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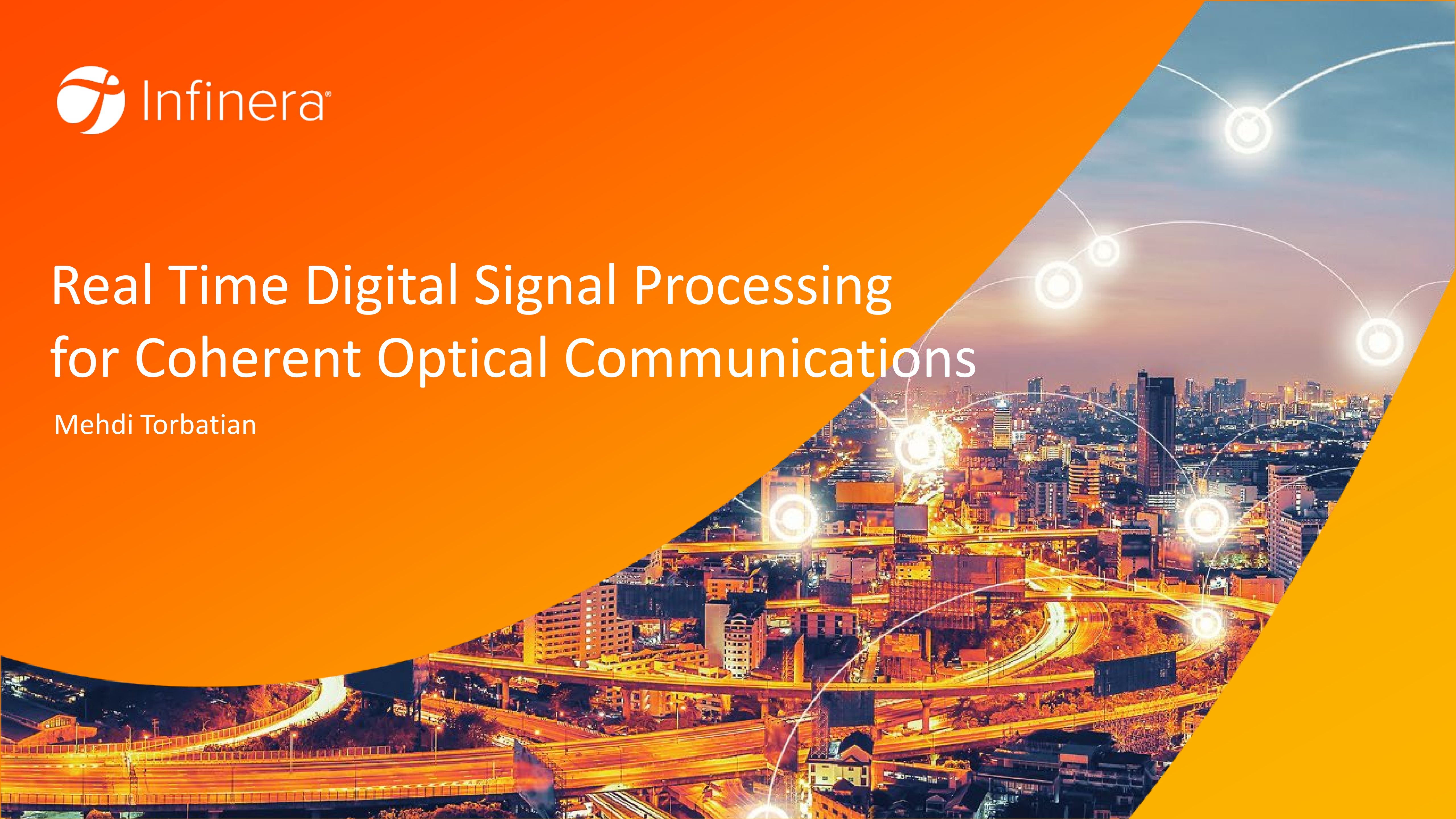
Real Time Digital Signal Processing for Coherent Optical Communications

Mehdi Torbatian



Outline

- DSP for Coherent Fiber Optics
  - Linear channel model
  - Basic building blocks of DSP
- Offline processing
  - Single burst processing procedure
- Real time processing
  - Streaming process, OLS, OLA ()
  - Parallelization
  - Loop bandwidth
  - Jitter Budget
  - Implementation SNR
  - RF front End
  - Burst events

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DSP for Coherent Fiber Optics

Fiber Optic channel

- Linear channel impairments
  - CD, PMD, SOP, PDL
  - Frequency offset, Phase noise
  - Amplified spontaneous emission (ASE) noise,
  - Implementation noise (fixed precision implementation)
  - RF front end impairments, Echo, ENOB

