ECEN720: High-Speed Links Circuits and Systems Spring 2025

Lecture 12: CDRs

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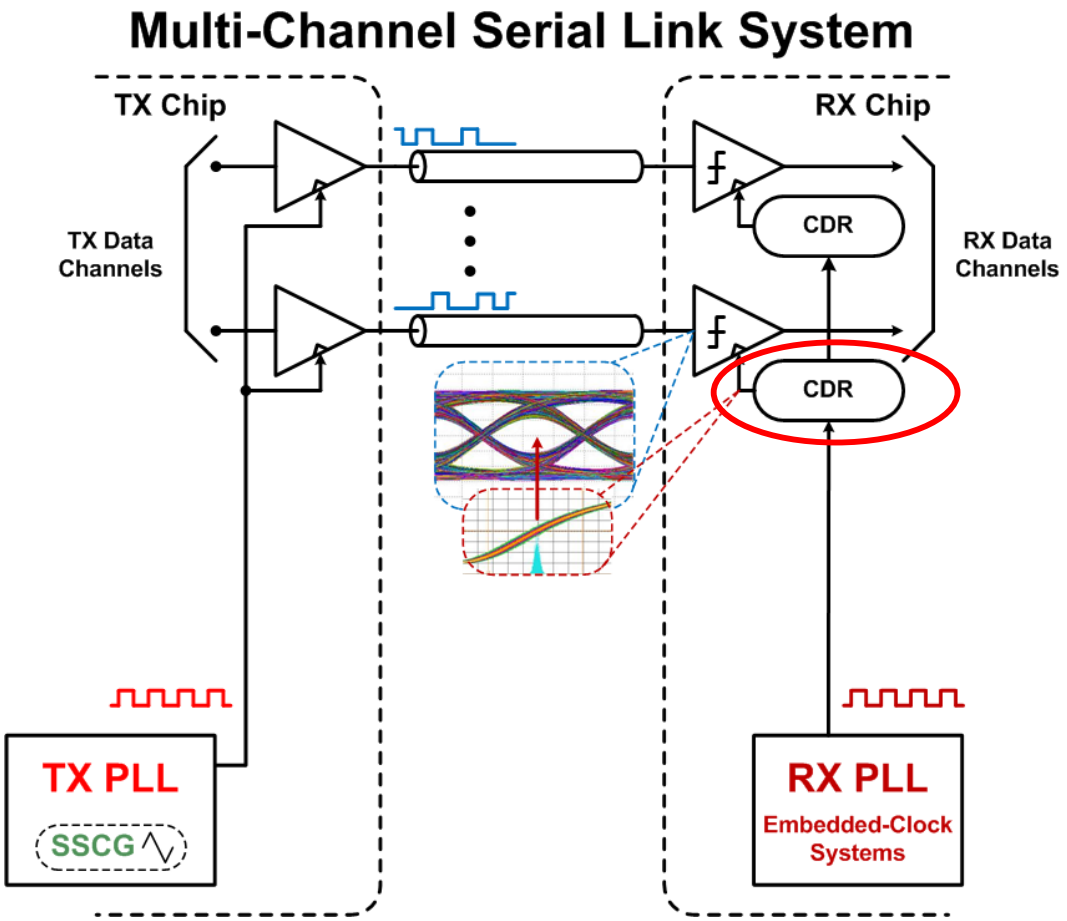
Announcements

- Project Preliminary Report due Apr 15
- Project Final Report due Apr 29

Agenda

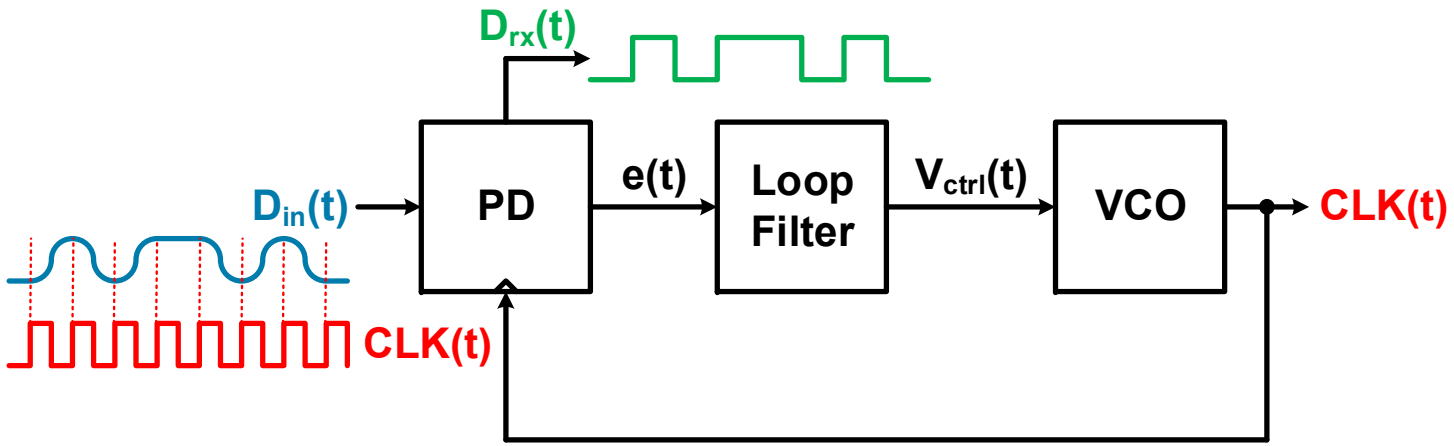
- CDR overview
- CDR phase detectors
- Single-loop analog PLL-based CDR
- Dual-loop CDRs
- Phase interpolators
- CDR jitter properties

Embedded Clock I/O Circuits



- TX PLL
- TX Clock Distribution
- CDR
  - Per-channel PLL-based
  - Dual-loop w/ Global PLL &
    - Local DLL/PI
    - Local Phase-Rotator PLLs
    - Global PLL requires RX clock distribution to individual channels

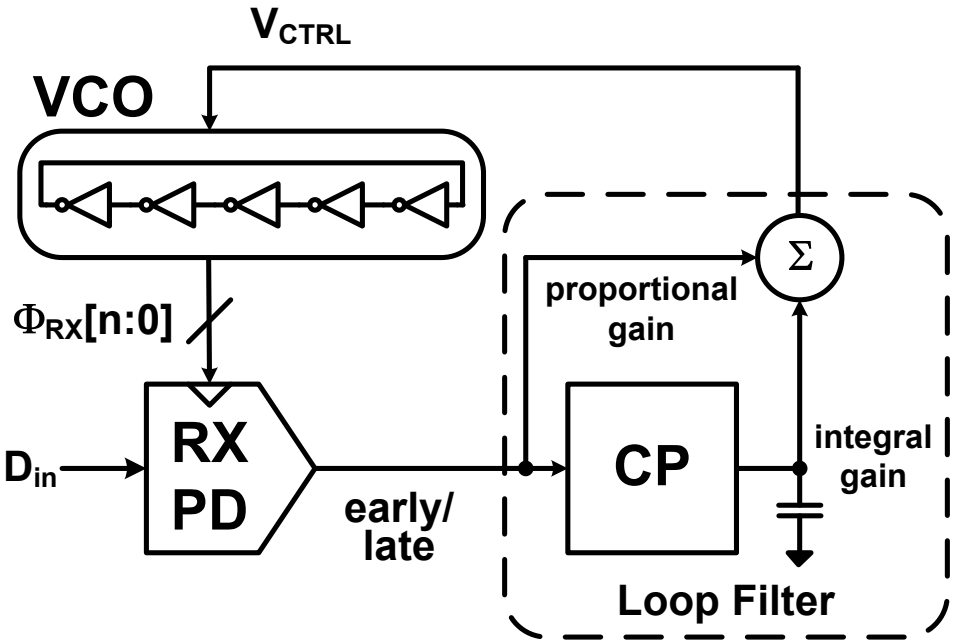
Clock and Data Recovery



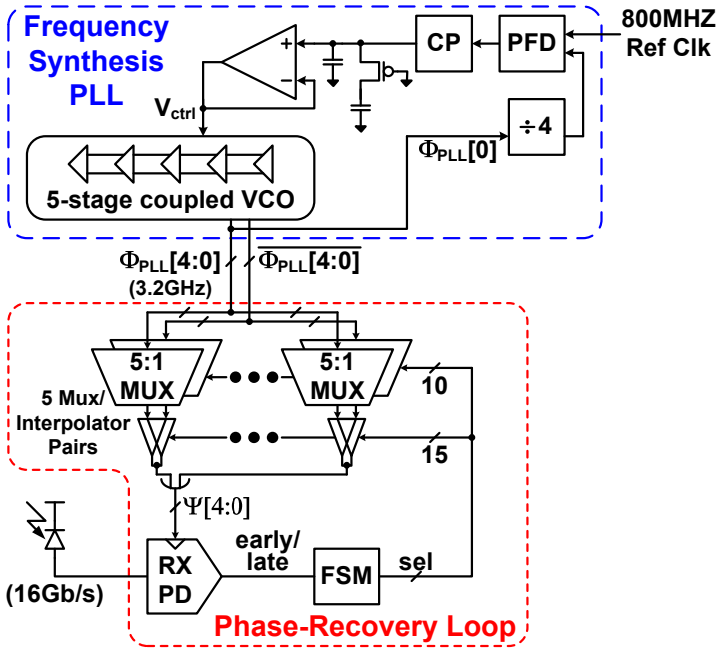
- A clock and data recovery system (CDR) produces the clocks to sample incoming data
- The clock(s) must have an effective frequency equal to the incoming data rate
  - 10GHz for 10Gb/s data rate
  - OR, multiple clocks spaced at 100ps
  - Additional clocks may be used for phase detection
- Sampling clocks should have sufficient timing margin to achieve the desired bit-error-rate (BER)
- CDR should exhibit small effective jitter

Embedded Clocking (CDR)

PLL-based CDR



Dual-Loop CDR



- Clock frequency and optimum phase position are extracted from incoming data
- Phase detection continuously running
- Jitter tracking limited by CDR bandwidth
  - With technology scaling we can make CDRs with higher bandwidths and the jitter tracking advantages of source synchronous systems is diminished
- Possible CDR implementations
  - Stand-alone PLL
  - "Dual-loop" architecture with a PLL or DLL and phase interpolators (PI)
  - Phase-rotator PLL

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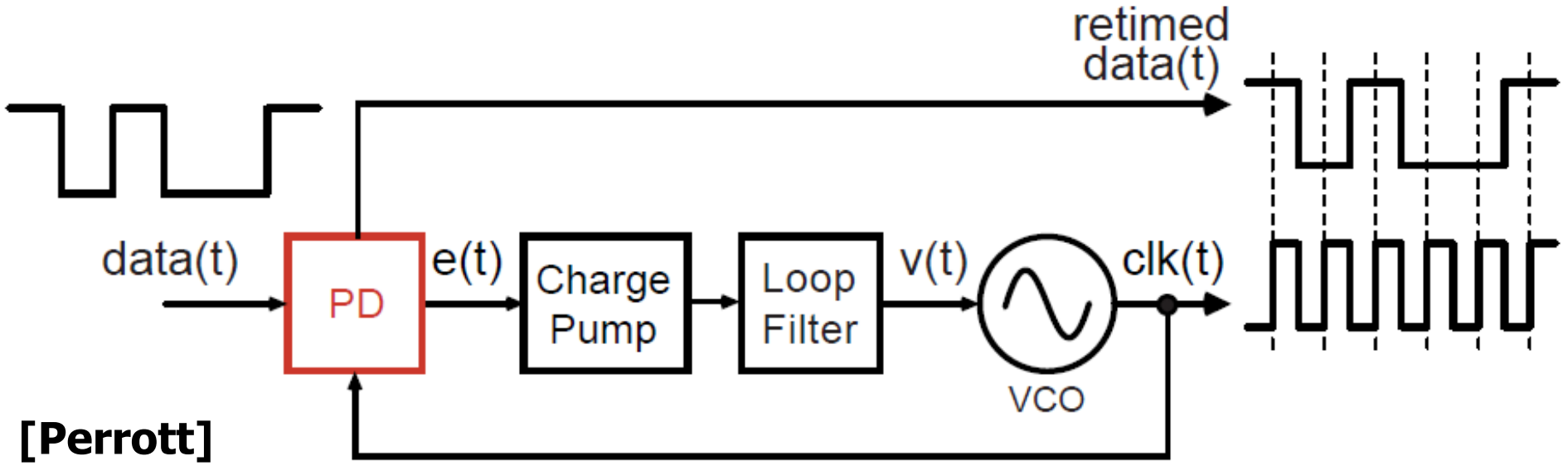
CDR Phase Detectors



