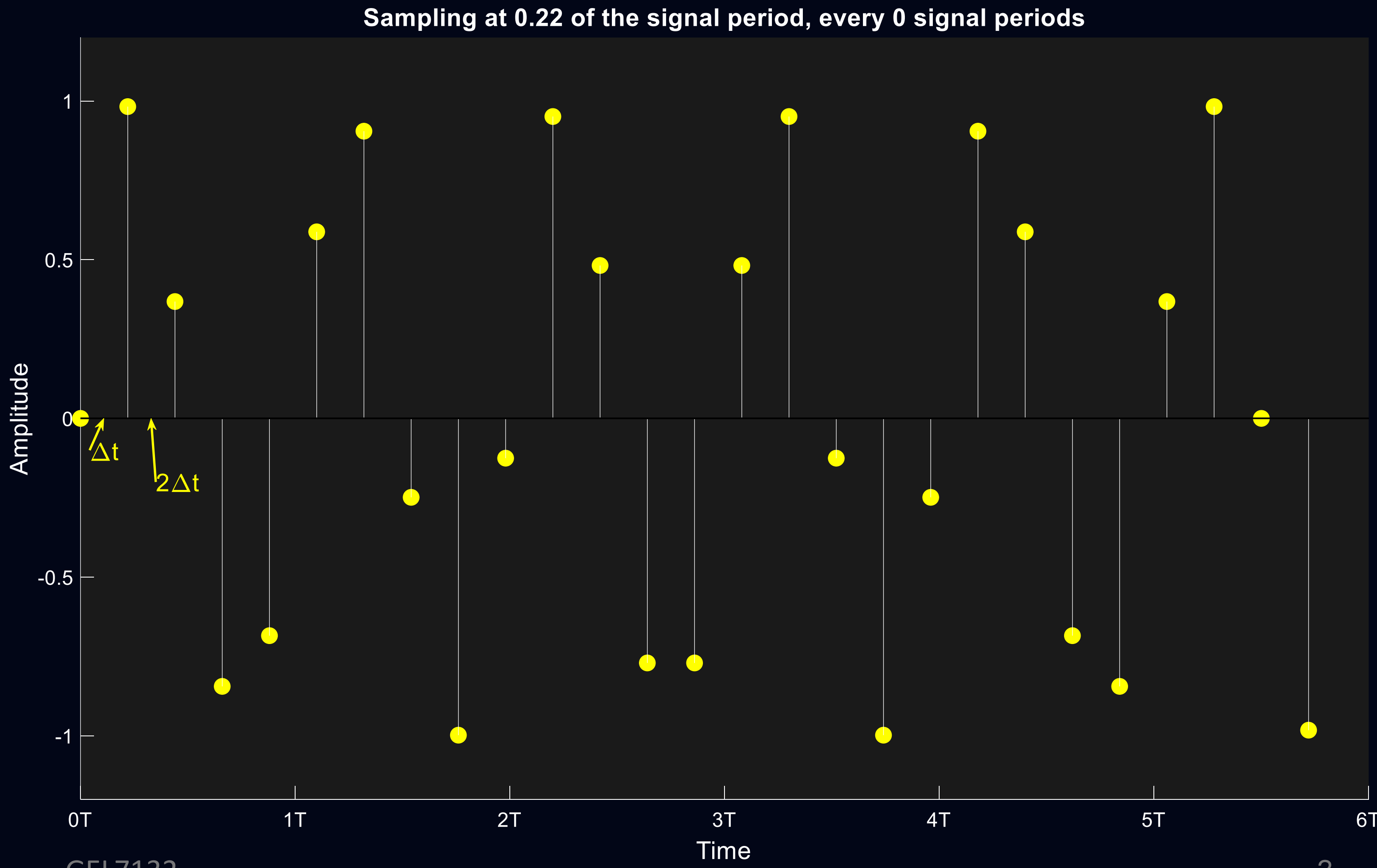
Real-time Sampling Oscilloscopes

Periodic Signals

Periodic signal – sine tone

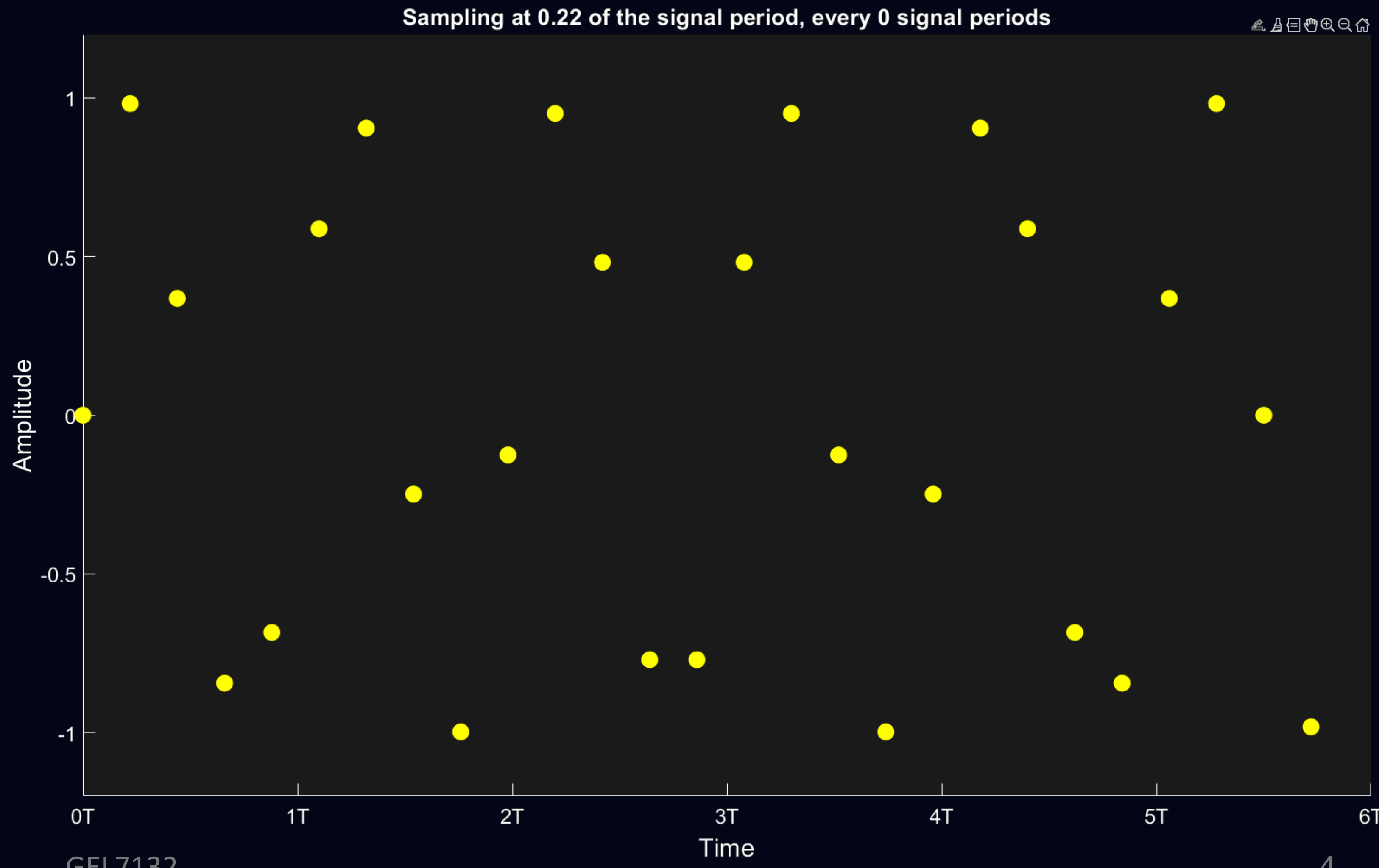


No folding



Sampling at 0.22 of the signal period, every 0 signal periods
Amplitude
1
0.5
0
-0.5
-1
Δt
2Δt
0T
1T
2T
3T
4T
5T
6T
Time