- Non-Linear channel impairments

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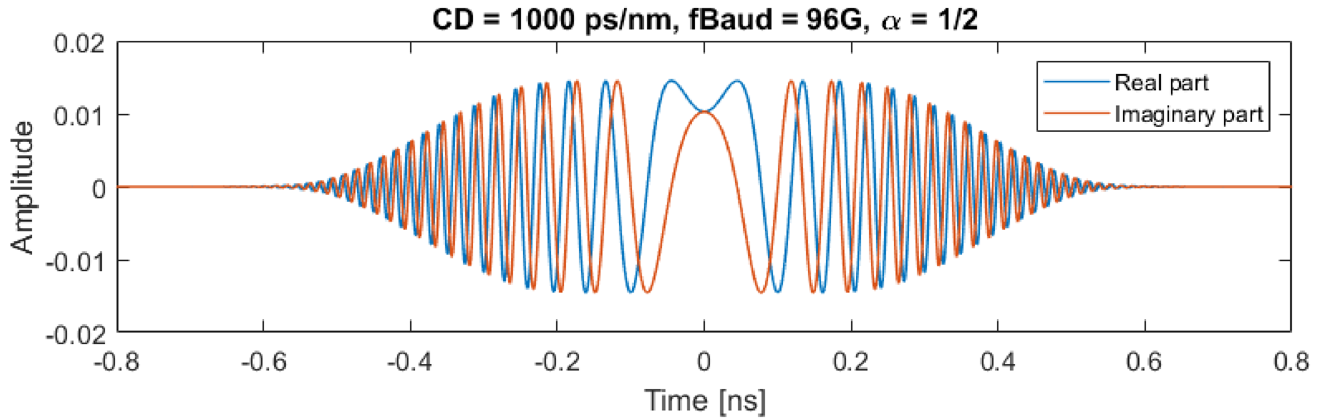
Chromatic Dispersion CD



$$\begin{bmatrix} c_{II}(t) & c_{QI}(t) \\ c_{IQ}(t) & c_{QQ}(t) \end{bmatrix} \otimes \begin{bmatrix} \mathrm{Re}\{E_x(t)\} \\ \mathrm{Im}\{E_x(t)\} \end{bmatrix}$$

$$H_{CD}(\omega) = e^{-j\frac{D\lambda^2}{4\pi c}\omega^2}$$

- Different frequencies of the light propagate with different group velocity in the fiber
- May spans over 100's of symbol; e.g., 1.2e-9/(1/96e9) = 115 symbols
- Nearly Static.
- Mixes I and Q channel
- Distortion in the phase, not in the amplitude→ Zero forcing equalizer in frequency domain

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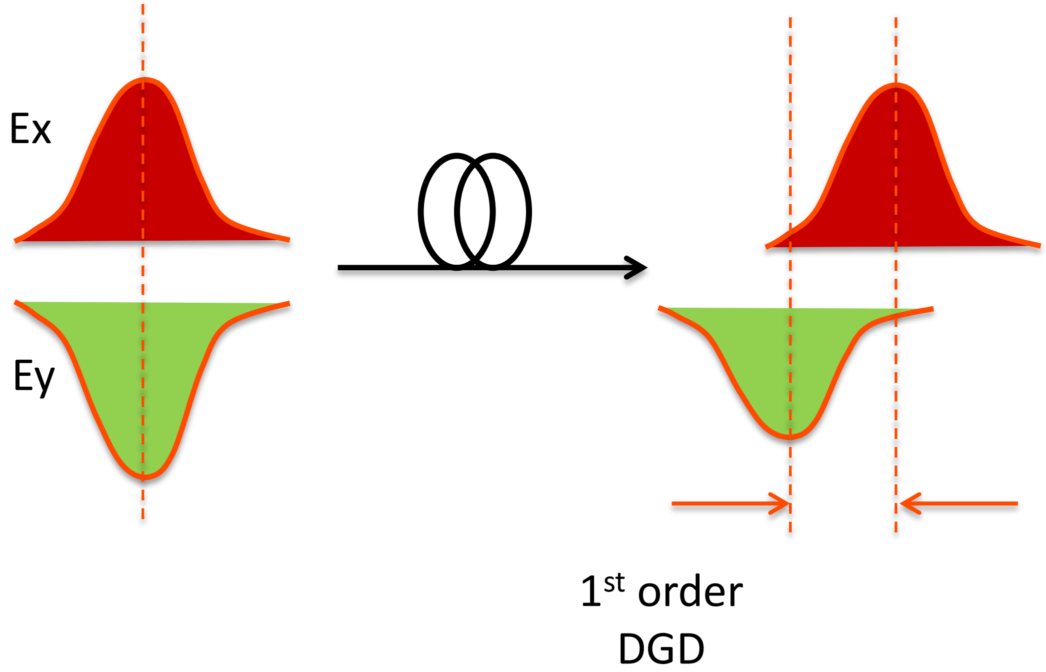
Polarization Mode Dispersion (PMD)

- Two principal states of polarizations (PSP) may have different group delay (DGD) when propagating through fiber.
- The input SOP is changing with time and generally does not line-up with PSPs
- Thus mixes X and Y polarizations
- A few symbols worth of ISI,
- DGD and PSP are changing in ms time scale, Very dynamic
- Needs Adaptive Equalization either in time or in frequency domain



$$H_{PMD}(\omega) = J_1^{-1} \cdot \begin{bmatrix} e^{-j\frac{1}{2}\tau(\omega-\omega 0)} & 0 \\ 0 & e^{j\frac{1}{2}\tau(\omega-\omega 0)} \end{bmatrix} \cdot J_2,$$

$$\begin{bmatrix} R_x \\ R_y \end{bmatrix} = \begin{bmatrix} c_{xx} & c_{yx} \\ c_{xy} & c_{yy} \end{bmatrix} \otimes \begin{bmatrix} E_x \\ E_y \end{bmatrix}$$