[Perrott]

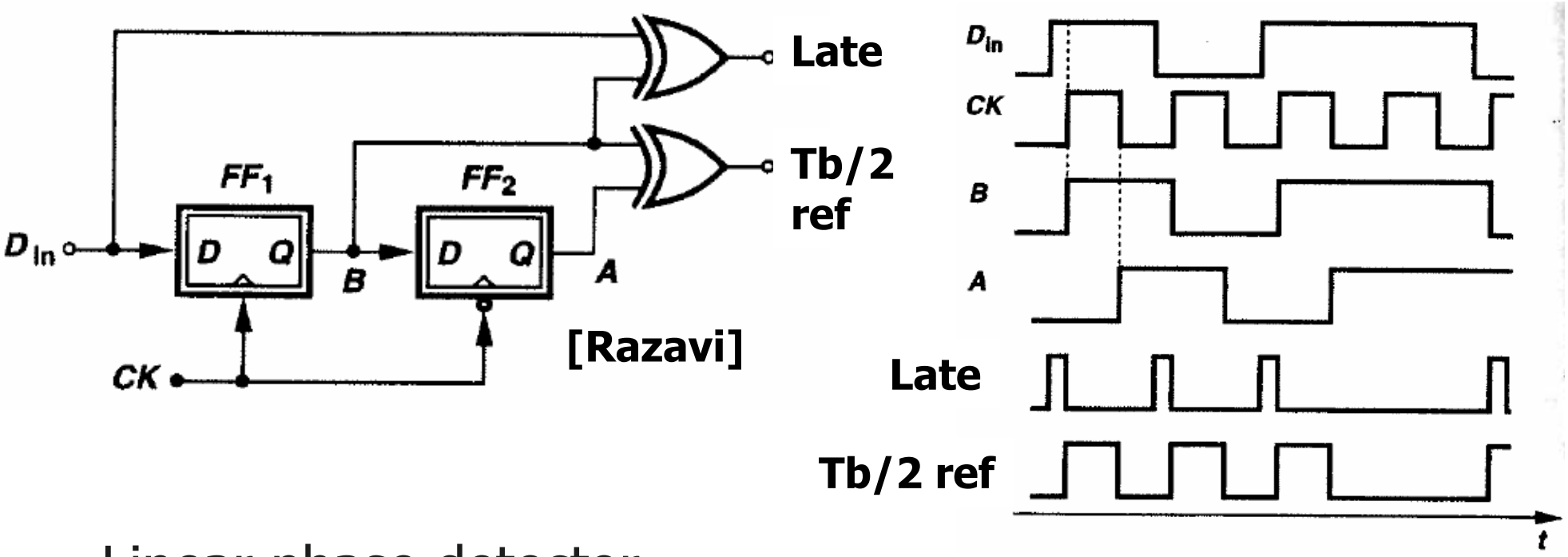
- A primary difference between CDRs and PLLs is that the incoming data signal is not periodic like the incoming reference clock of a PLL

- A CDR phase detector must operate properly with missing transition edges in the input data sequence

CDR Phase Detectors

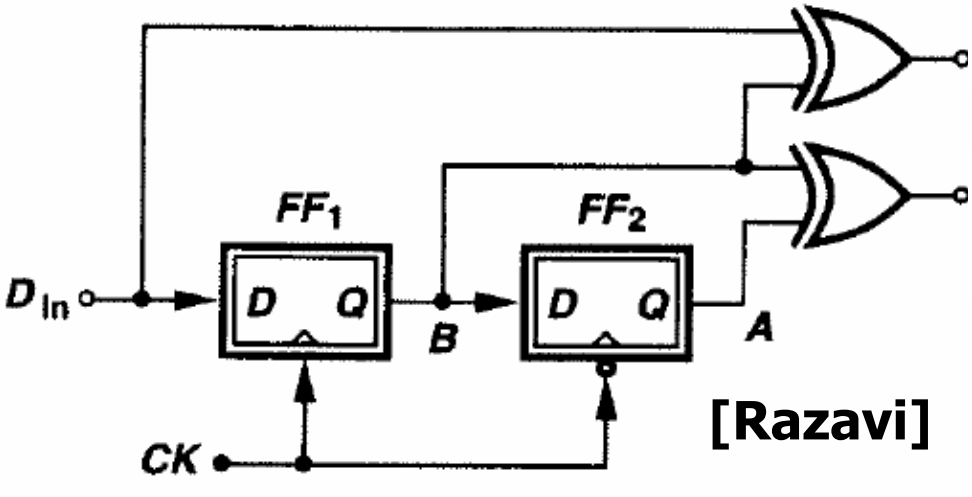
- CDR phase detectors compare the phase between the input data and the recovered clock sampling this data and provides information to adjust the sampling clocks' phase
- Phase detectors can be linear or non-linear
- Linear phase detectors provide both **sign and magnitude** information regarding the sampling phase error
  - Hogge
- Non-linear phase detectors provide **only sign** information regarding the sampling phase error
  - Alexander or 2x-Oversampled or Bang-Bang
  - Oversampling (>2)
  - Baud-Rate

Hogge Phase Detector

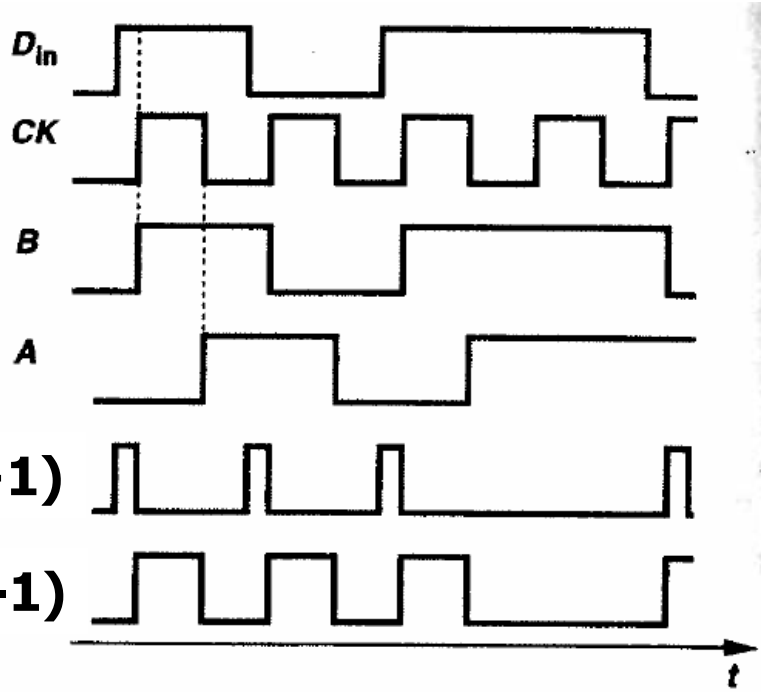


- Linear phase detector
- With a data transition and assuming a full-rate clock
  - The late signal produces a signal whose pulse width is proportional to the phase difference between the incoming data and the sampling clock
  - A Tb/2 reference signal is produced with a Tb/2 delay
- If the clock is sampling early, the late signal will be shorter than Tb/2 and vice-versa

Hogge Phase Detector

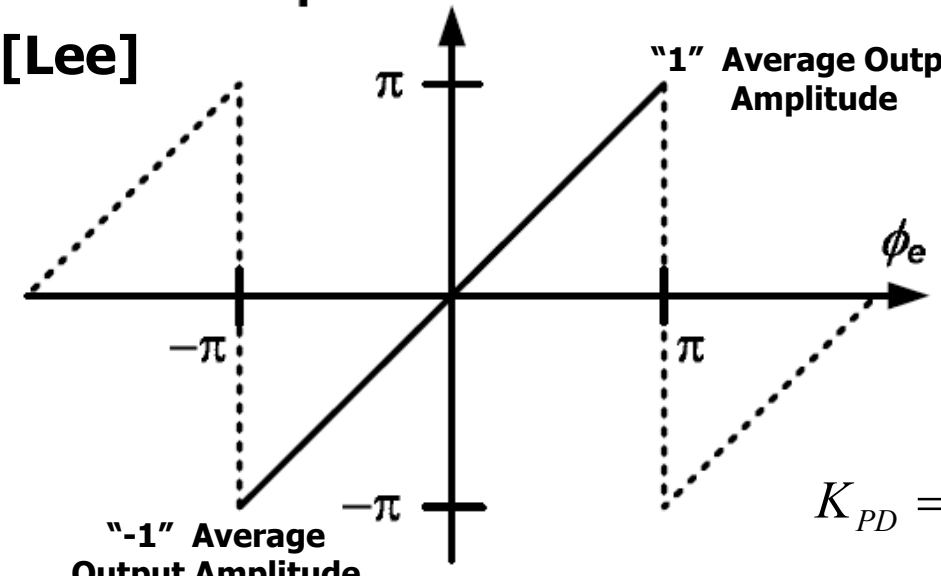


[Razavi]



(Late – Tb/2 ref)
Output Pulse Width

[Lee]

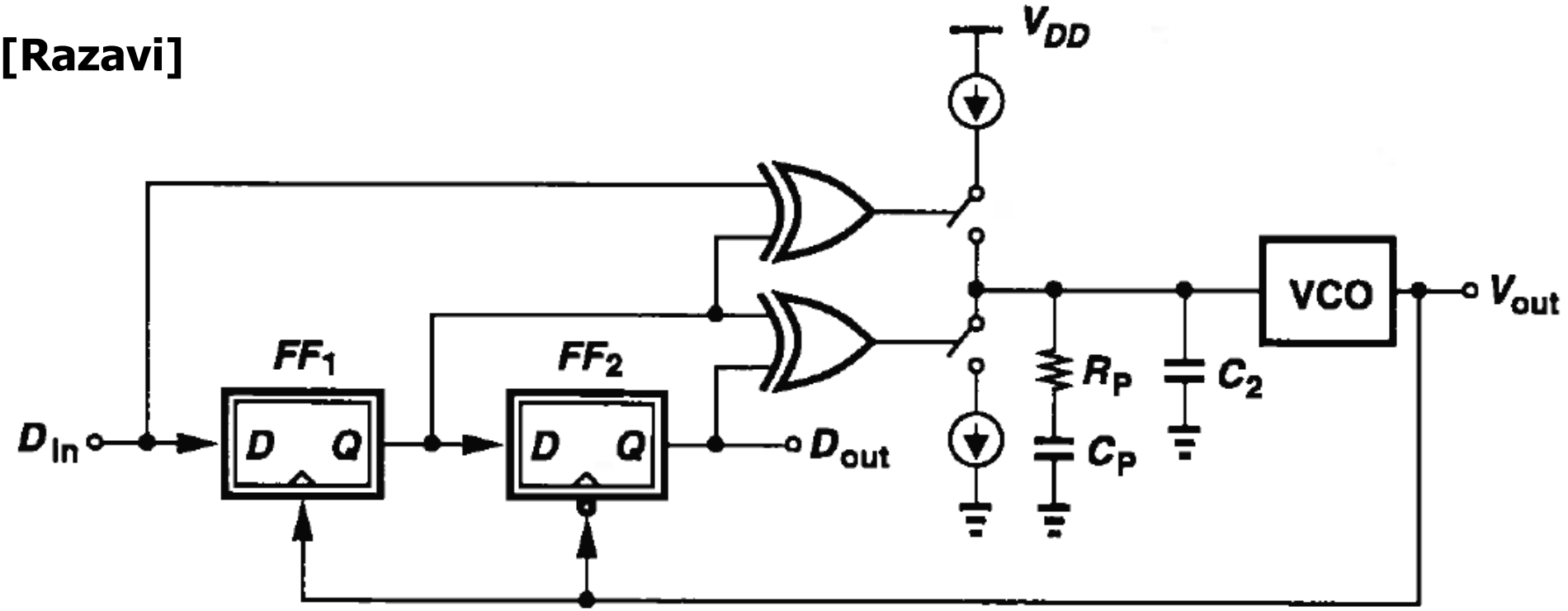


$$K_{PD} = \frac{1}{\pi}(TD)$$

- For phase transfer 0rad is w.r.t optimal Tb/2 (π) spacing between sampling clock and data
  - $\phi_e = \phi_{in} - \phi_{clk} - \pi$
- TD is the transition density – no transitions, no information
  - A value of 0.5 can be assumed for random data