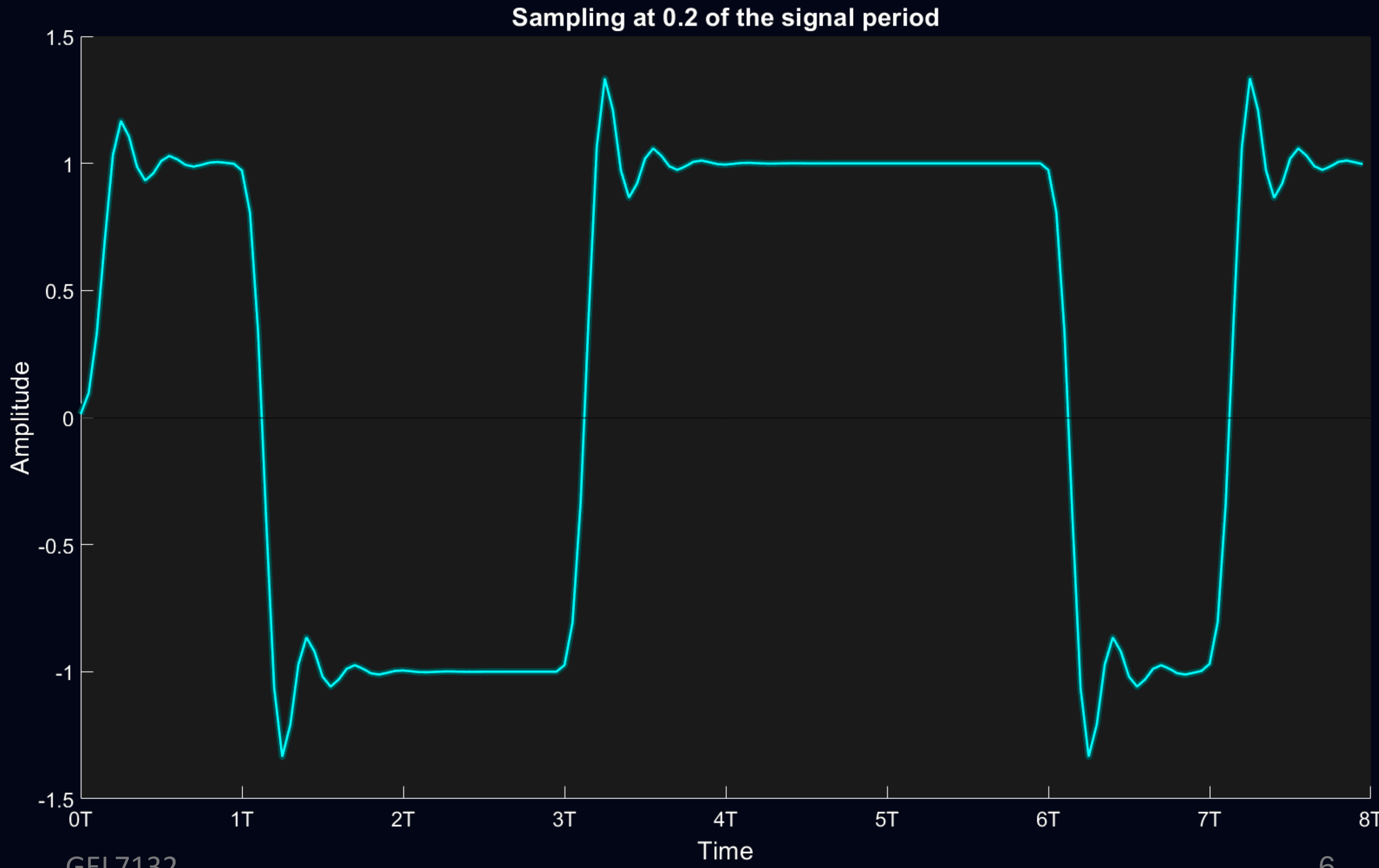
Spline at output



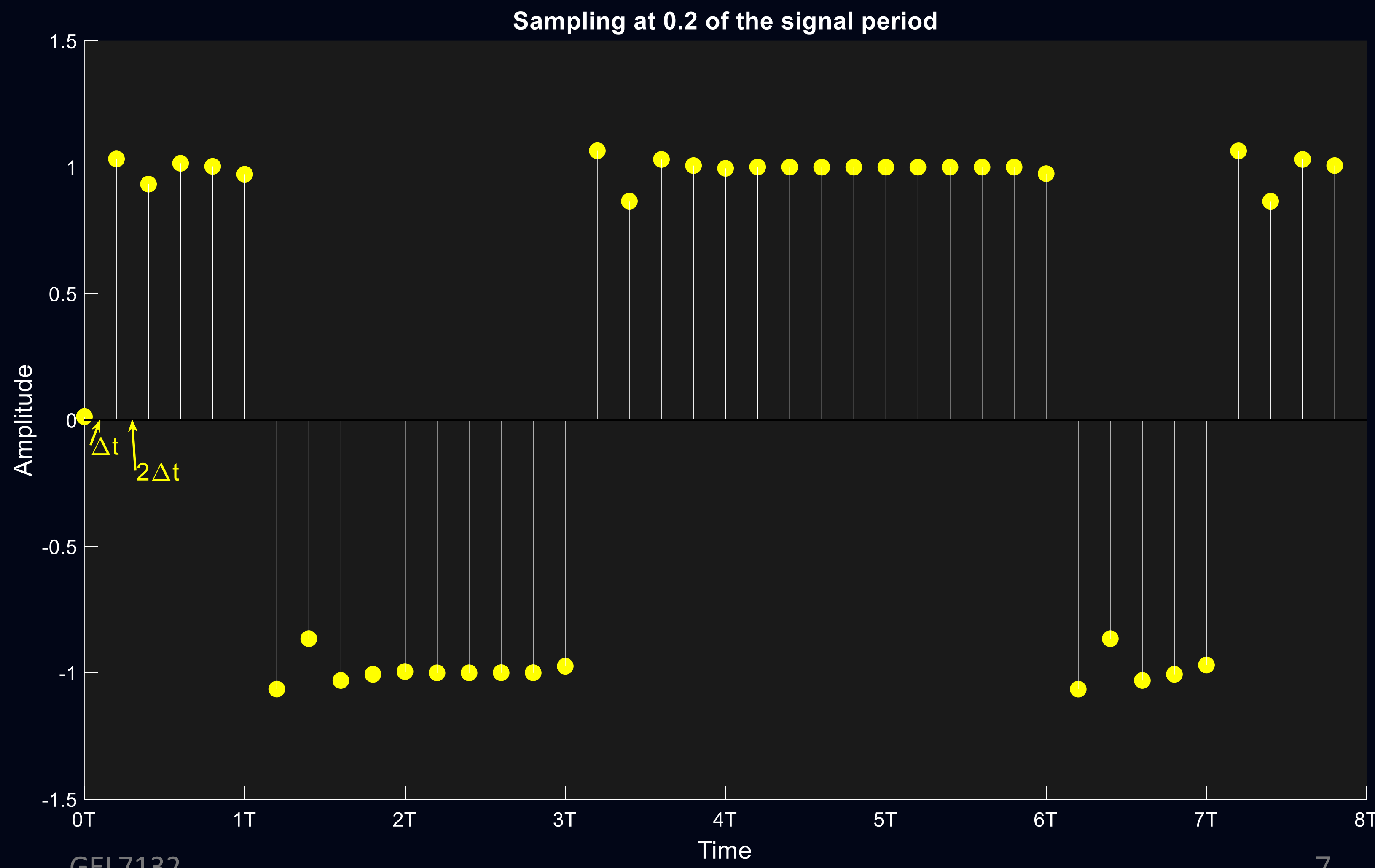
Real-time
Sampling Oscilloscopes

Data Signals

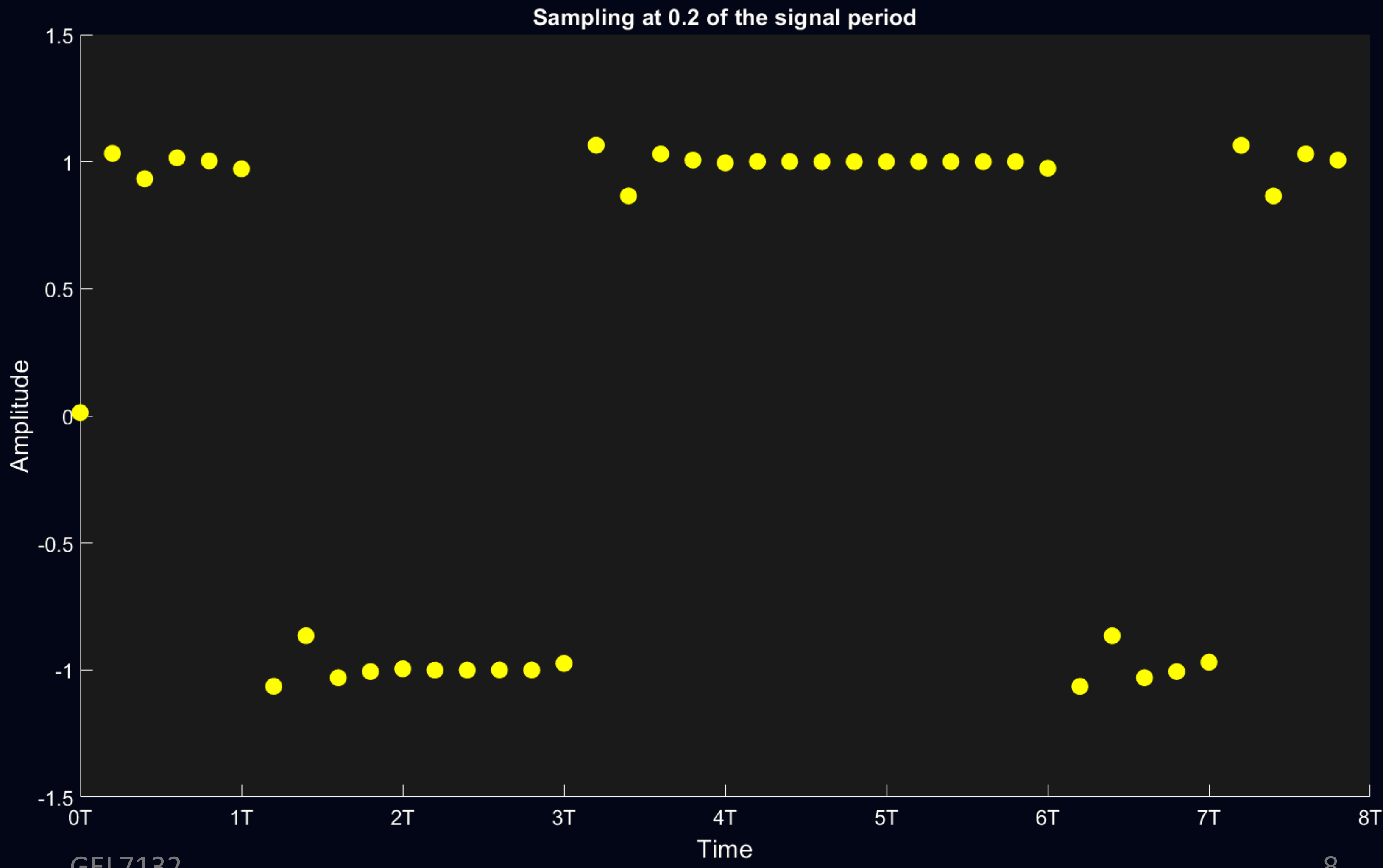
Sampling a data signal