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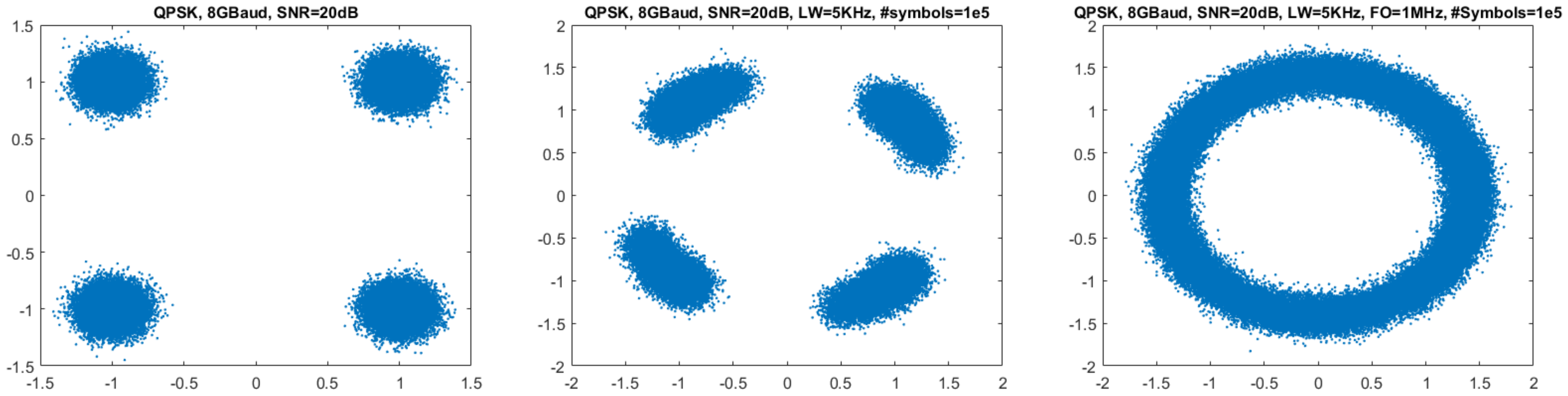
Laser Phase Noise and Frequency Offset



- Arises from both TX and Rx lasers
- Is considered as a multiplicative noise in the received signal
- Is modeled as a first order Wiener process
- Is compensated in carrier recovery circut

$$r[k] = s[k] \cdot e^{j\varphi[k]} + z[k]$$

$$\phi[k] = \sum_{n=-\infty}^{k} \phi[n]$$

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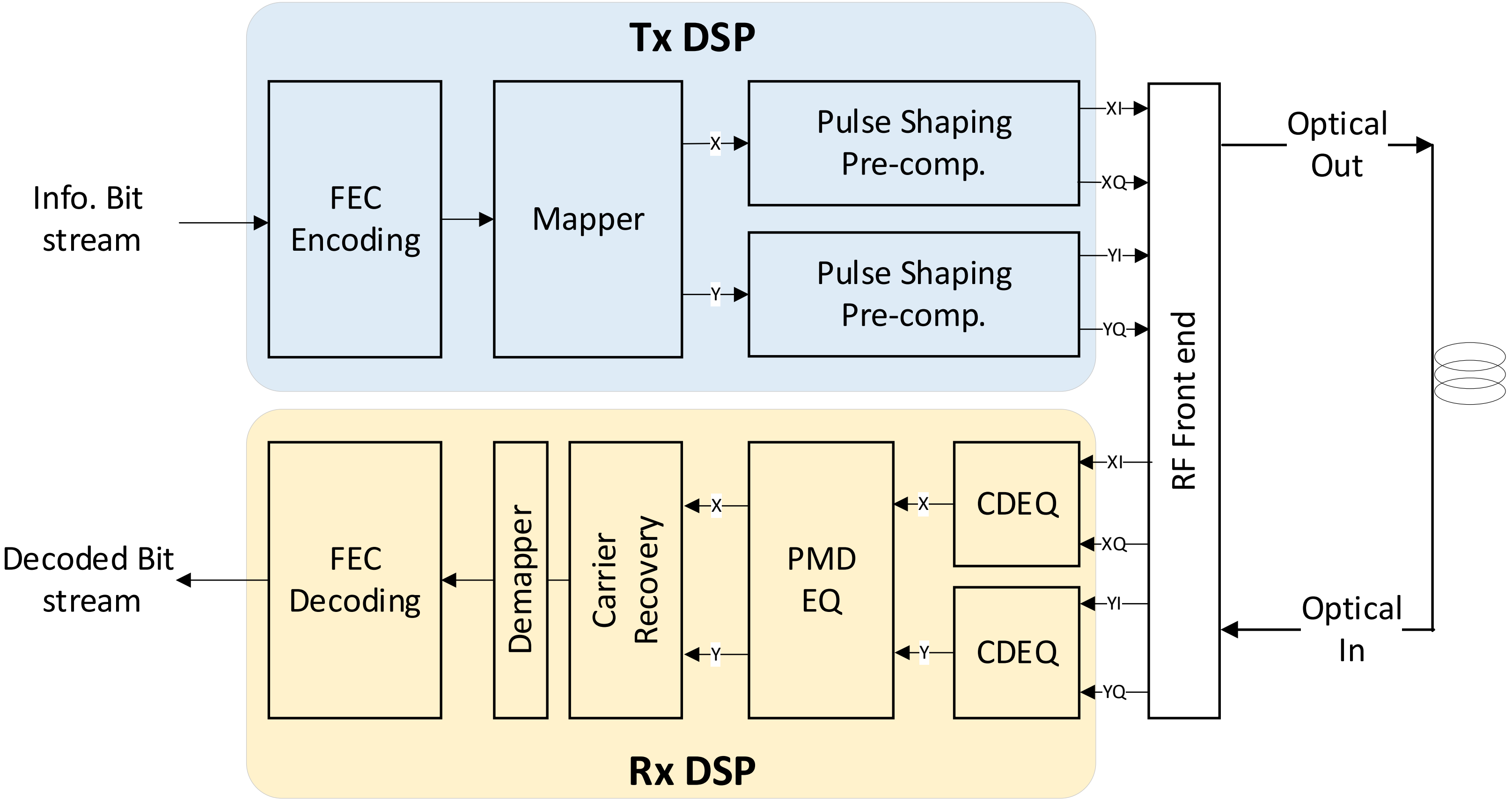
TX/RX Overall DSP Flow