PLL-Based CDR with a Hogge PD

[Razavi]



- XOR outputs can directly drive the charge pump
- Need a relatively high-speed charge pump

Alexander (2x-Oversampled) Phase Detector

- Most commonly used CDR phase detector
- Non-linear (Binary) "Bang-Bang" PD
  - Only provides sign information of phase error (not magnitude)
- Phase detector uses 2 data samples and one "edge" sample
- Data transition necessary

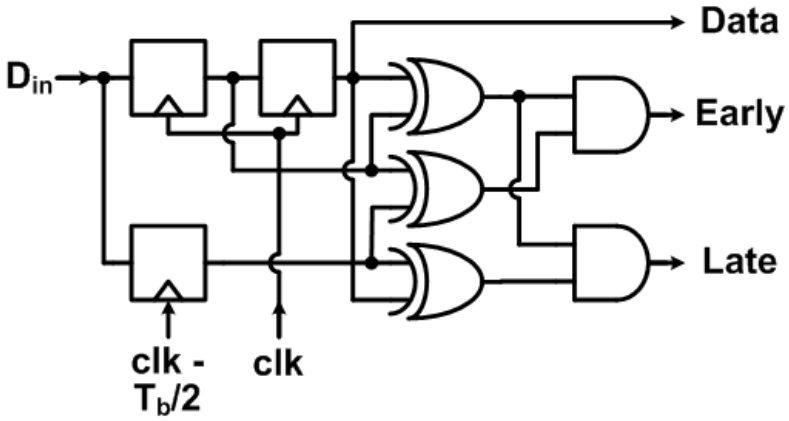
$$D_n \oplus D_{n+1}$$

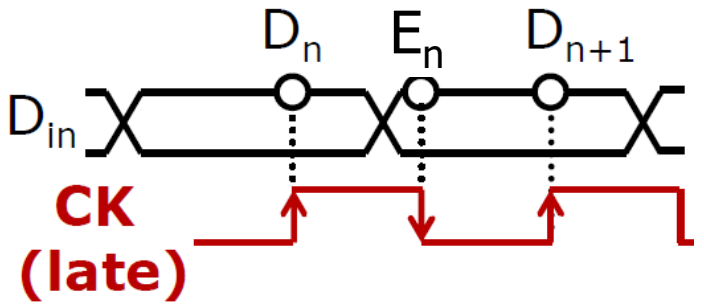
  - If "edge" sample is same as second bit (or different from first), then the clock is sampling "late"

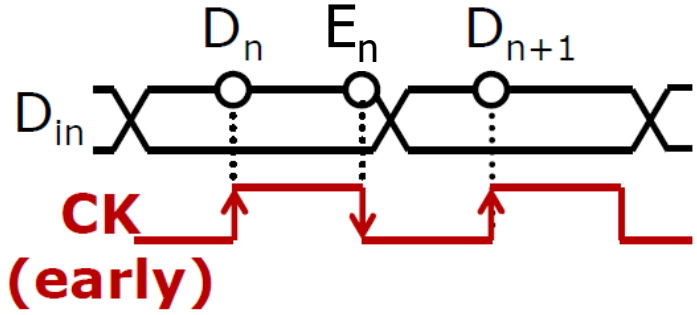
$$E_n \oplus D_n$$

  - If "edge" sample is same as first bit (or different from second), then the clock is sampling "early"

$$E_n \oplus D_{n+1}$$

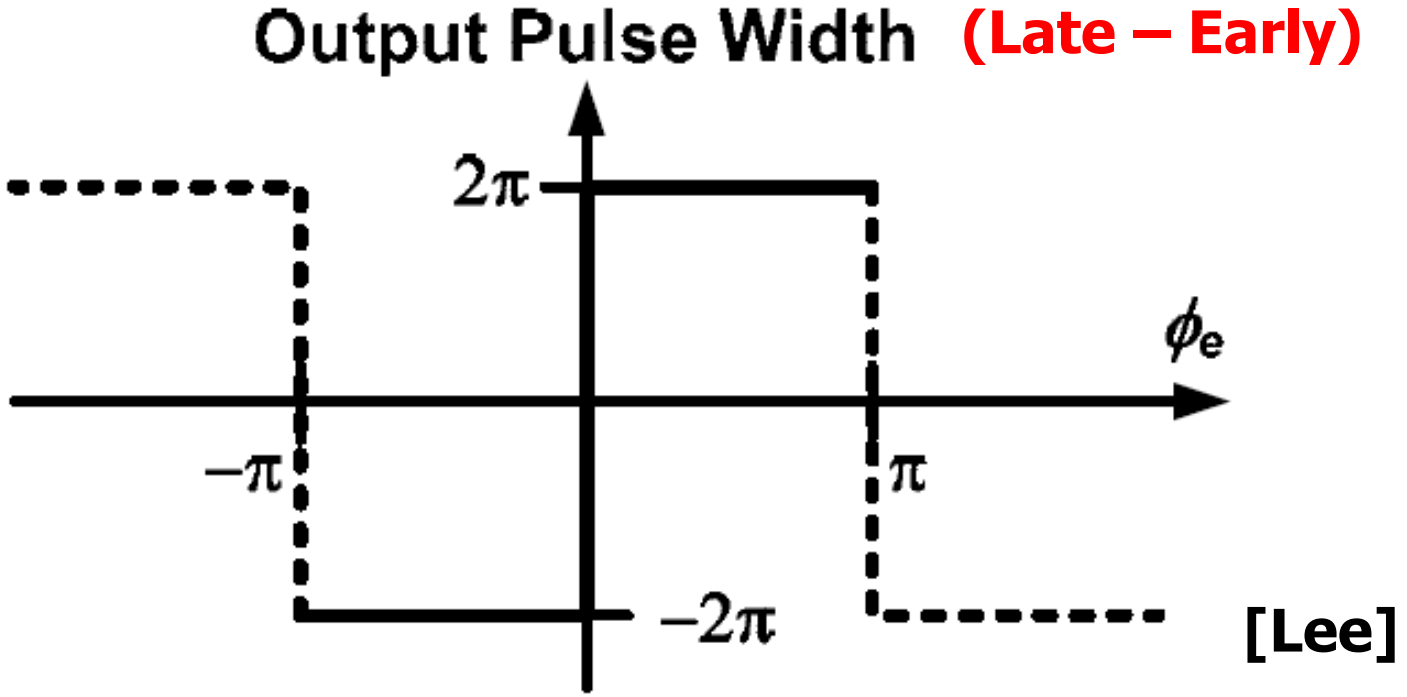






[Sheikholeslami]

Alexander Phase Detector Characteristic (No Noise)



[Lee]

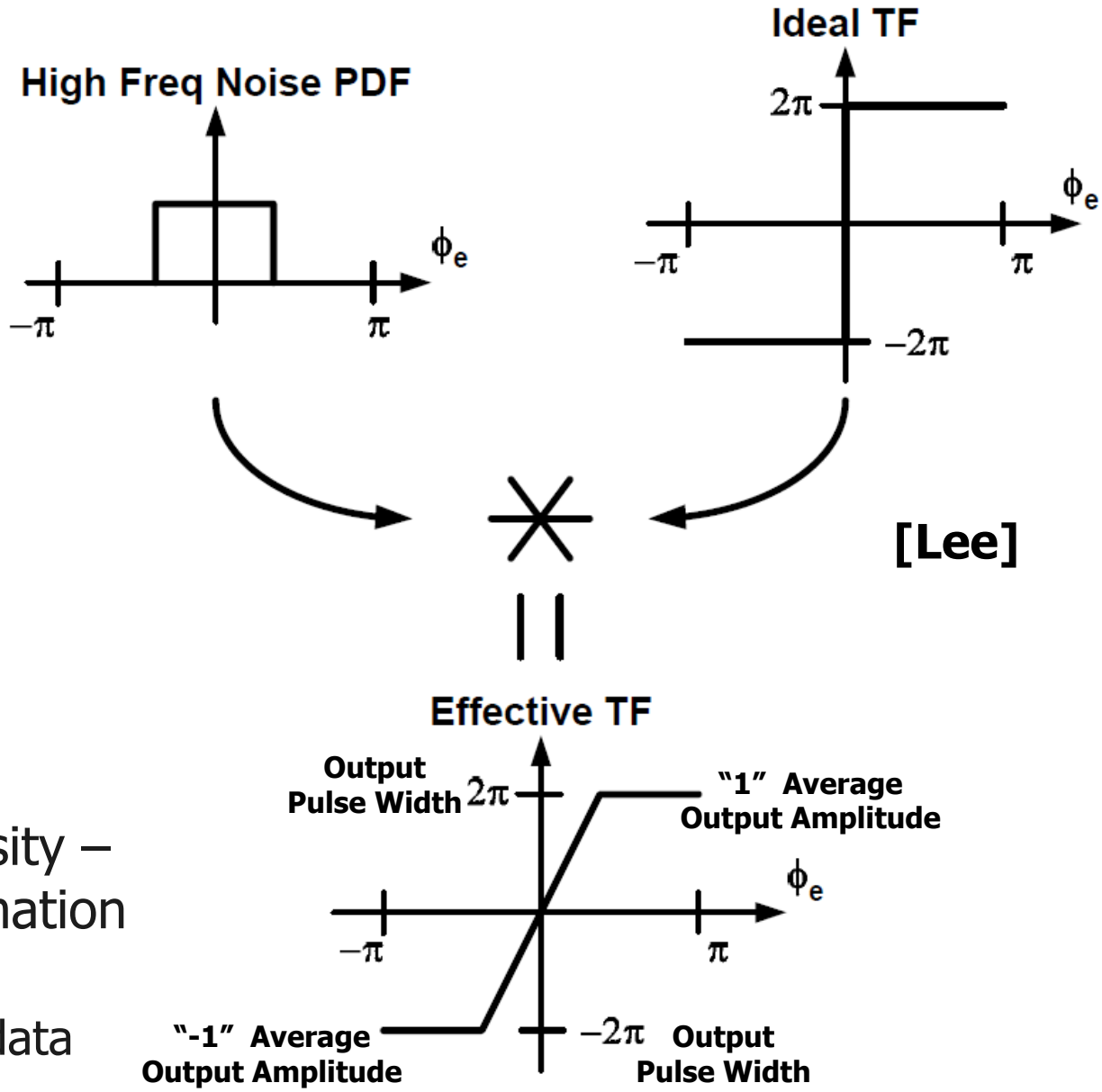
- Phase detector only outputs phase error sign information in the form of a late OR early pulse whose width doesn't vary
- Phase detector gain is ideally infinite at zero phase error
  - Finite gain will be present with noise, clock jitter, sampler metastability, ISI

Alexander Phase Detector Characteristic (With Noise)

- Total transfer characteristic is the convolution of the ideal PD transfer characteristic and the noise PDF
- Noise linearizes the phase detector over a phase region corresponding to the peak-to-peak jitter