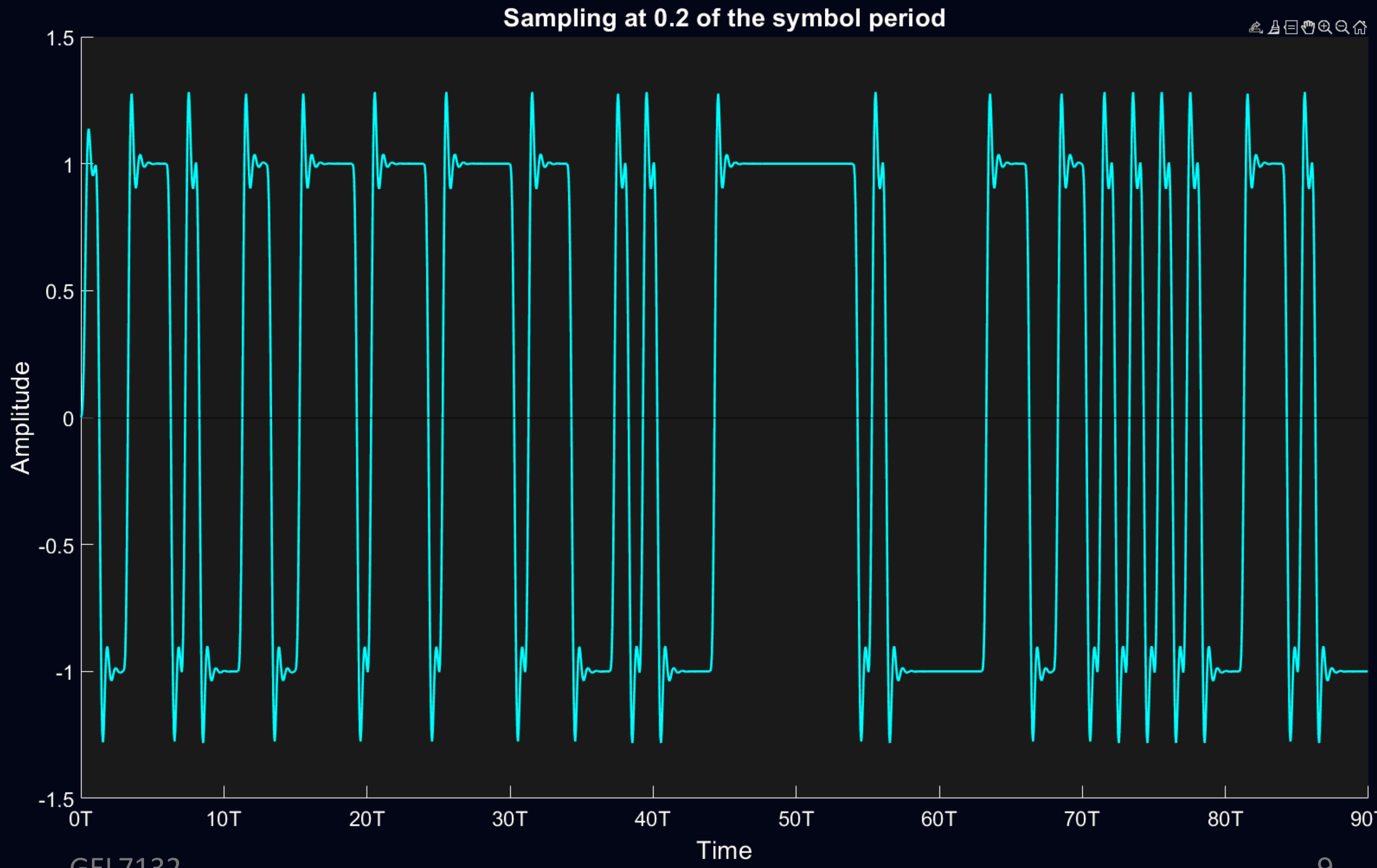
Sampling a data signal



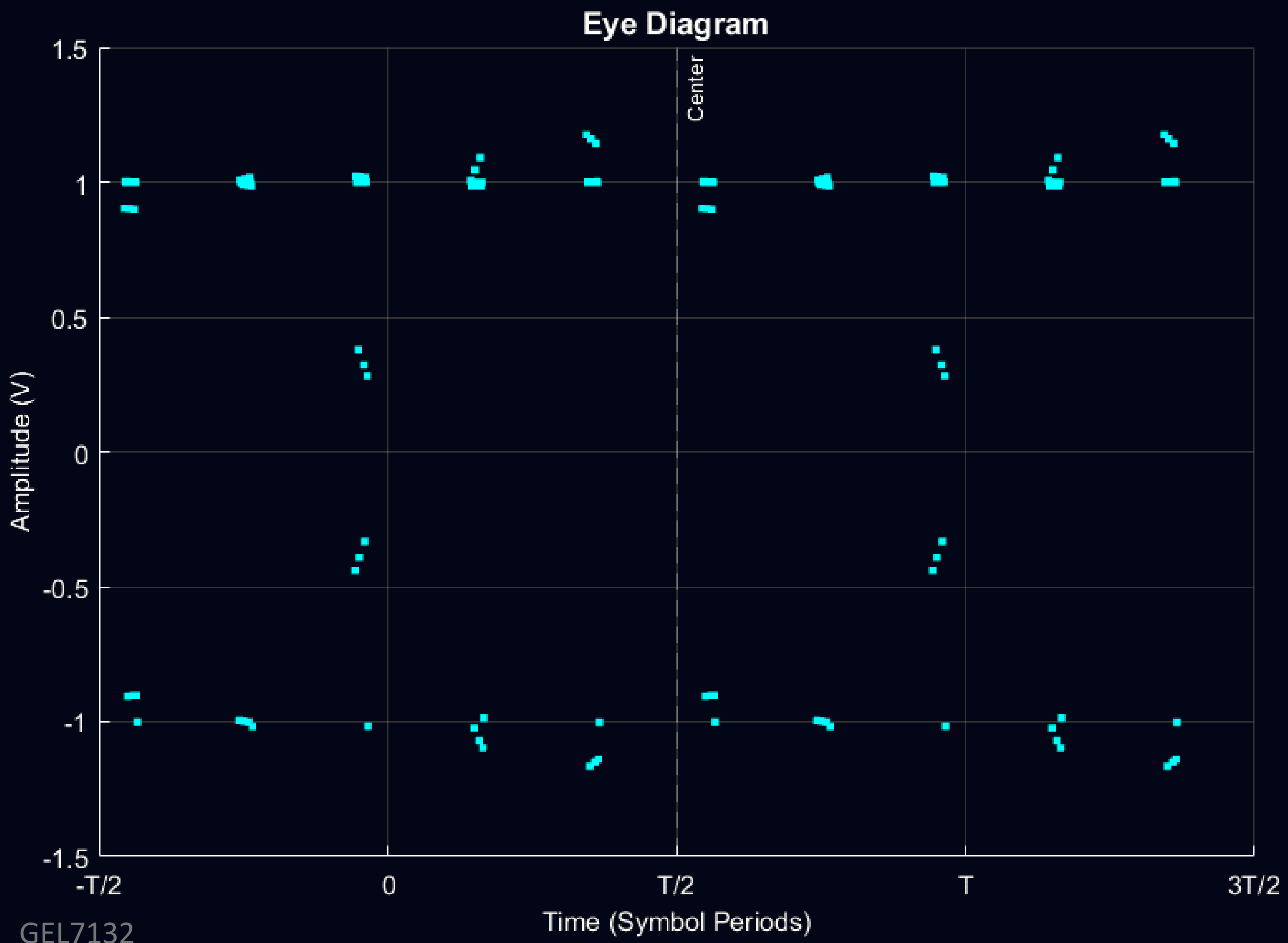
Sampling a data signal



Sampling a data signal



Sampling a data signal



Periodic signals & Eye diagrams

- Works well, but overkill
- Equivalent-time
  - for a given bandwidth
    - Lower noise floor
    - Higher dynamic range (more bits of resolution)
  - less jitter
  - much lower cost