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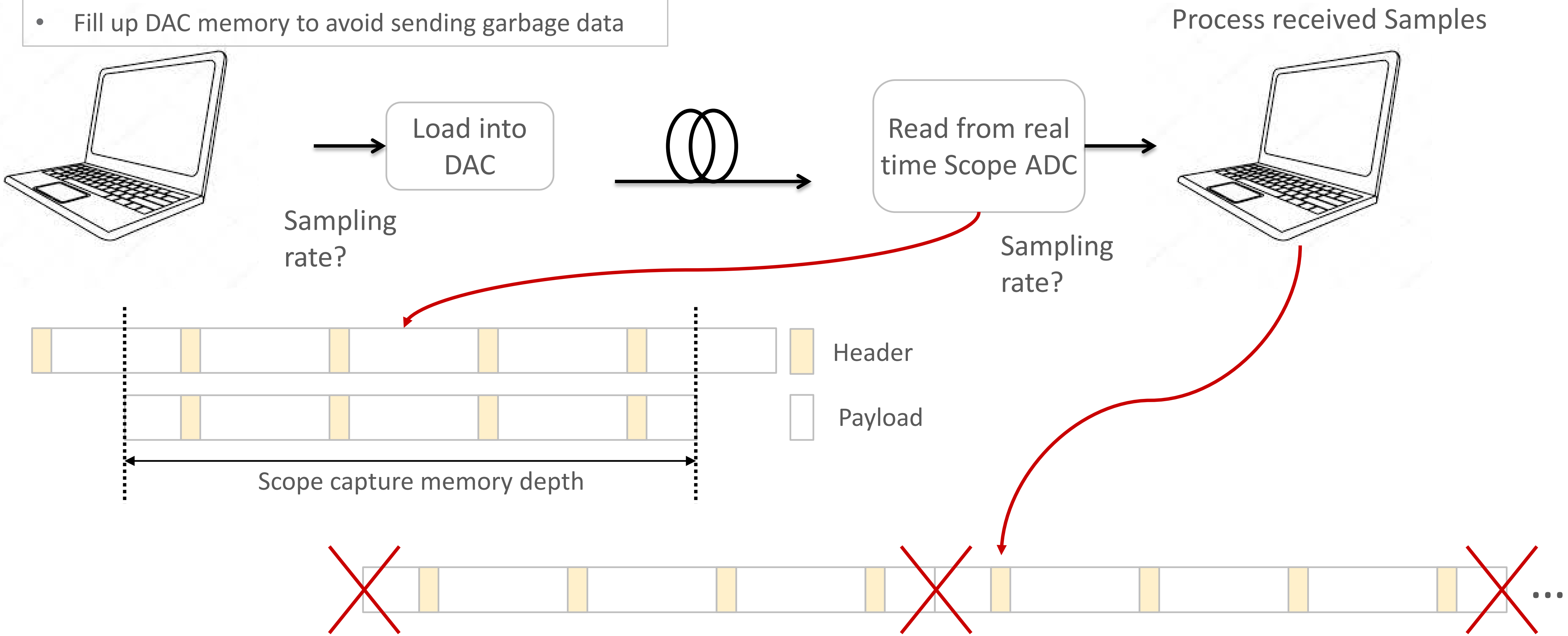
Offline Processing

Offline Processing Routine

- Generate Tx Signal
- Prepare samples with desired DSP
- Input sampling rate matches the DAC sampling rate
- Fill up DAC memory to avoid sending garbage data



→ At the receiver, the captured data may be **repeated** to have a longer sequence of samples **for post-processing**

→ * Incomplete frames may be dropped or accounted for in post-processing

Offline Rx-Side Data Processing

Measure and Correct Rx Side IQ Impairments	All TX samples are available
Resample to DSP Sample Rate (e.g. 2 x)	e.g., Using a MATLAB resample function
4 Channel Independent AGC	All samples are available at once
Coarse Frequency Offset Estimation/Correction	By searching a range of Freq offset. TX data is available for reference
CD Compensation	In frequency domain. One big FFT/IFFT circuit
CLK Recovery and Phase Estimation/Correction	Estimate the delay and compensate for it. No ppm
Framing and Fine Frequency Estimate	All TX samples are available
RCOS Matched Filtering	In time or frequency domain in one shut
PMD Equalizer	Symbol by symbol processing in a loop with most likely no latency, Training may be done on all symbols
Carrier Recovery	Symbol by symbol processing in a loop with most likely no latency
TX IQ compensation	All TX symbols are available
Decoding and Collect statistics	

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Likely Assumptions in Offline Processing