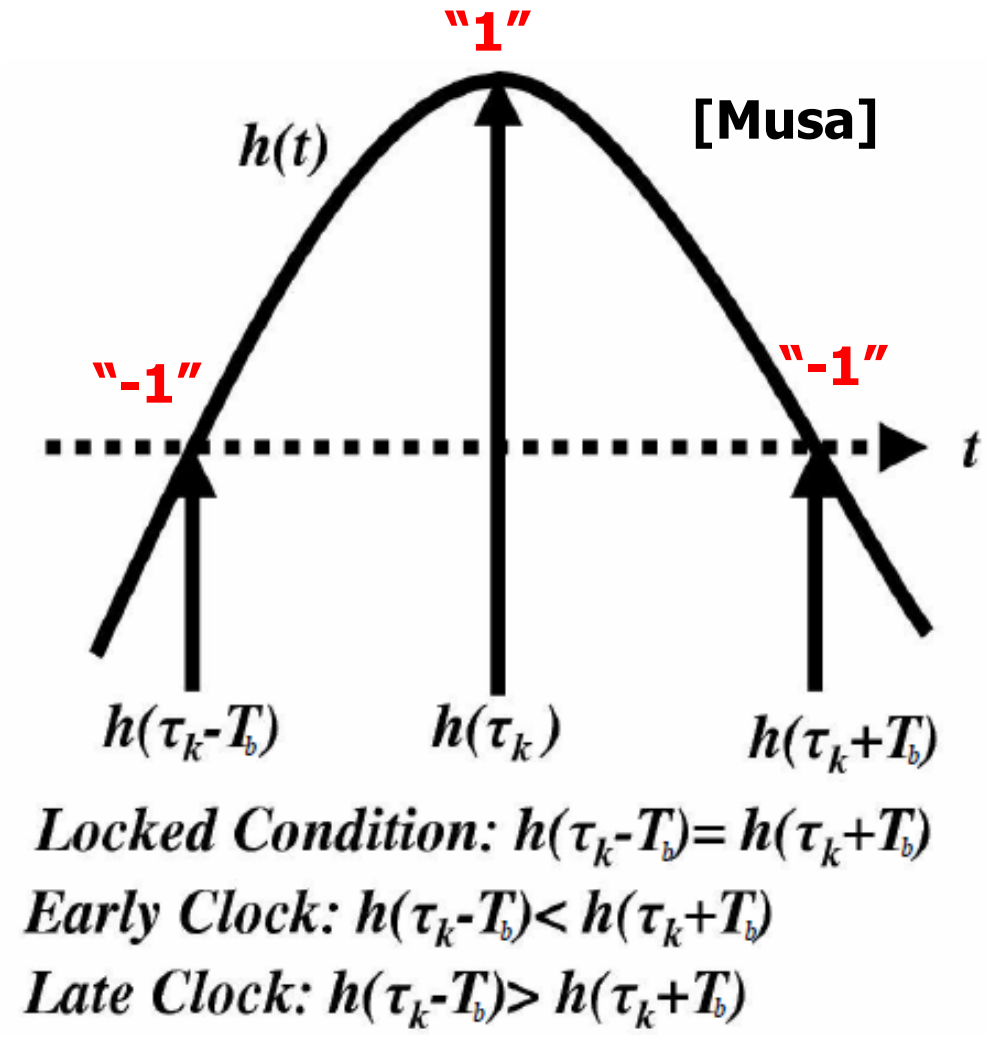
$$K_{PD} \approx \frac{2}{J_{PP}}(TD)$$

  - TD is the transition density – no transitions, no information
    - A value of 0.5 can be assumed for random data



Mueller-Muller Baud-Rate Phase Detector

- Baud-rate phase detector only requires one sample clock per symbol (bit)
- Mueller-Muller phase detector commonly used
- Attempting to equalize the amplitude of samples taken before and after a pulse



Mueller-Muller Baud-Rate Phase Detector

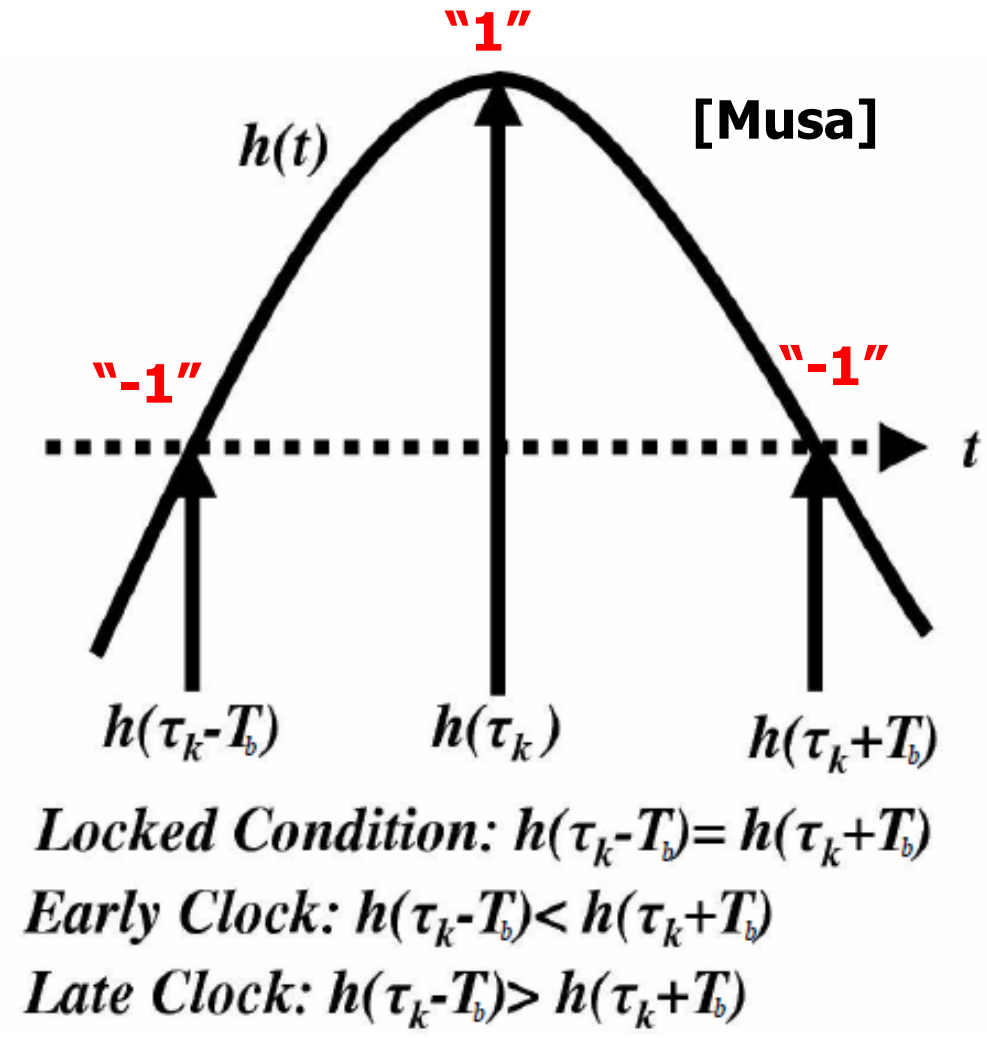
MM-PD is measuring the effective

$$h_1 - h_{-1}$$

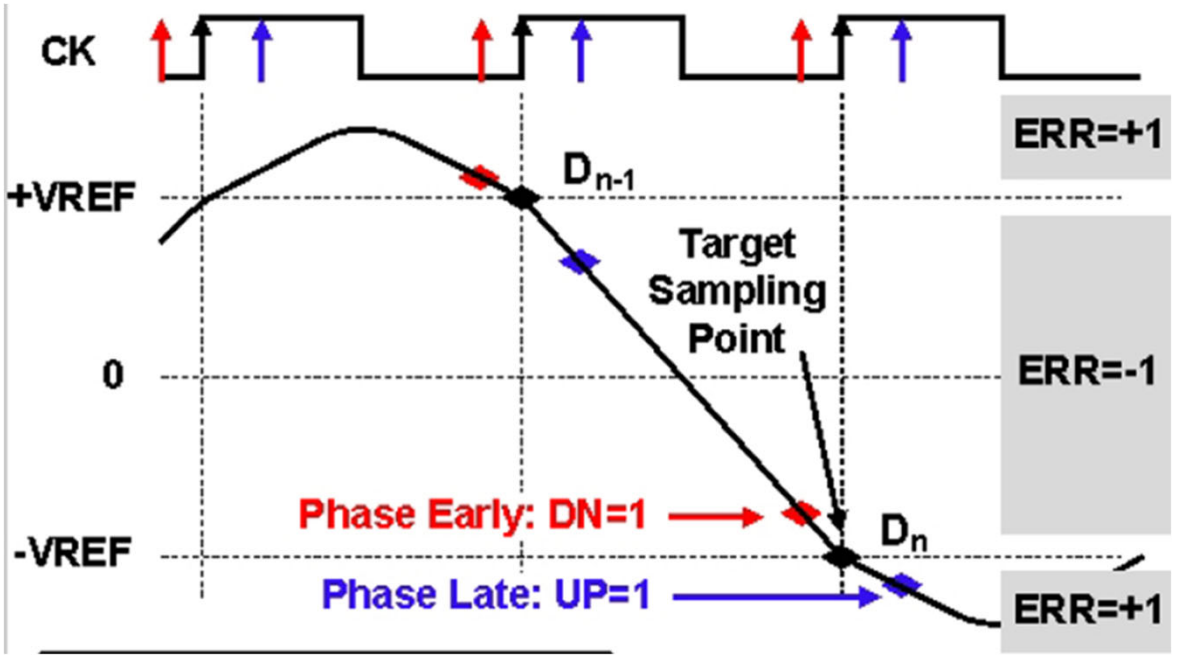
which can be computed by

$$E[y_k \cdot d_{k-1}] - E[y_k \cdot d_{k+1}]$$

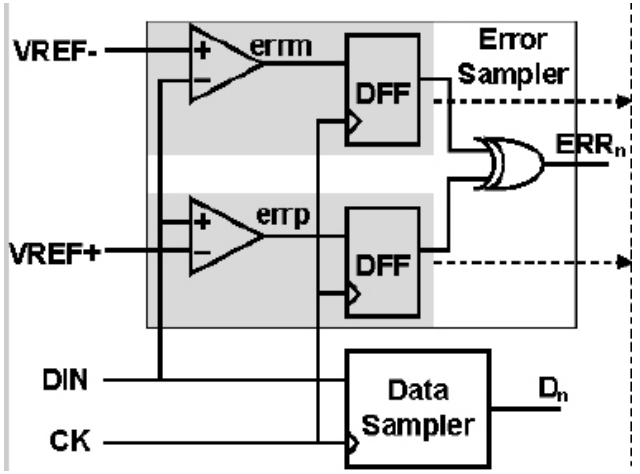
- If this is positive, then the effective post-cursor ISI is too high and we are sampling too early
- If this is negative, then the effective pre-cursor ISI is too high and we are sampling too late



Mueller-Muller Baud-Rate Phase Detector

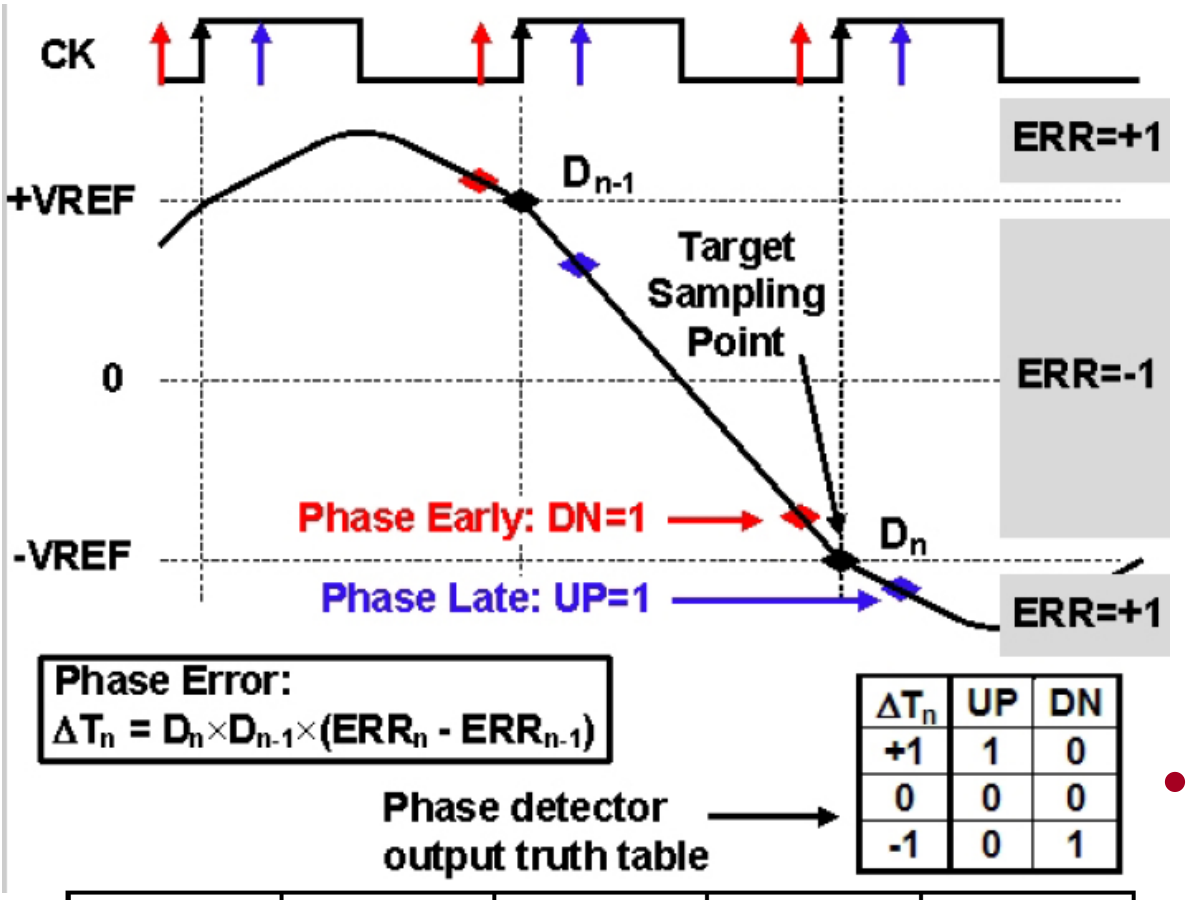


[Spagna ISSCC 2010]