Real-time
Sampling Oscilloscopes

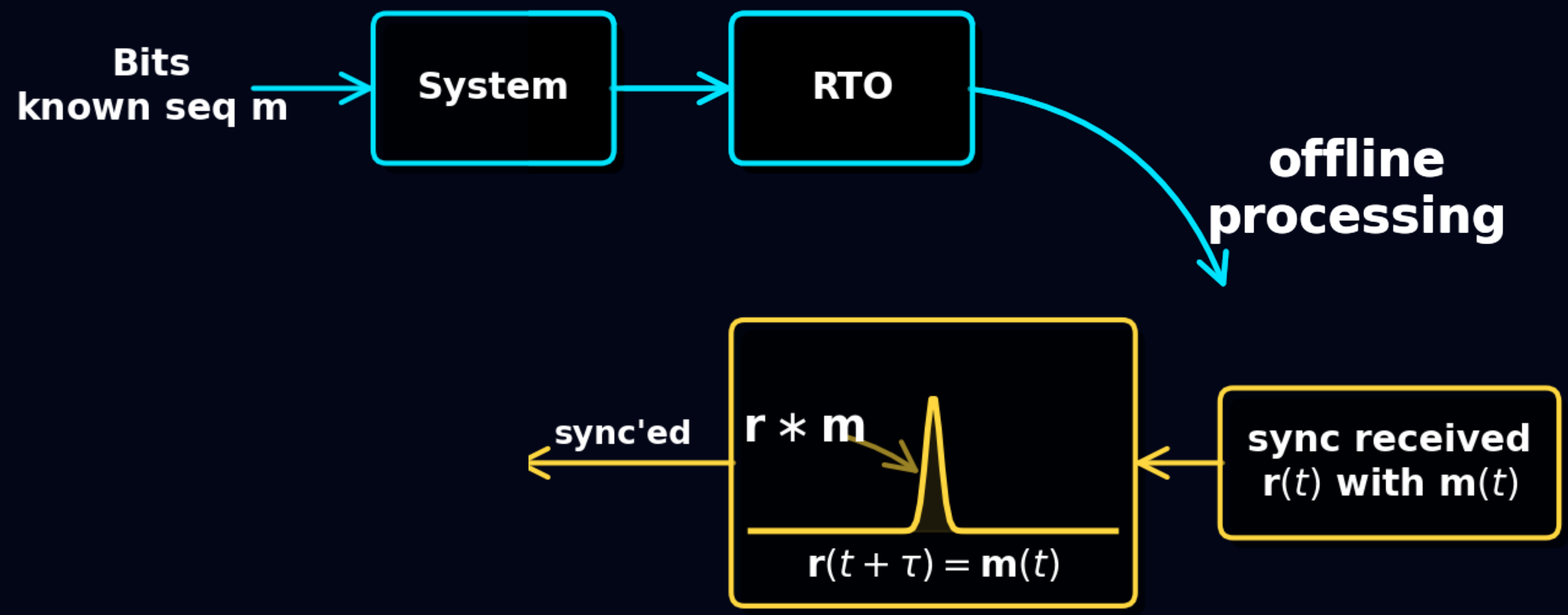
Bit Error Rate Estimation on Data Signals

Bit error rate estimation

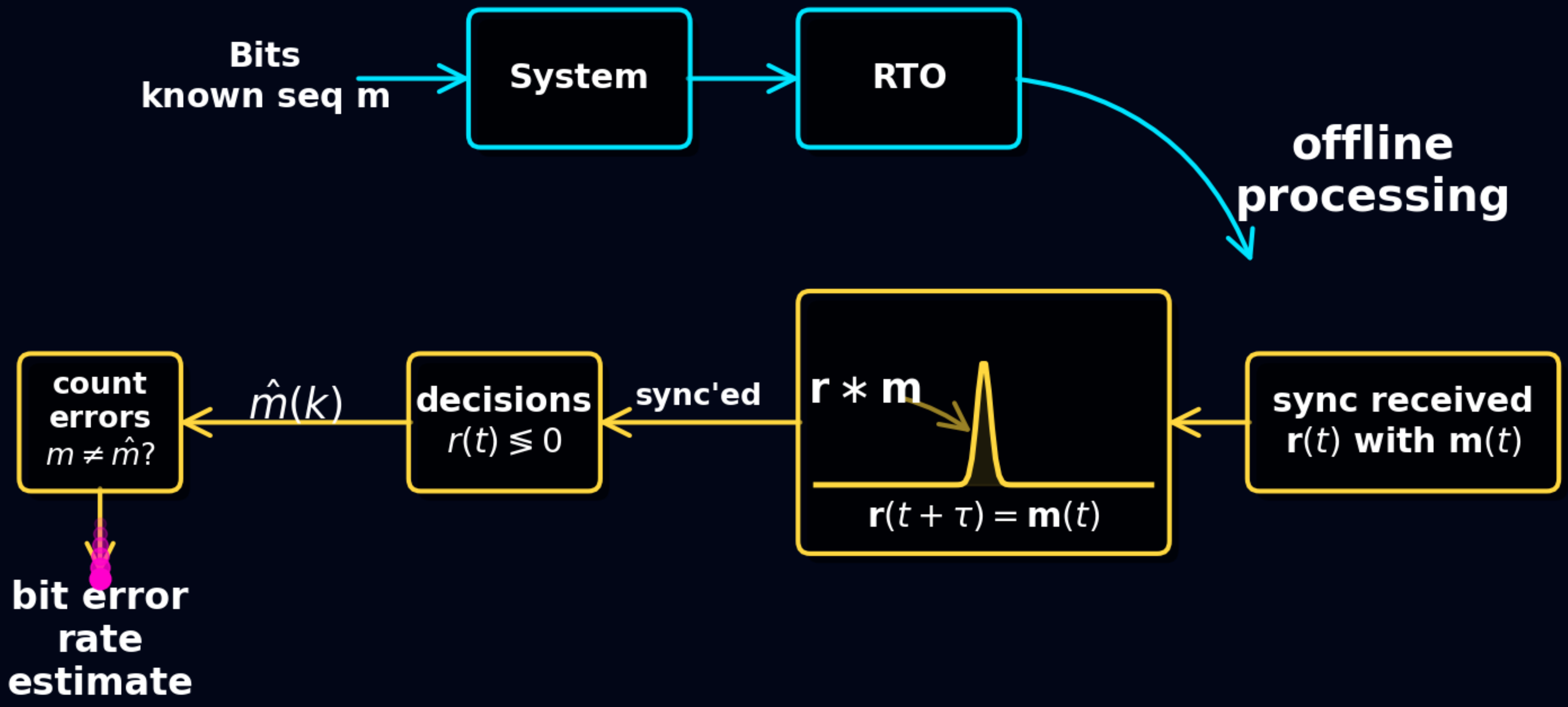
- Known sequence of transmitted bits
- Real-time capture