- MATLAB/Python is available.
- All TX symbols/samples are available.
- Laser might be shared between TX and RX: perfect synchronization
- No PPM offset, just a fixed delay between Tx and Rx signals: easy clock recovery

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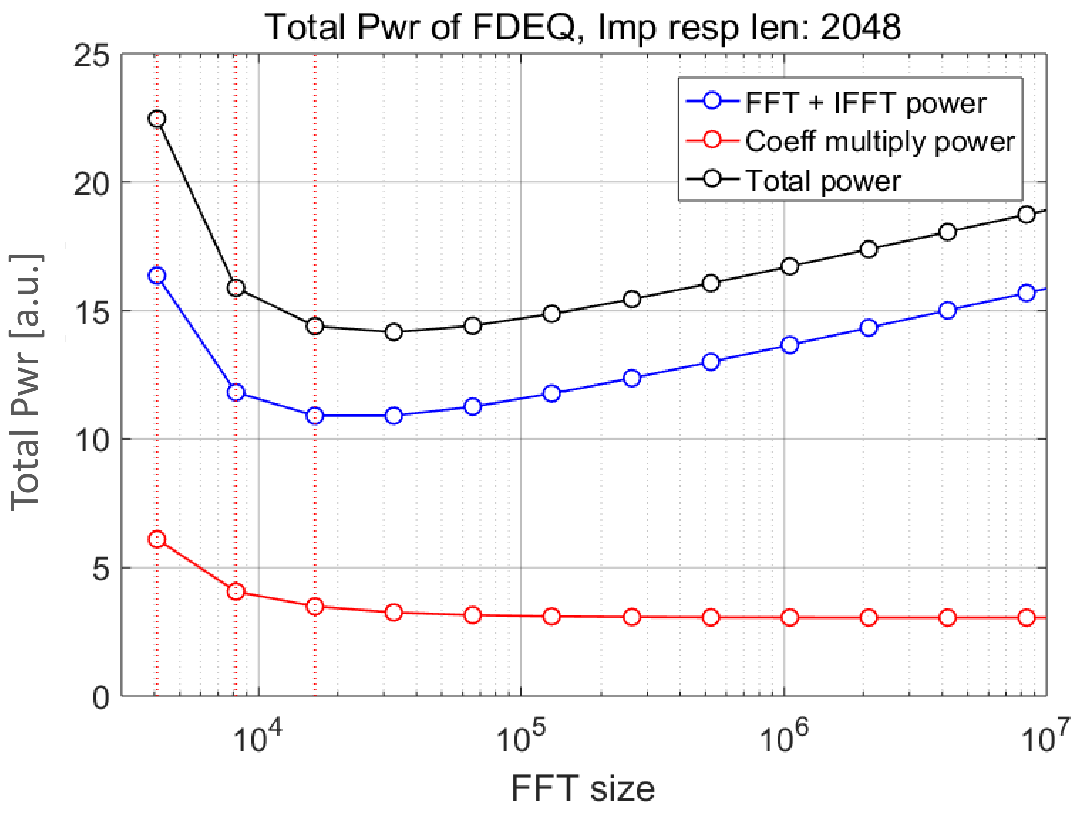
Real Time Processing

Example: CD Compensation

- Offline processing : $y[n] \ = \mathrm{IFFT}(\mathrm{FFT}(x[n]).* \ H_{cd}^{-1})$
- Real time processing:
  - Data transfer is a streaming process → CD compensation in one FFT/IFFT shot is not feasible
  - Solution: limited size FFT/IFFT circuit + OLS/OLA to compensate for edge effect
  - What size of FFT/IFFT do I need? What percentage of OLS ratio do I need?
    - » What range of CD compensation do we want to support?
    - » Which combination of FFT size and OLS ratio results in the least power consumption?
    - » Is this a single carrier system or multi subcarrier system?
    - » What is the baud rate?
    - » What is the sampling rate?
  - How do we implement FFT/IFFT circuits?



50/50 OLS is NOT efficient
25/75 or 12.5/87.5 are more efficient

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Filtering Long Sequences

- Linear filtering = linear convolution
- Linear convolution → multiplication in frequency domain $x(t) * h(t) = \mathcal{F}^{-1}\left(X(f).H(f)\right)$
- Discrete Fourier Transform (DFT) for samples signals

$$X(k) = \sum_{n=0}^{N-1} e^{-j2\pi k\frac{n}{N}}, k = 0,1,\ldots,N-1, \qquad x(n) = \sum_{k=0}^{K-1} e^{j2\pi k\frac{n}{N}}, n = 0,1,\ldots,N-1$$

- Circular convolution $x(n) \otimes h(n) \overset{DFT}{\longleftrightarrow} X[k].H[k]$