- Comparing the current sample versus the desired reference level (e_n) and correlating that with the appropriate data sample (d_n) gives pre/post-cursor information
- This requires additional error samplers w/ |VREF| thresholds
- e_n gives d_{n-1} post-cursor (h_1) information
- e_{n-1} give d_n pre-cursor (h_{-1}) information

Mueller-Muller Baud-Rate Phase Detector



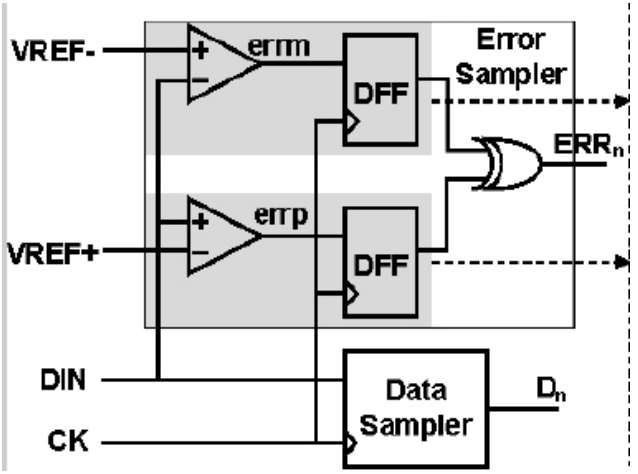
Phase Error:
$\Delta T_n = D_n \times D_{n-1} \times (ERR_n - ERR_{n-1})$

Phase detector output truth table

ΔT_n	UP	DN
+1	1	0
0	0	0
-1	0	1

d_j	d_{j-1}	e_j	e_{j-1}	φ_{err_j}
1	-1	1	-1	LATE
-1	1	1	-1	LATE
1	-1	-1	1	EARLY
-1	1	-1	1	EARLY
All other cases				HOLD

[Spagna ISSCC 2010]



- Simplified MM-PD only considers transition patterns
- If consecutive error samples are different, phase error polarity is given by e_j

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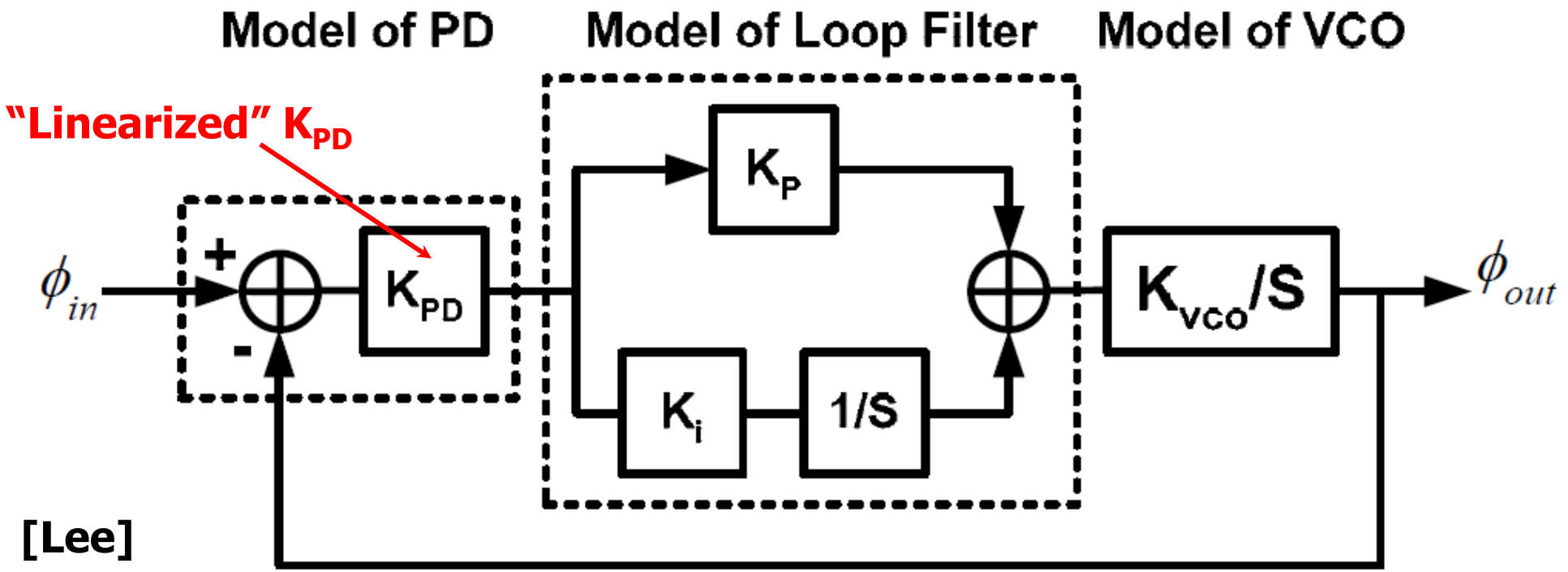
Analog PLL-based CDR

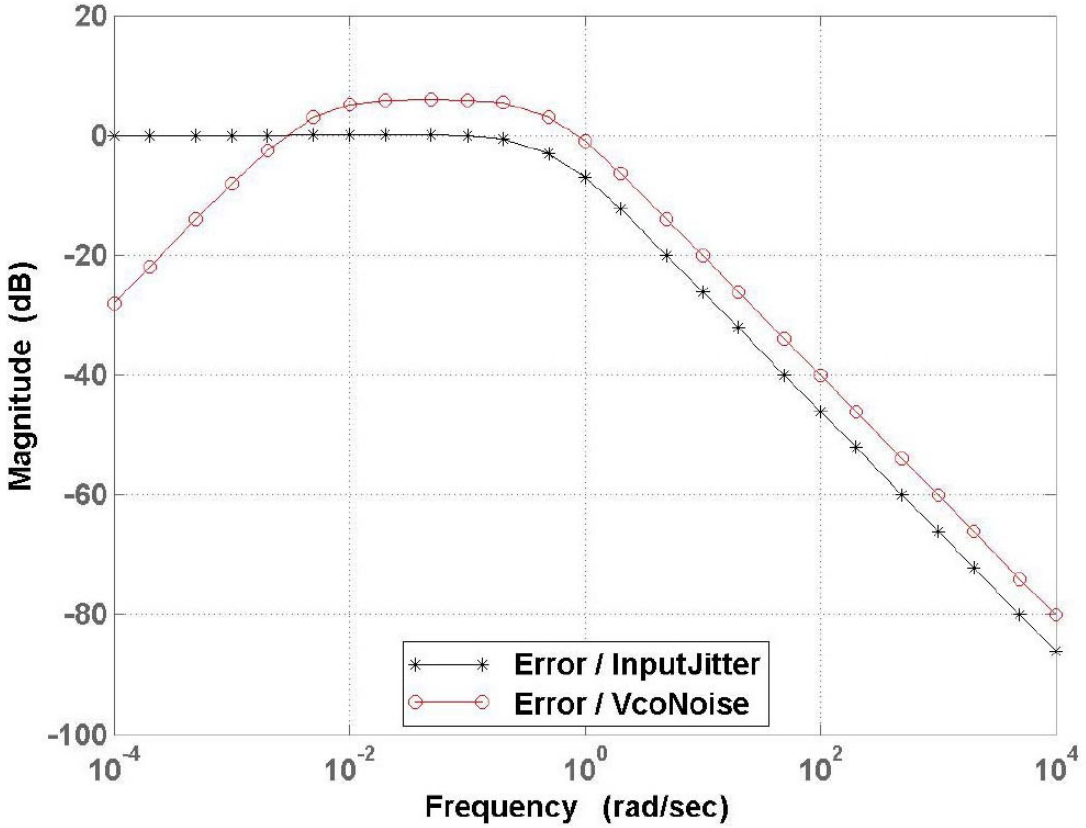


[Lee]

$$\frac{\phi_{out}}{\phi_{in}} = \frac{s \cdot K_P \cdot K_{PD} \cdot K_{VCO} + K_i \cdot K_{PD} \cdot K_{VCO}}{s^2 + s \cdot K_P \cdot K_{PD} \cdot K_{VCO} + K_i \cdot K_{PD} \cdot K_{VCO}}$$

$$K_P = I_C \cdot R \qquad K_i = \frac{I_C}{C} \qquad \omega_n = \sqrt{K_i \cdot K_{PD} \cdot K_{VCO}} \qquad \zeta = \frac{K_P}{K_i} \cdot \frac{\omega_n}{2}$$

Analog PLL-based CDR

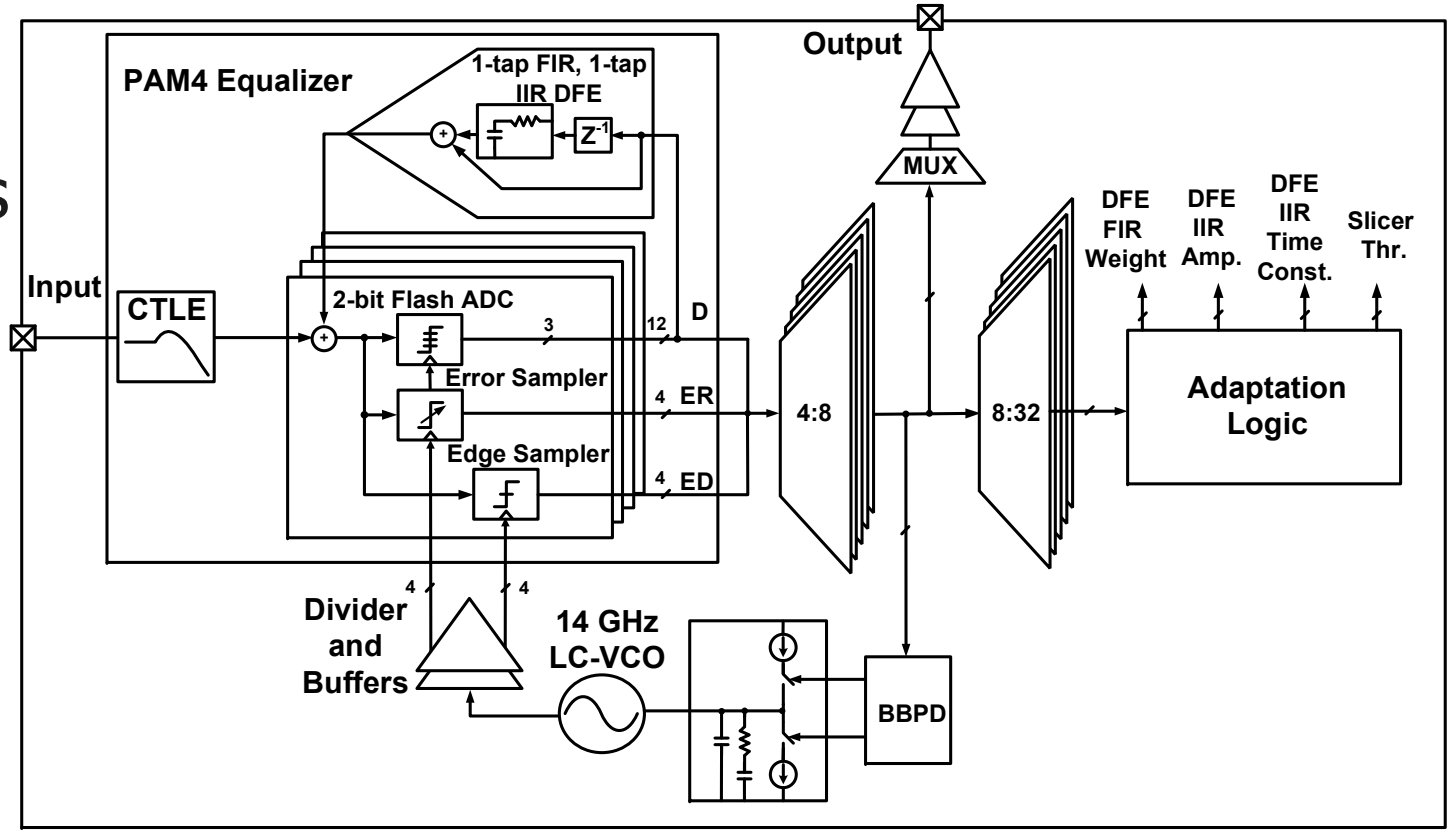


[Lee]