Bit error rate estimation

Bit error rate estimation



Bit error rate estimation

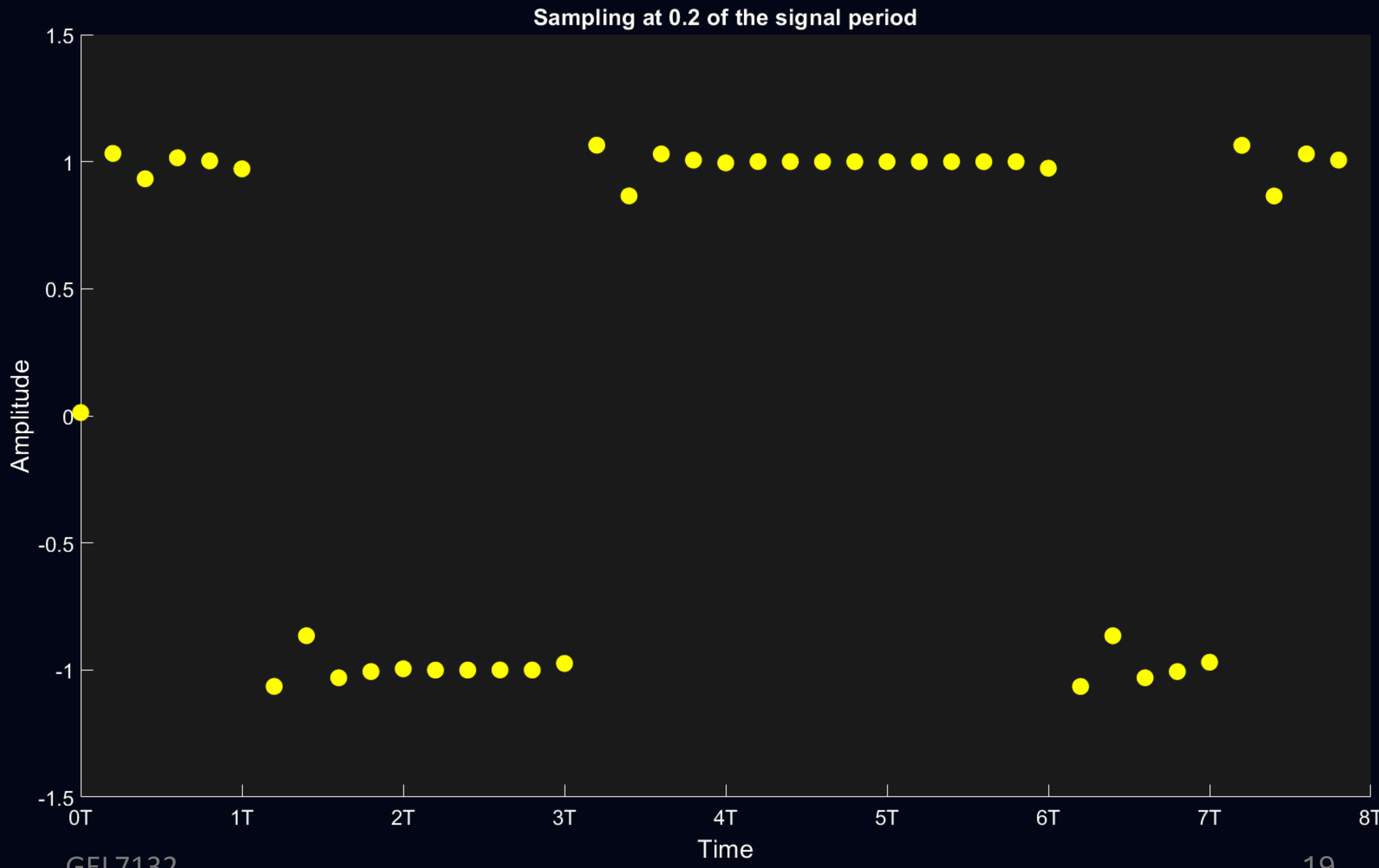


Bit error rate estimation

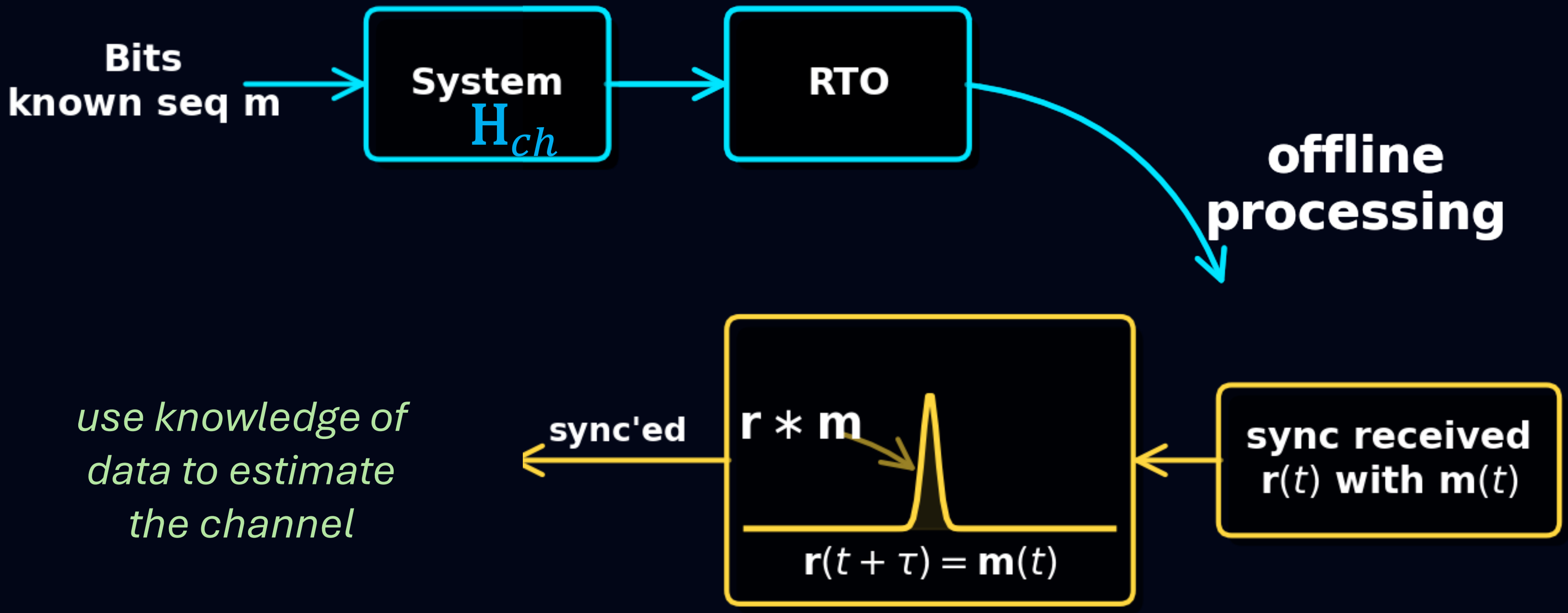
Real-time
Sampling Oscilloscopes

Equalization of Data Signals

Exploiting observation of data correlation