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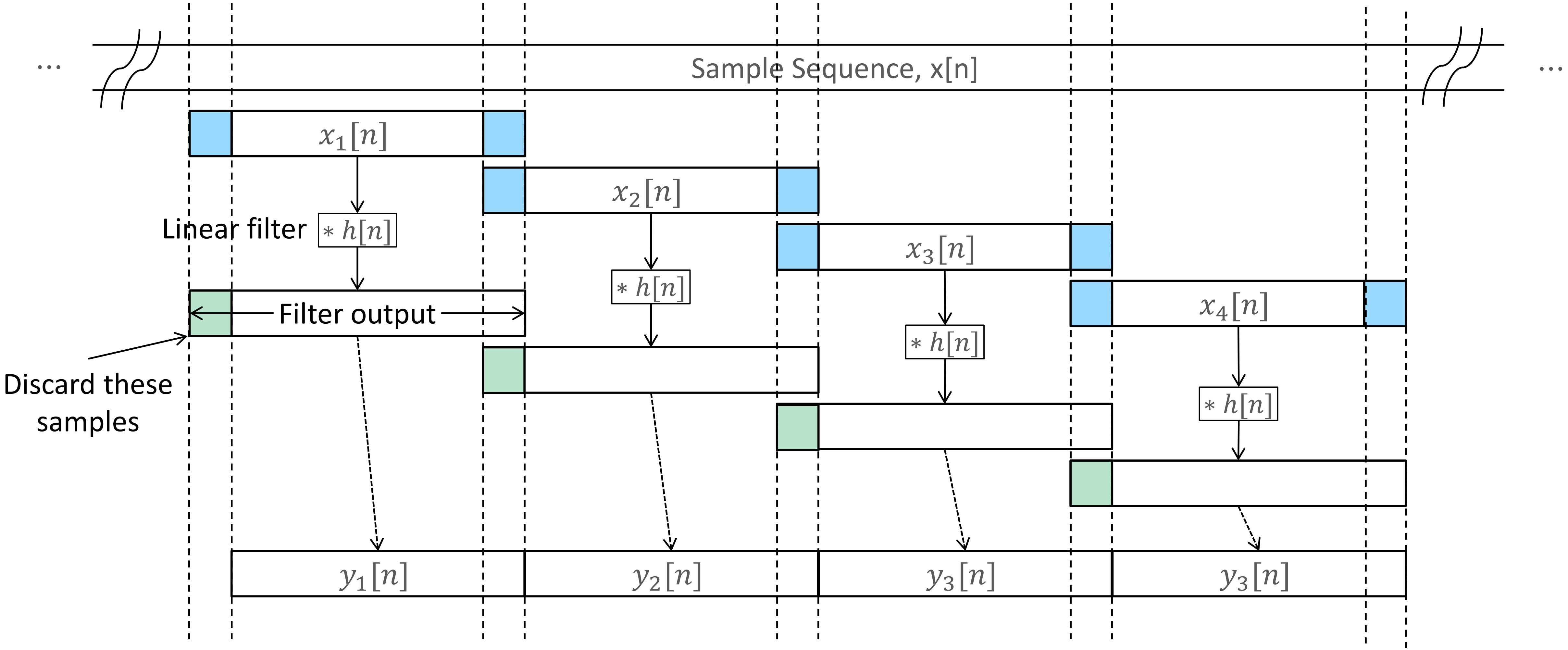
Overlap-Save Method



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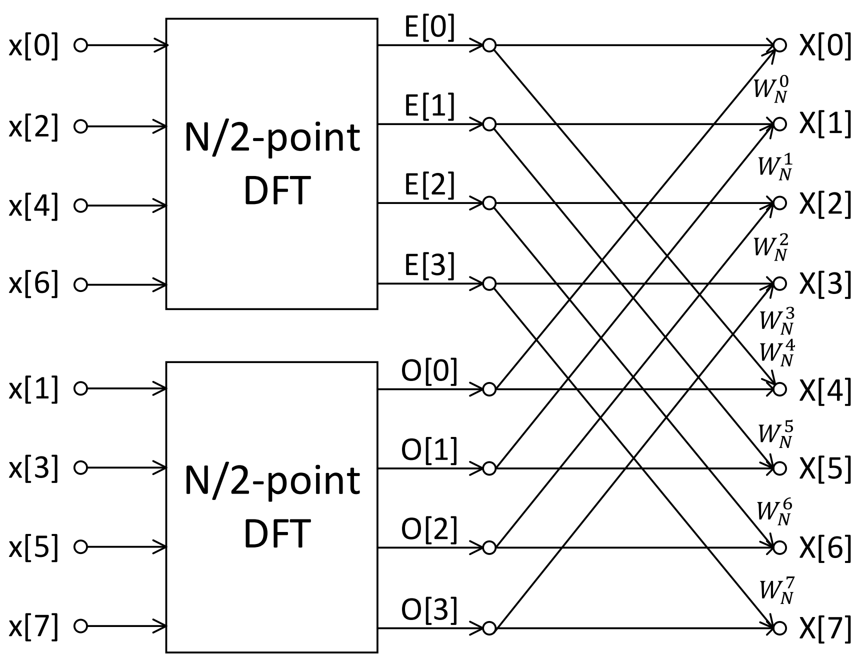
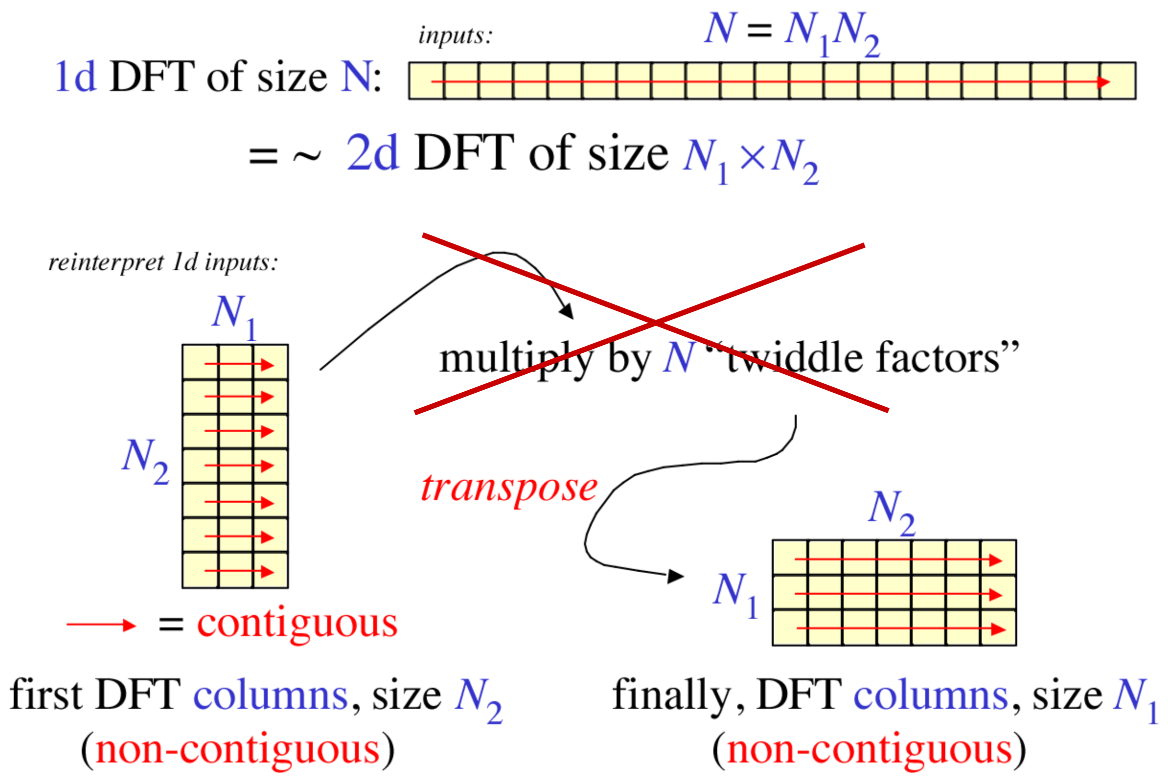
How Do we implement FFT?