- CDR "bandwidth" will vary with input phase variation amplitude with a non-linear phase detector
- Final performance verification should be done with a time-domain non-linear model

56Gb/s PAM4 Analog PLL-based CDR

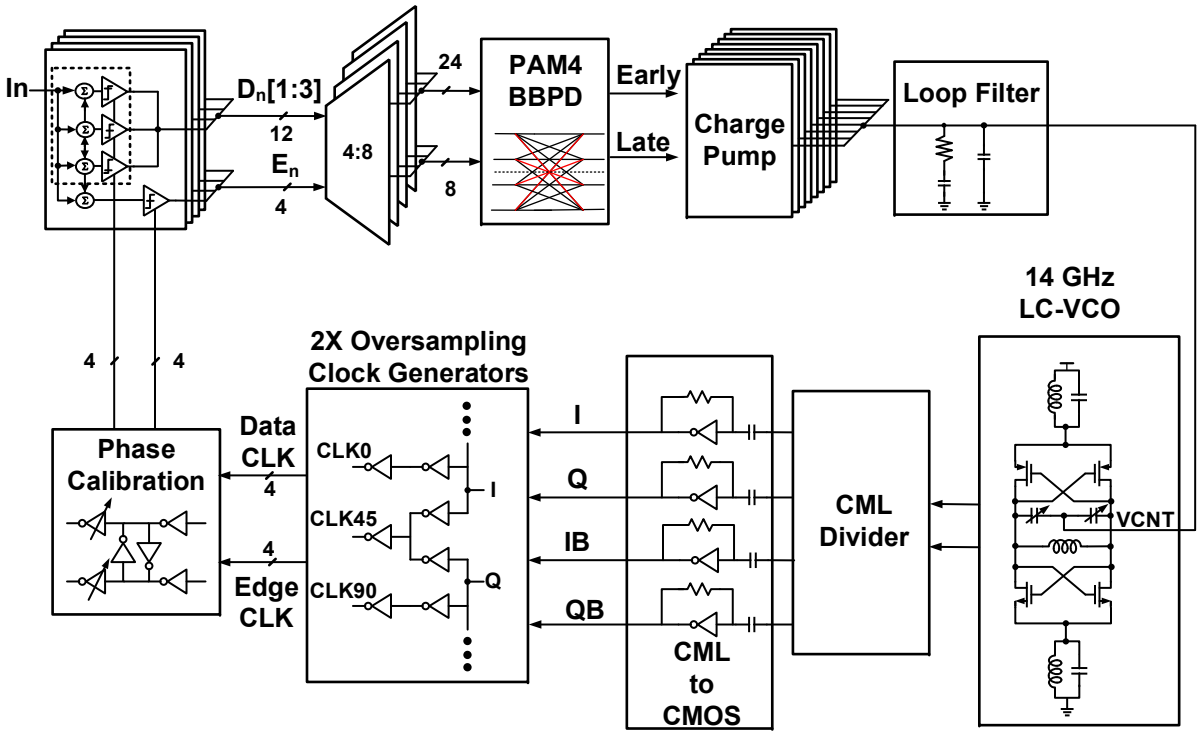
- Quarter-rate architecture
- 3 data samplers for PAM4 detection
- 1 edge sampler for CDR and DFE adaptation
- 1 error sampler for threshold adaptation



[Roshan-Zamir JSSC 2019]

56Gb/s PAM4 Analog PLL-based CDR

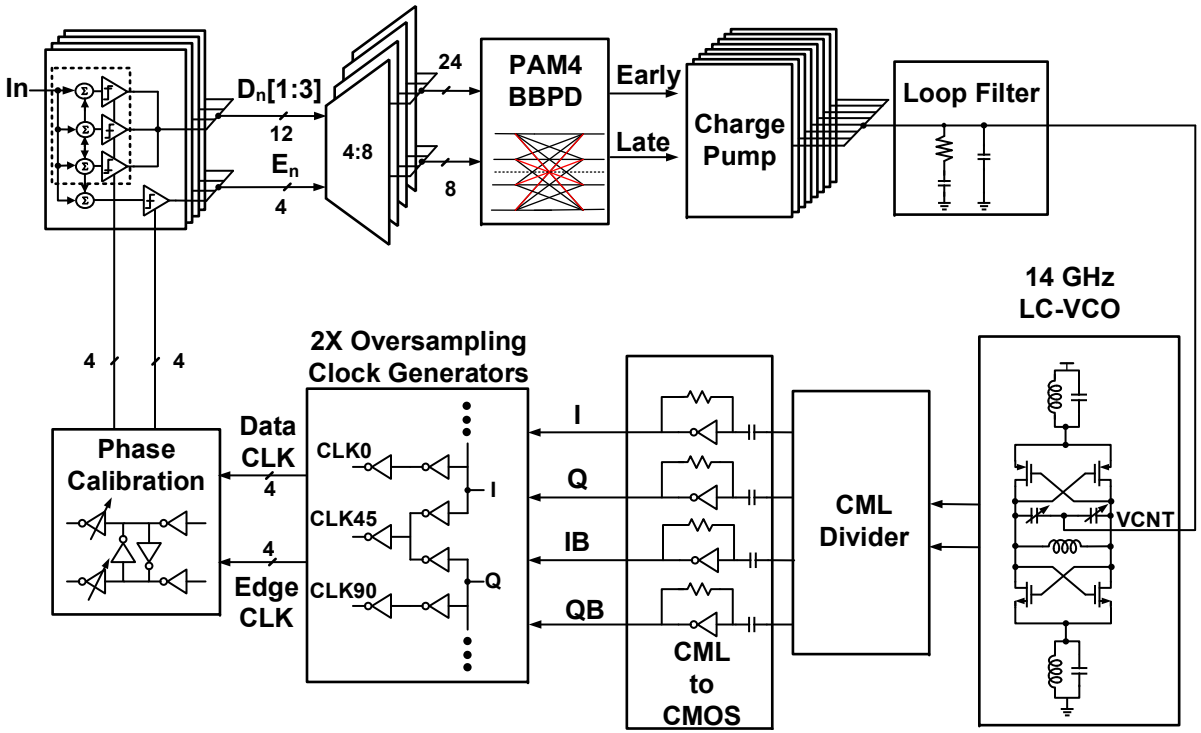
- PLL-based CDR to reduce power consumption
- Bang-bang phase detector works on symmetric PAM4 transitions to minimize detection errors
- Parallel charge pumps minimize logic and loop delay



[Roshan-Zamir JSSC 2019]

56Gb/s PAM4 Analog PLL-based CDR

- LC-VCO w/ additional source LC filter improves phase noise
- 8-phase quarter-rate clock
  - CML divider
  - 2X oversampling clock



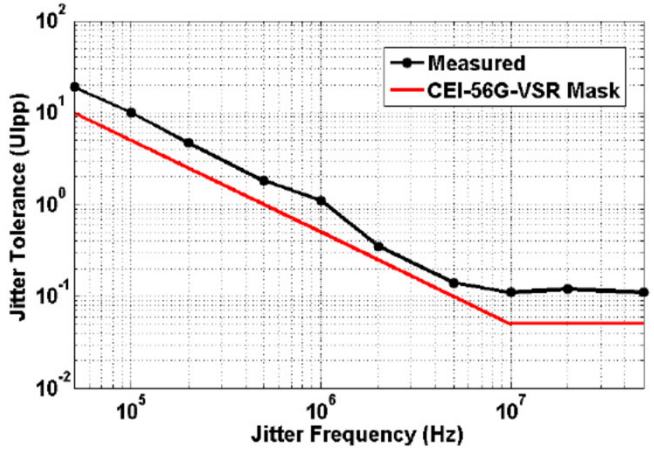


Fig. 16. Measured PAM4 jitter tolerance (BER = 10^{-9}) operating over Channel 2.

[Roshan-Zamir JSSC 2019]

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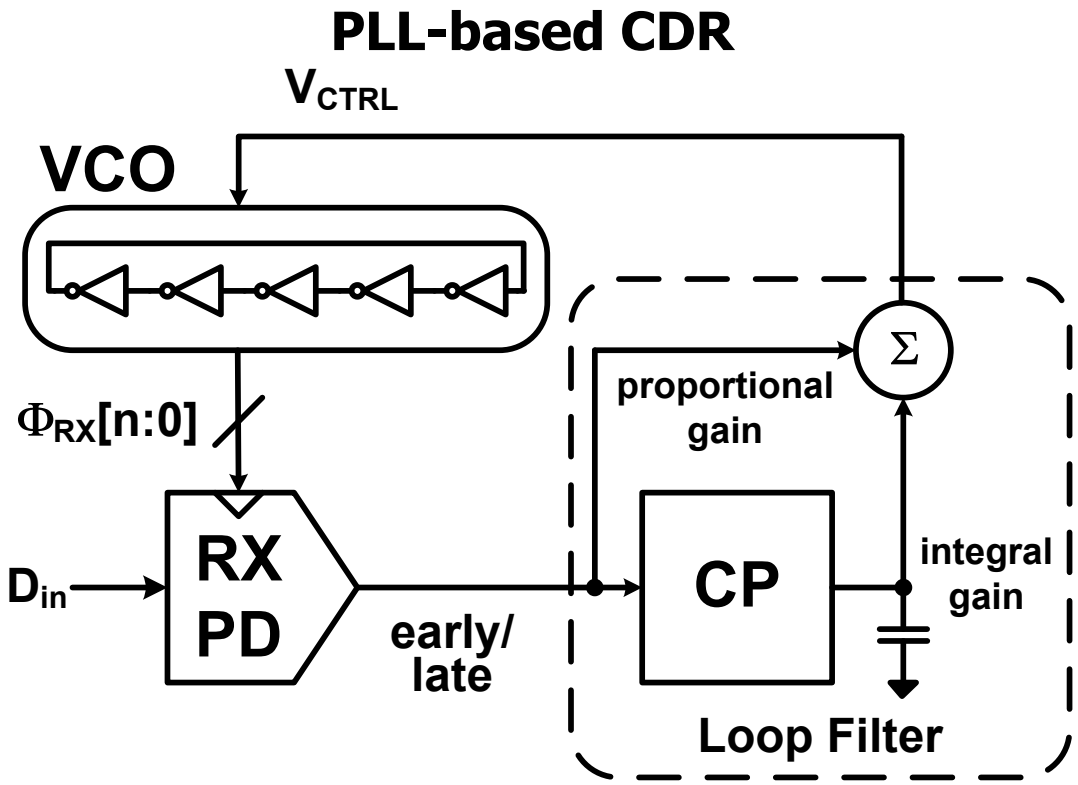
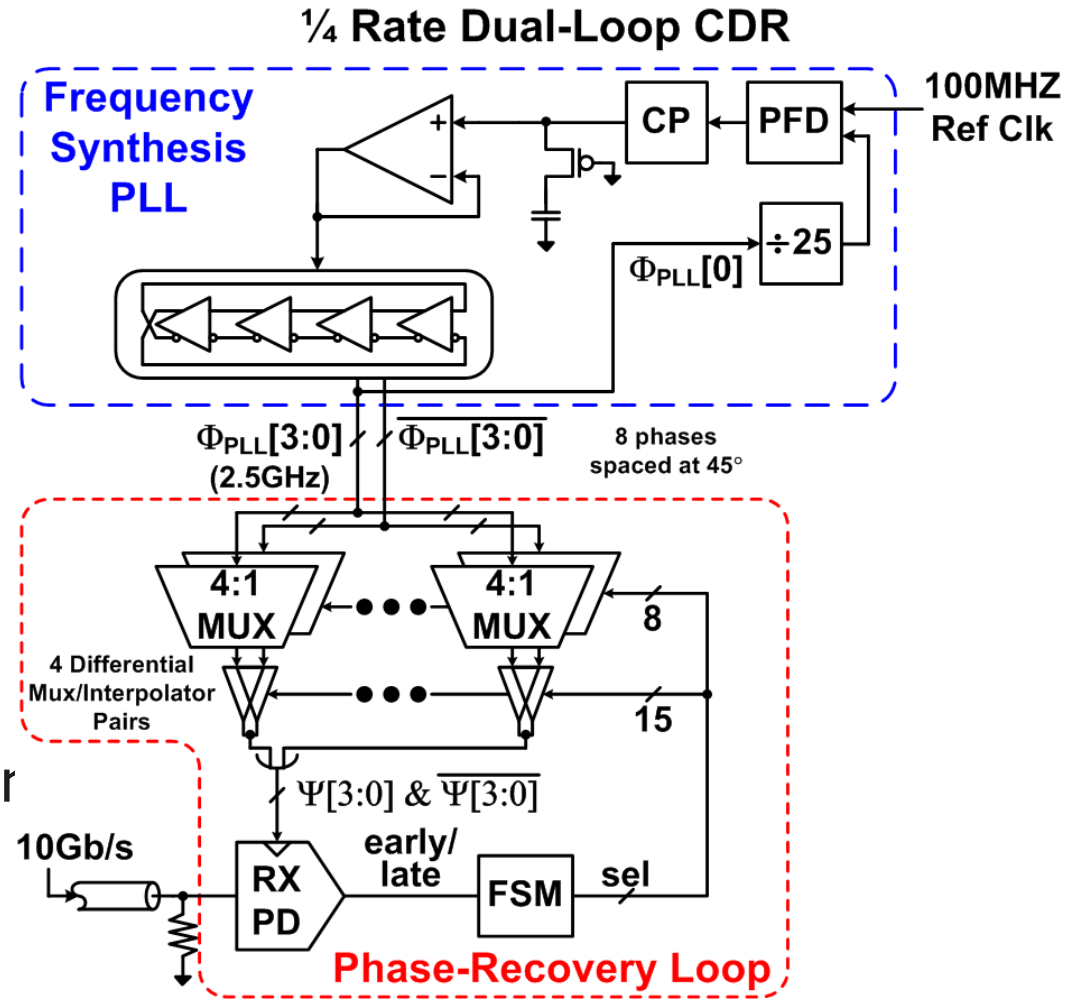
Single-Loop CDR Issues