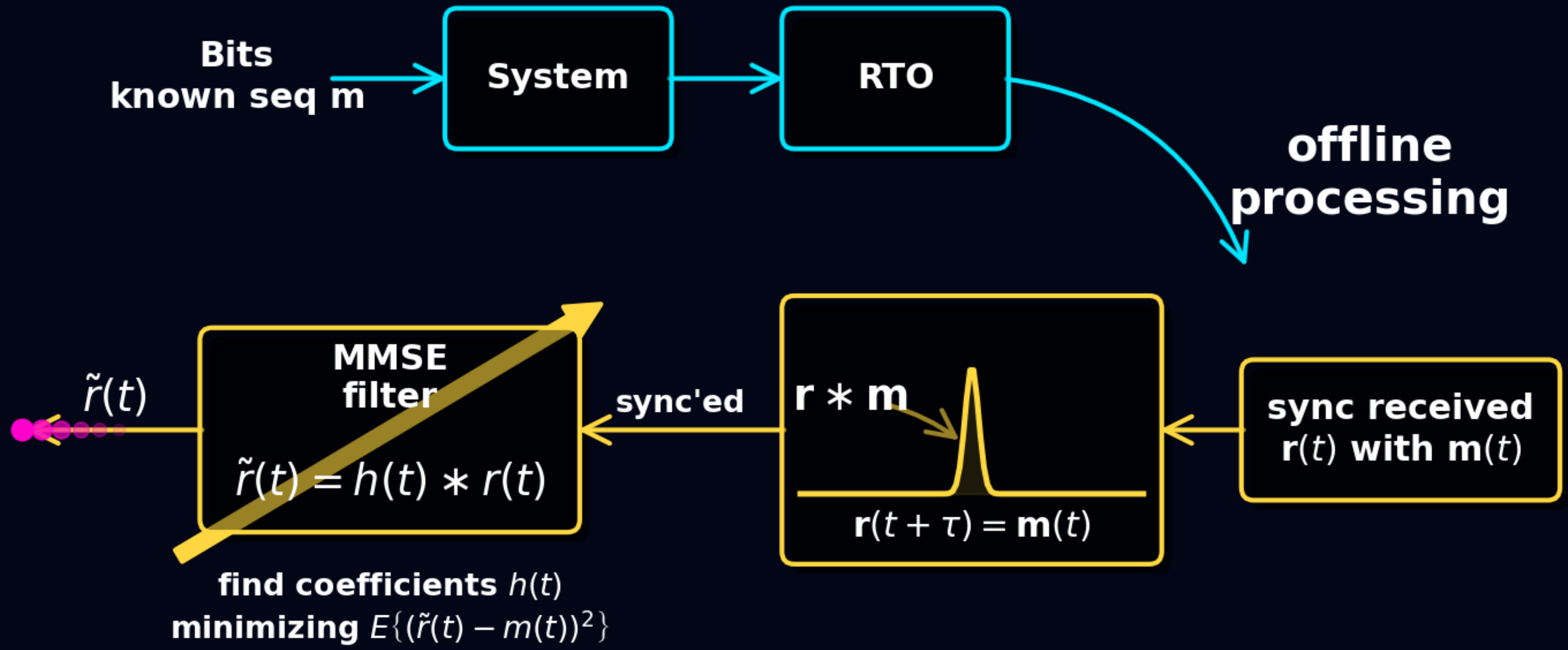
Channel estimation



use knowledge of data to estimate the channel

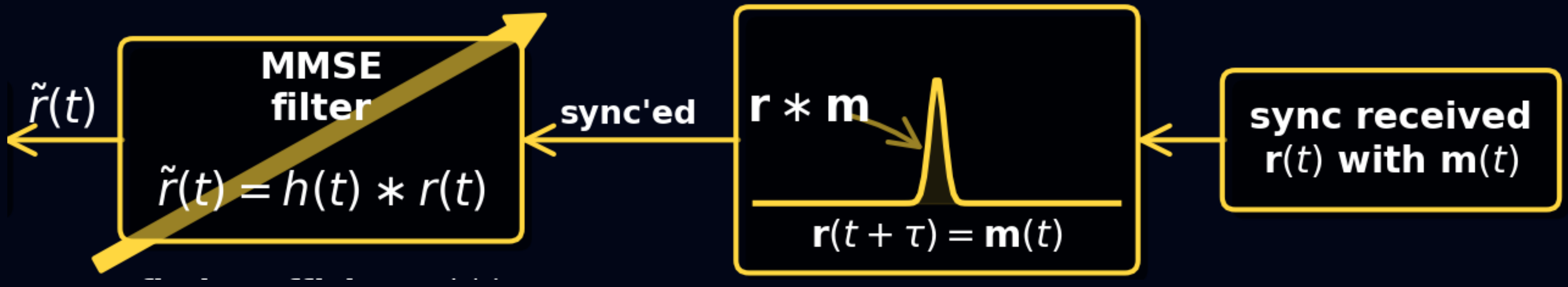
$$\mathbf{H}_{\mathrm{MMSE}} = \left(\mathbf{H}_{ch}^{H}\mathbf{H}_{ch} + \sigma_n^2\mathbf{I}\right)^{-1}\mathbf{H}_{ch}^{H}$$