For power of 2 FFTs



Arbitrary FFT size $N = N_1 . N_2$



- Perform N_1 DFTs of size N_2.
- Multiply by complex roots of unity (twiddle factors).
- Perform N_2 DFTs of size N_1.

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Which Prime Factors Should we Avoid?

- FFT3
- FFT5
- FFT7

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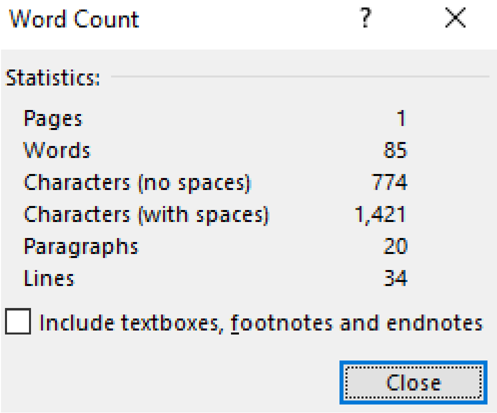
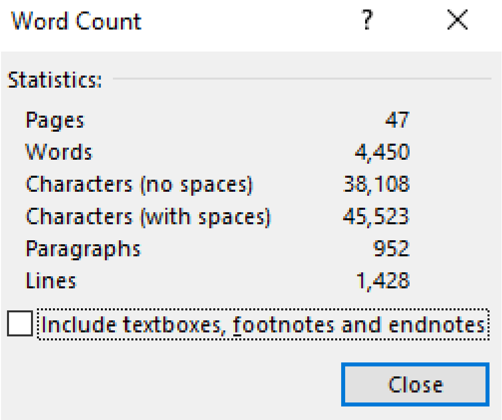
Real-Time and Offline DSP: Design Effort

How many lines of code for FF-CR?

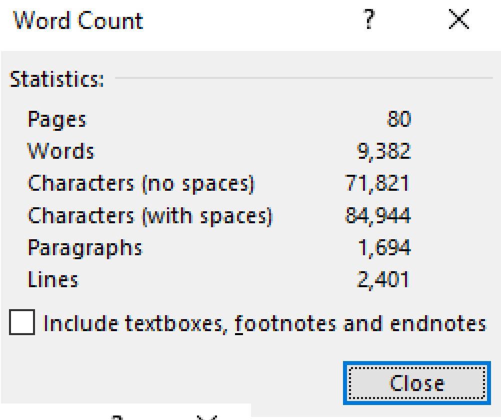
– Matlab floating point script for Offline processing:
  34 lines, 774 characters



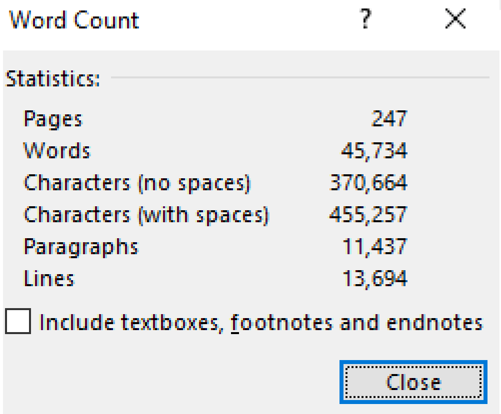
– Matlab bit-accurate fixed point, with right parallelism:
  1428 lines, 38K characters