- Phase detectors have limited frequency acquisition range
  - Results in long lock times or not locking at all
  - Can potentially lock to harmonics of correct clock frequency
- VCO frequency range variation with process, voltage, and temperature can exceed PLL lock range if only a phase detector is employed

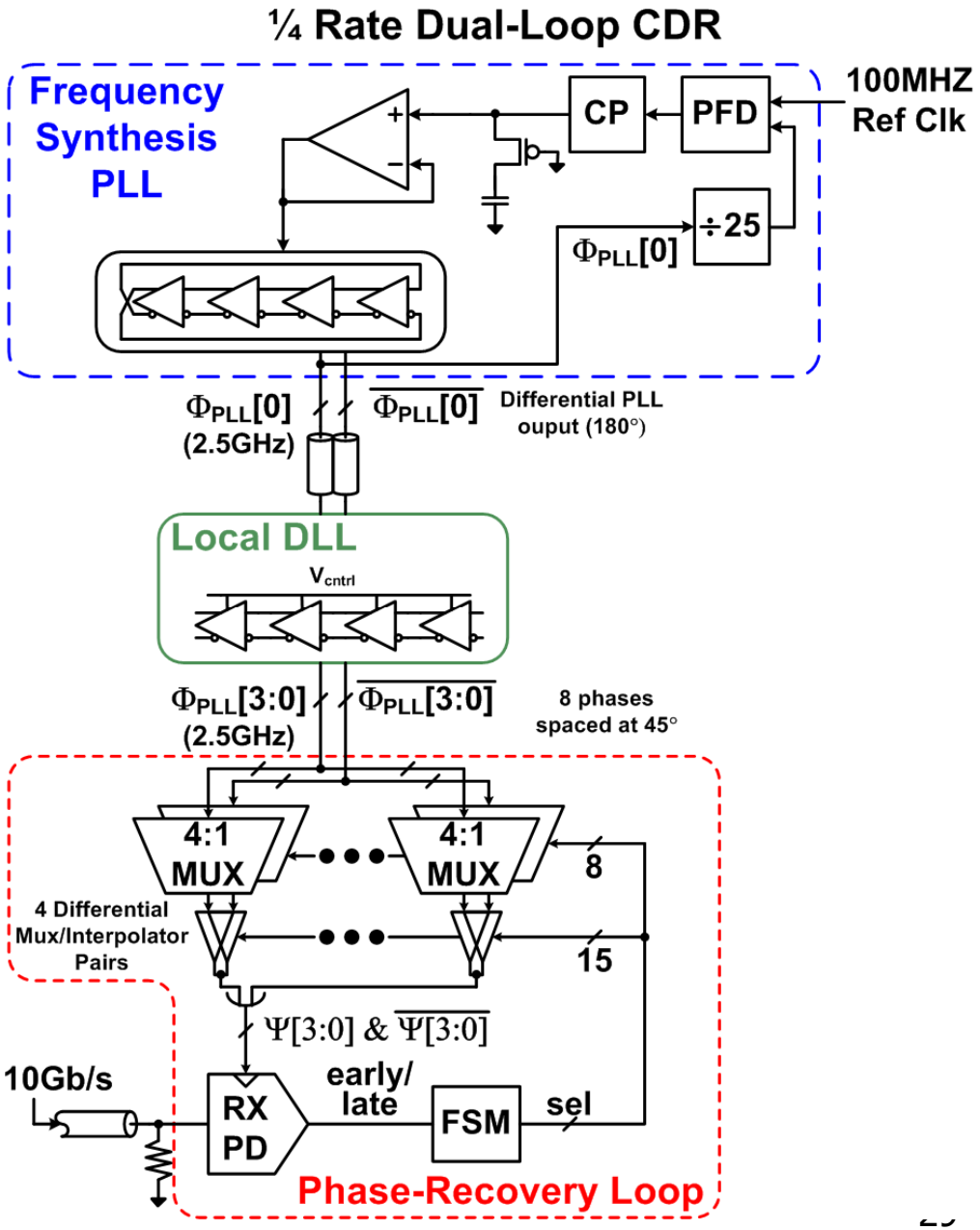
Phase Interpolator (PI) Based CDR

- Frequency synthesis loop can be a global PLL
- Can be difficult to distribute multiple phases long distance
  - Need to preserve phase spacing
  - Clock distribution power increases with phase number
  - If CDR needs more than 4 phases consider local phase generation



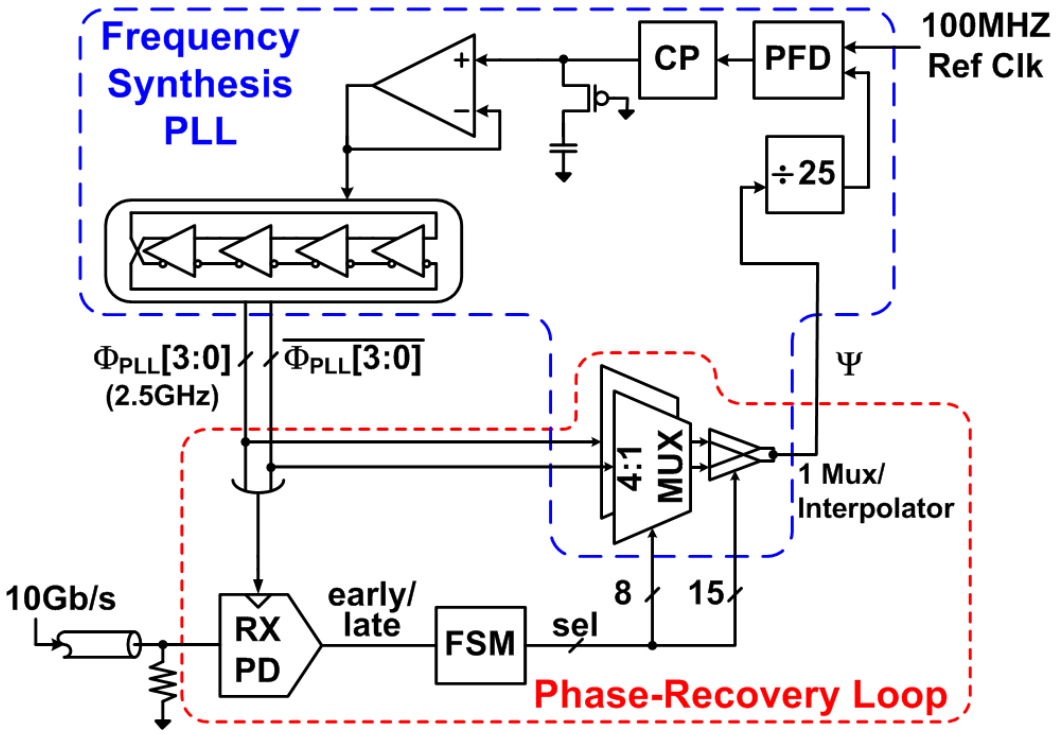
DLL Local Phase Generation

- Only differential clock is distributed from global PLL
- Delay-Locked Loop (DLL) locally generates the multiple clock phases for the phase interpolators
  - DLL can be per-channel or shared by a small number (4)
- Same architecture can be used in a forwarded-clock system
  - Replace frequency synthesis PLL with forwarded-clock signals



Phase Rotator PLL

- Phase interpolators can be expensive in terms of power and area
- Phase rotator PLL places **one** interpolator in PLL feedback to adjust all VCO output phases simultaneously
- Now frequency synthesis and phase recovery loops are coupled
  - Need PLL bandwidth greater than phase loop
    - Useful in filtering VCO noise



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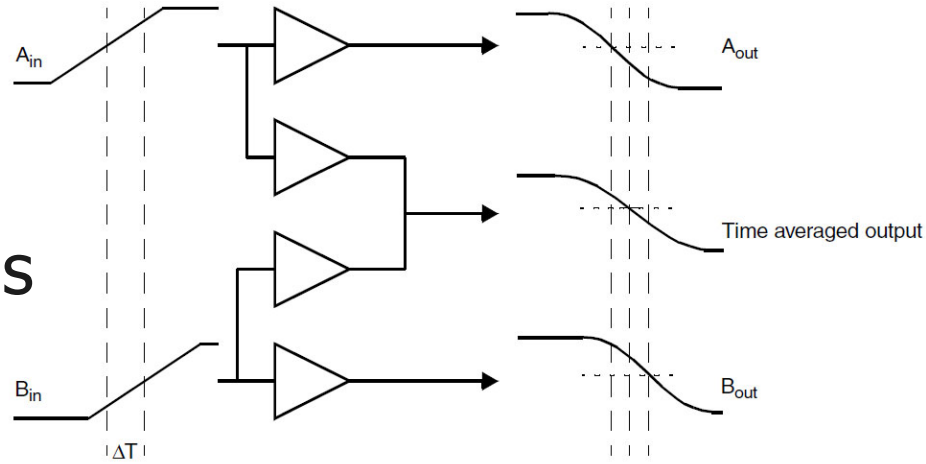
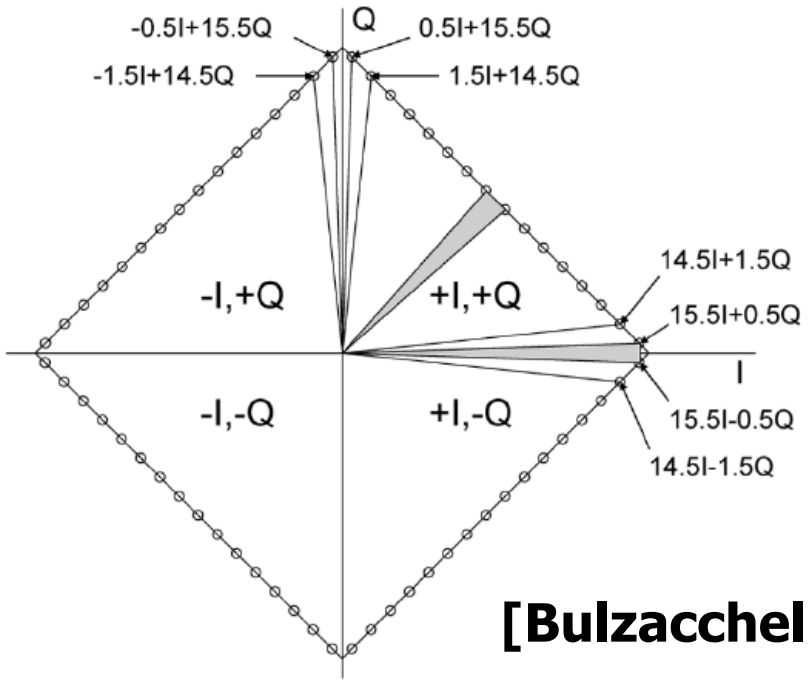
Phase Interpolators