Channel estimation

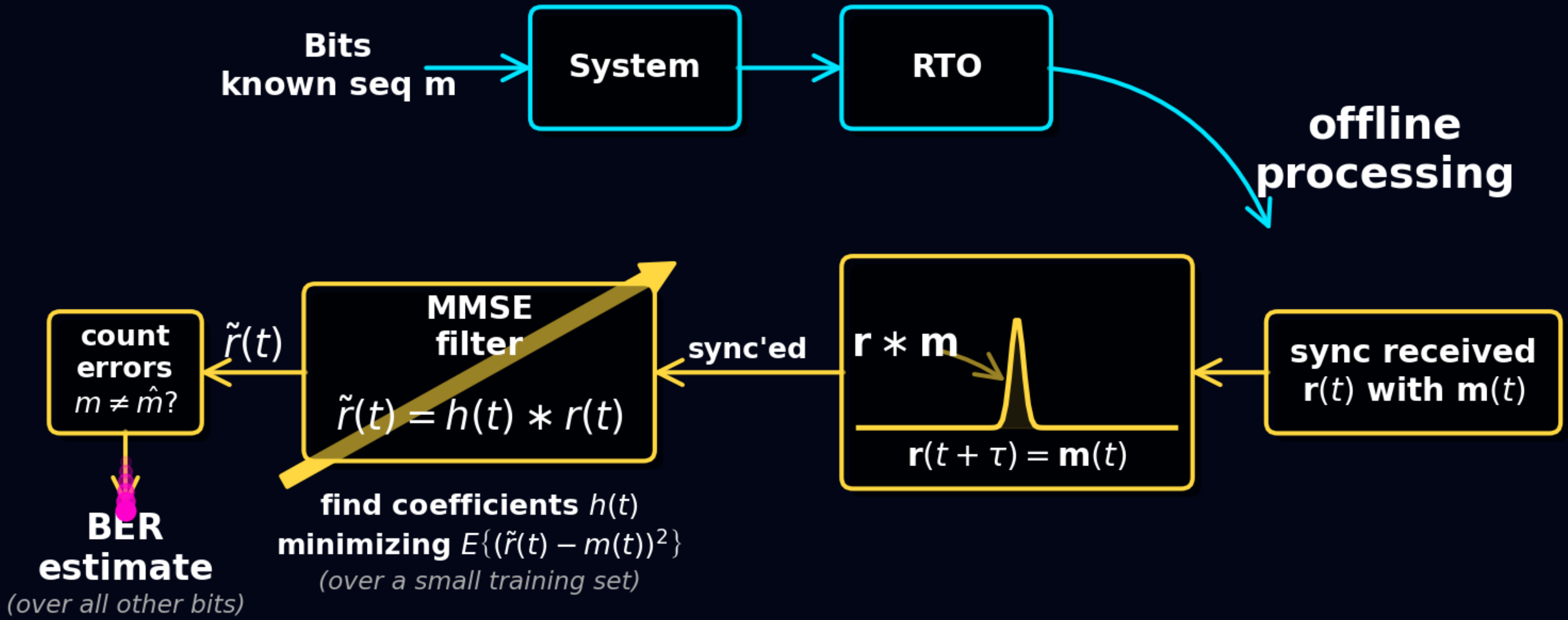


Channel estimation

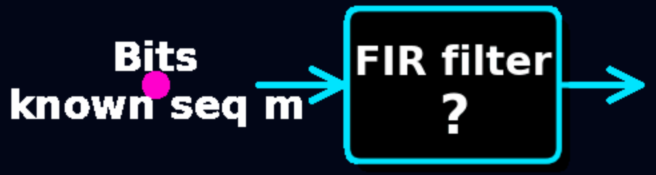
Channel Equalization



Channel Equalization

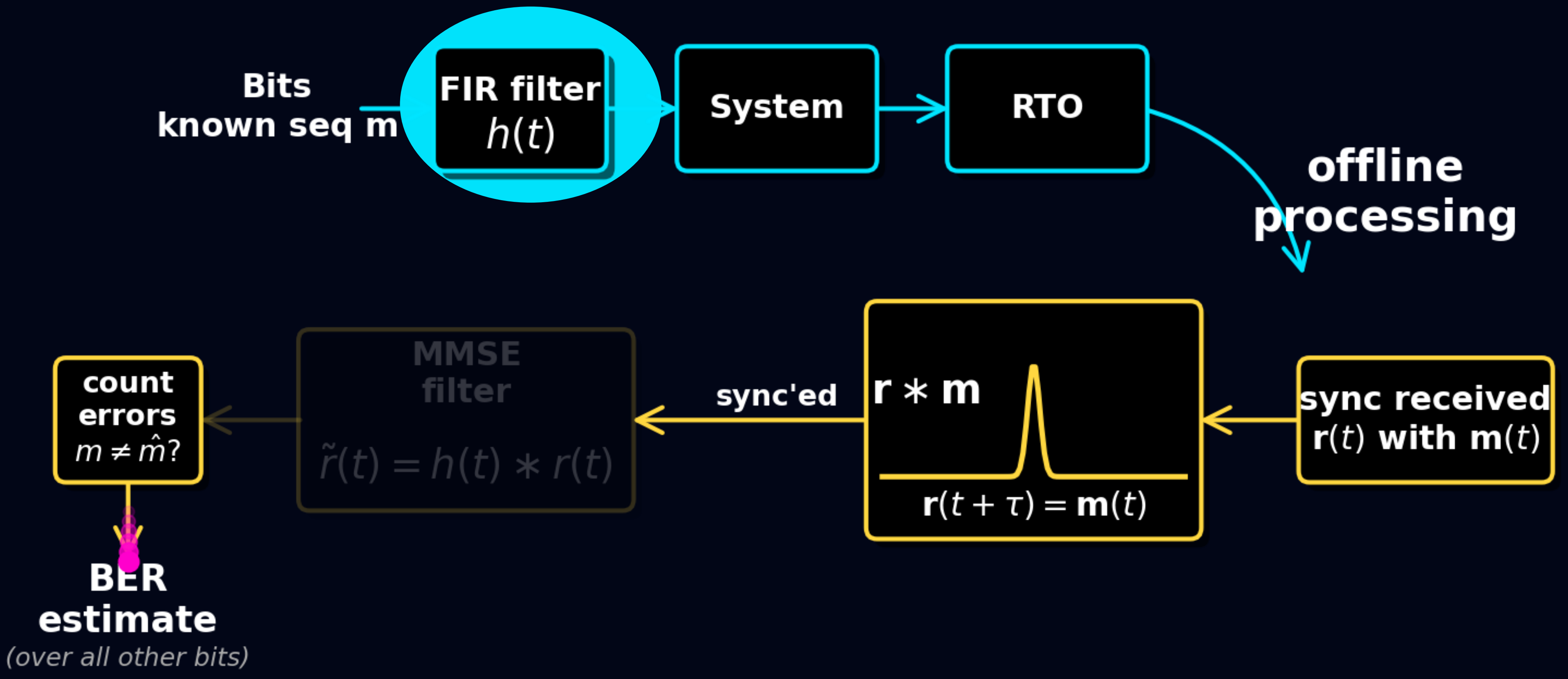


Pre-equalization

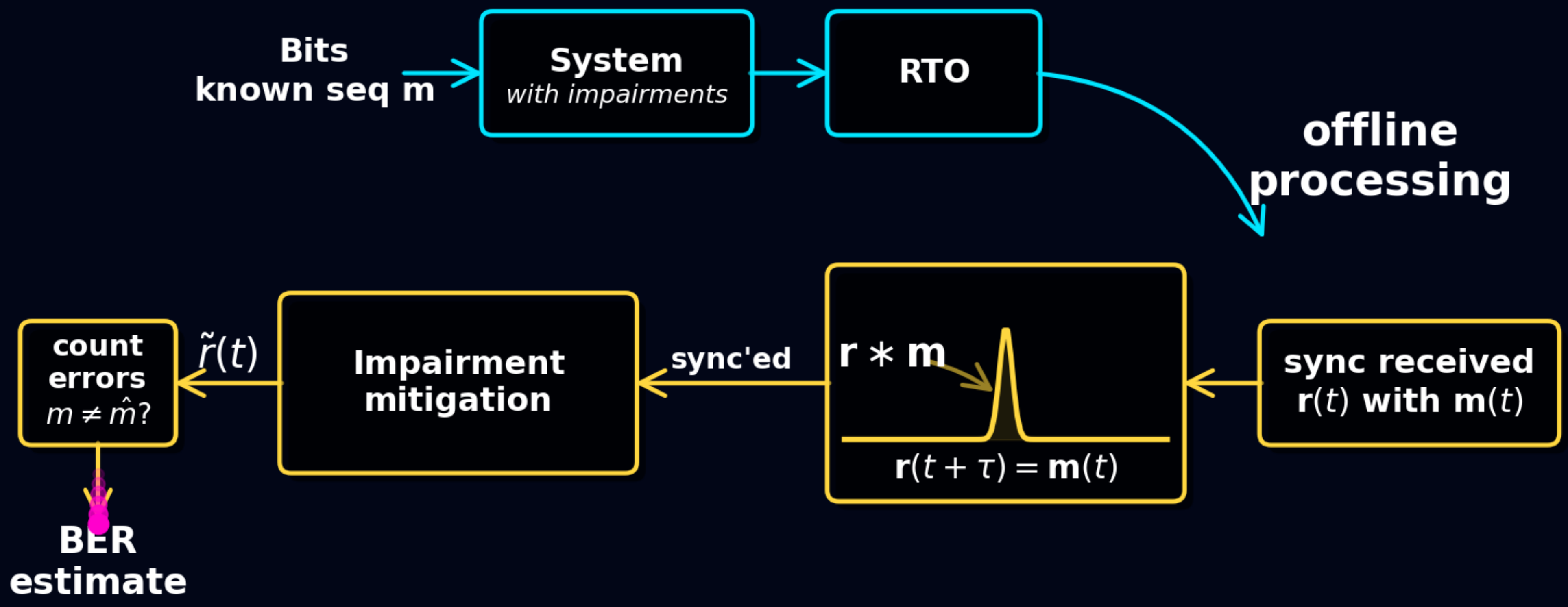


Pre-equalization

DAC digital-to-analog converter



Impairment mitigation



Impairment mitigation

Offline Equalization with an RTO

- Estimation
  - Channel frequency response
  - Noise power
- Adaptation
  - Data aided (knowledge of transmitted data)
    - All data (cheating, but good for eliminating a particular component)
    - Training sequence (accepted practice)
  - Decision directed (using data “guesses”)
    - Continuous updating good for time-varying channel
- Equalizer type
  - Can be used with various types of equalizers