– C model for verification:
  2401 lines, 72K characters
  93x Offline script



– RTL (Verilog):
  34 .v files, 13.7K lines, 370K characters
  480x Offline script



System Design Considerations

- Data rate, e.g. 200G to 800G
- Baud rate , e.g., 96Gbaud
- CD tolerance Range. e.g, 0-400,000 ps/nm
- DGD tolerance, e.g., 200 ps
- PDL tolerance, e.g., 4dB
- SOP tracking range,

- Sampling rate at different stages of Tx/Rx DSP?
- FFT/IFFT sizes at Tx/Rx?
- OLS ratios?
- α factor?
- Clock rate at each stage?
- Parallelization factor at each stage?
- Tracking speed/loop bandwidth?
- Acceptable range of latency?
- Analog front end spec?
- Jitter Analysis?
- Link budget analysis?
- Modem SNR?

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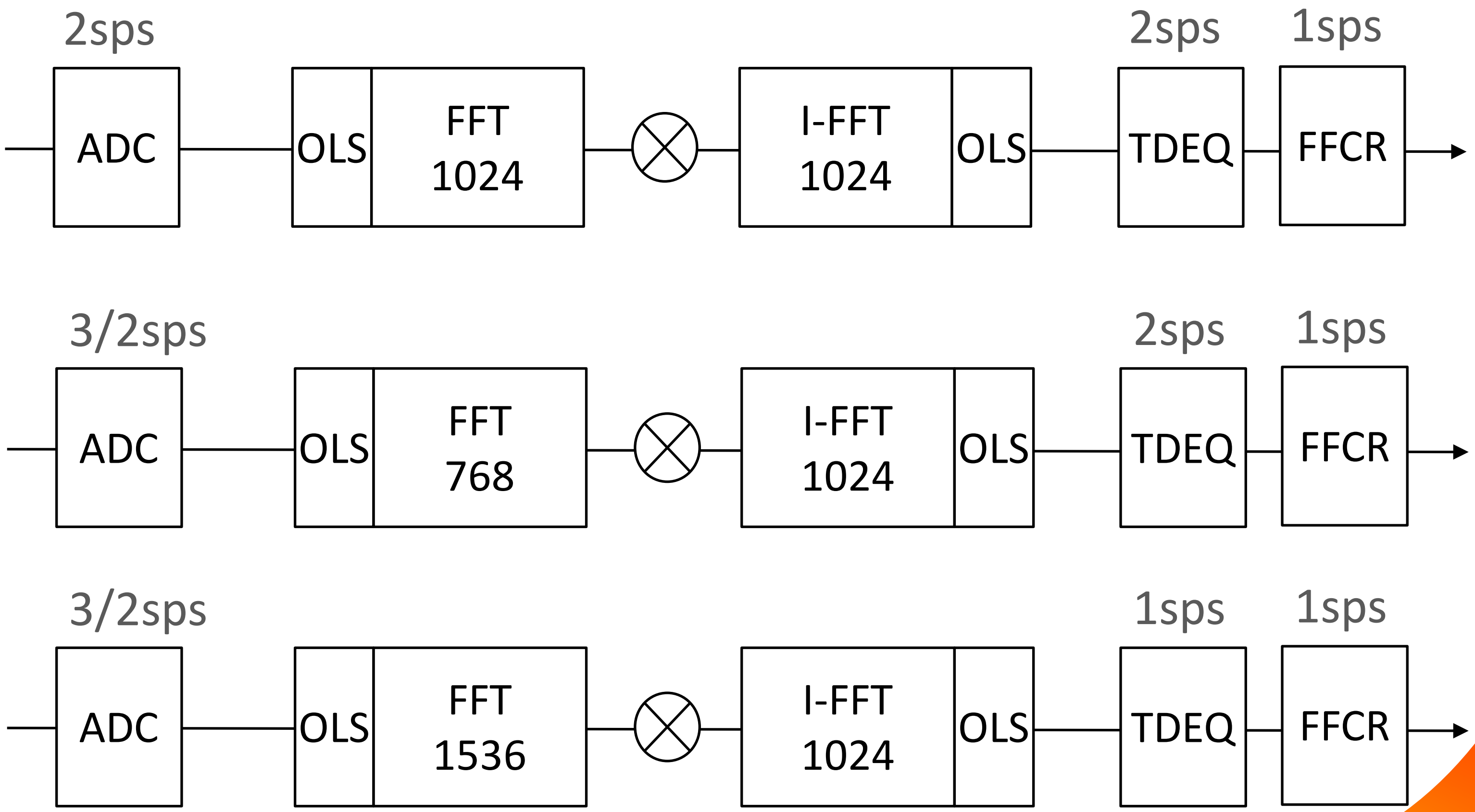
Real-Time and Offline DSP: Signal Sampling Rate

- Offline code: resample(), interp1()

- Real-time design:
  - Polyphase decimation filters
  - FFTs and IFFTs



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Parallelization

- Parallelization is a design factor. E.g., LDPC parity check matrix

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Tracking Speed

- 2th order PLL Structure
- Clock recovery loop
- PMD Equalizer Loop
- Carrier recovery loop

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Jitter Analysis

- Sources of Jitter
- Effect of Jitter on performance
- Jitter budget mask
- DSP circuit to tack jitter

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Modem SNR

- Quantization noise and SNR degradation budget

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Link Budget Analysis

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