- Phase interpolators realize digital-to-phase conversion (DPC)
- Produce an output clock that is a weighted sum of two input clock phases
- Common circuit structures
  - Tail current summation interpolation
  - Voltage-mode interpolation
- Interpolator code mapping techniques
  - Sinusoidal
  - Linear

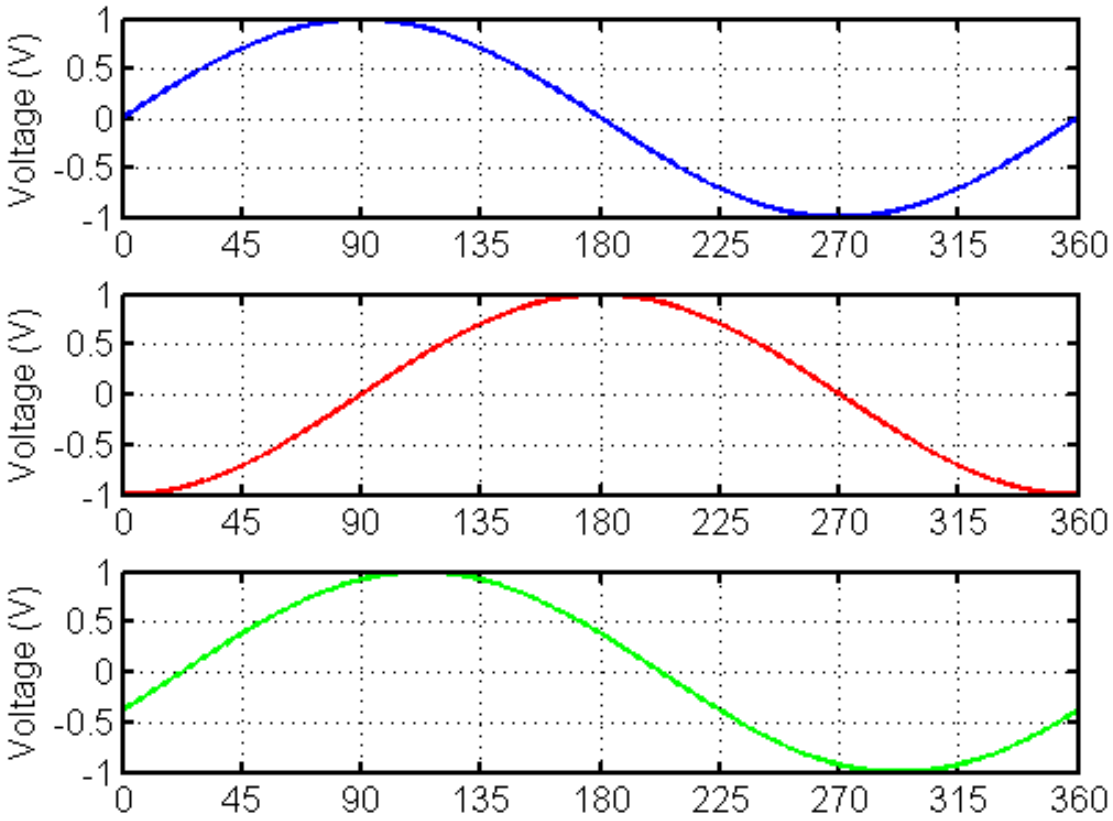
[Weinlader]



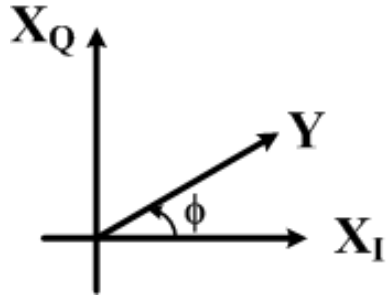


[Bulzacchelli]

Sinusoidal Phase Interpolation



$$X_I = A\sin(\omega t)$$



$$X_Q = A\sin(\omega t - \pi/2) = -A\cos(\omega t)$$

$$Y = A\sin(\omega t - \phi)$$

$$= A\cos(\phi)\sin(\omega t) - A\sin(\phi)\cos(\omega t) \quad \left(0 \le \phi \le \frac{\pi}{2}\right)$$

$$= \cos(\phi)X_I + \sin(\phi)X_Q = a_1 X_I + a_2 X_Q$$

- Arbitrary phase shift can be generated with linear summation of I/Q clock signal

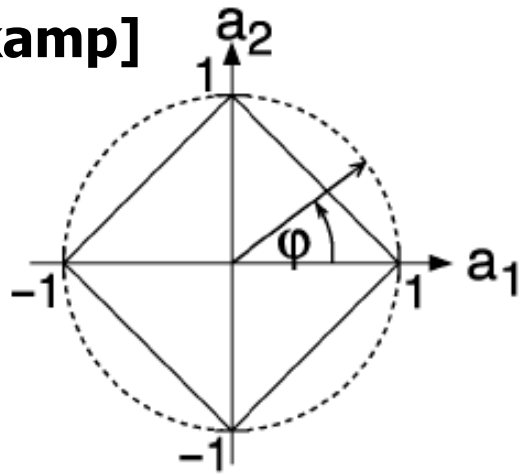
$$Y = A\sin(\omega t - \phi) = a_1 X_1 + a_2 X_Q$$

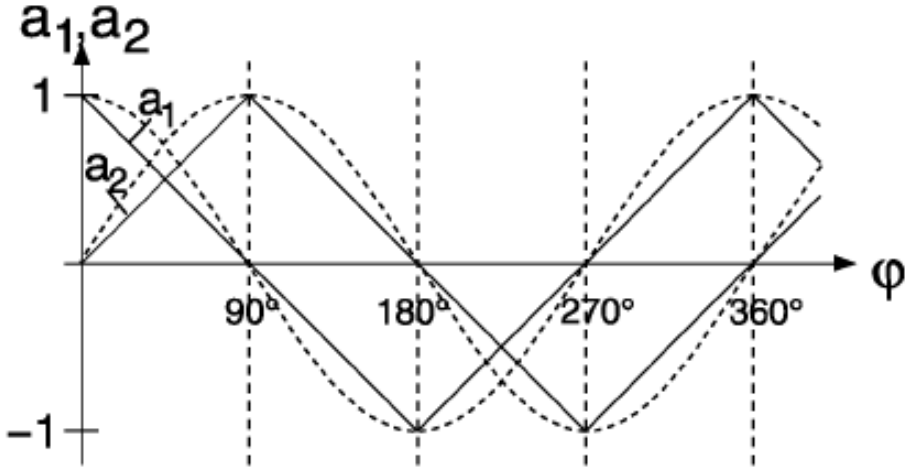
$$\textbf{where } a_1 = \cos(\phi) \textbf{ and } a_2 = \sin(\phi)$$

$$a_1^2 + a_2^2 = 1$$

Sinusoidal vs Linear Phase Interpolation

[Kreienkamp]



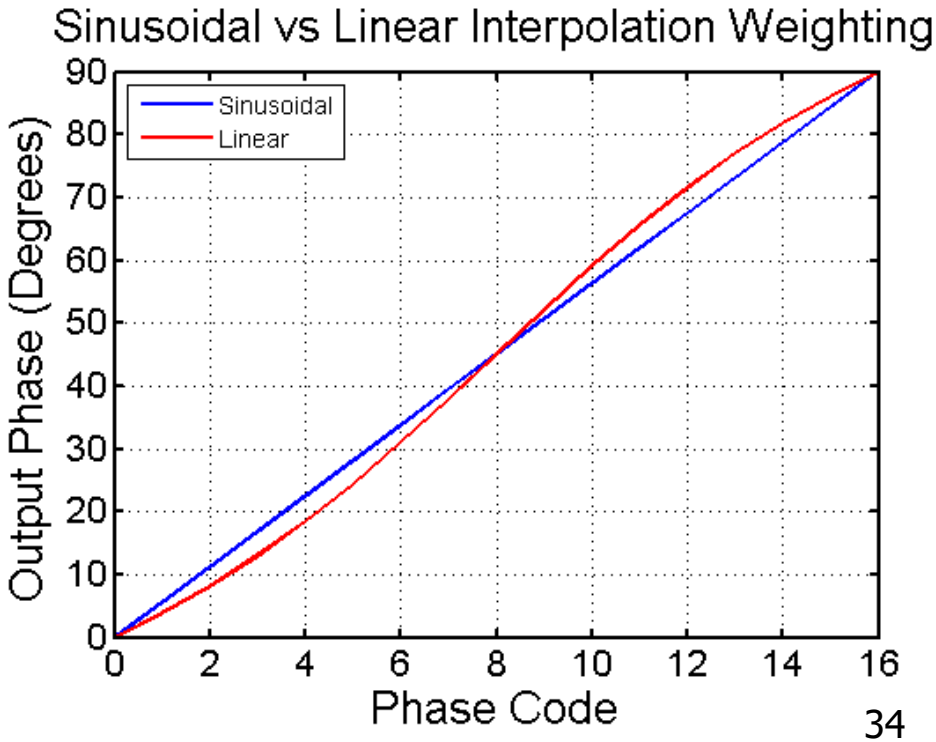


- It can be difficult to generate a circuit that implements sinusoidal weighting

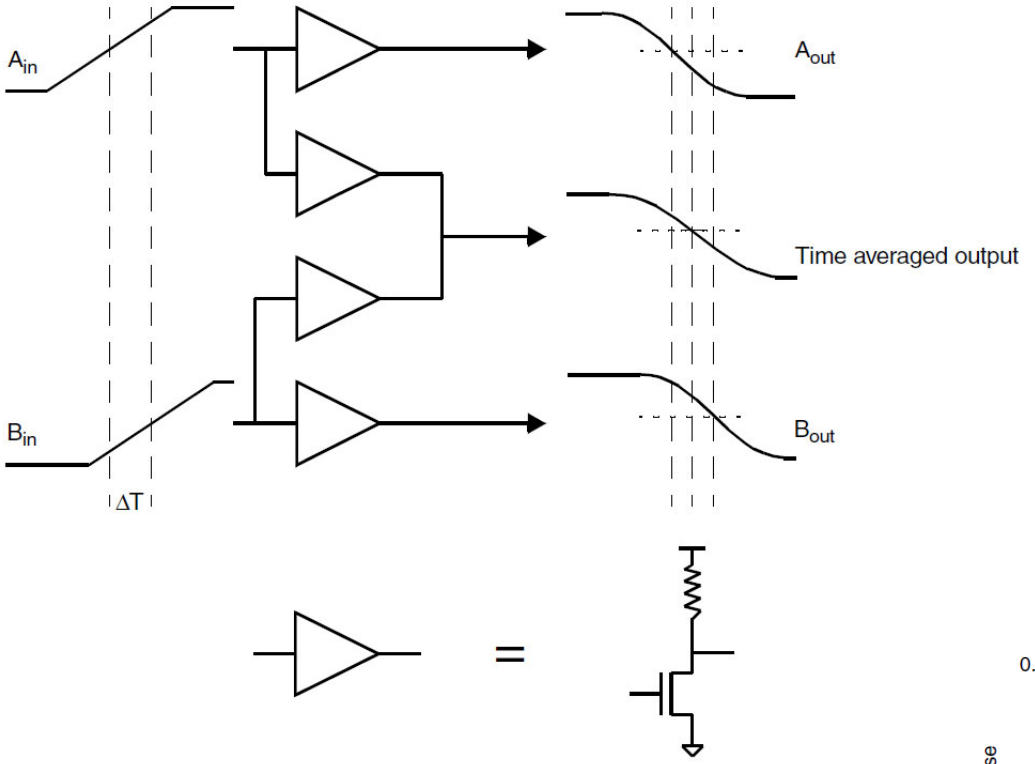
$$a_1^2 + a_2^2 = 1$$

- In practice, a linear weighting is often used

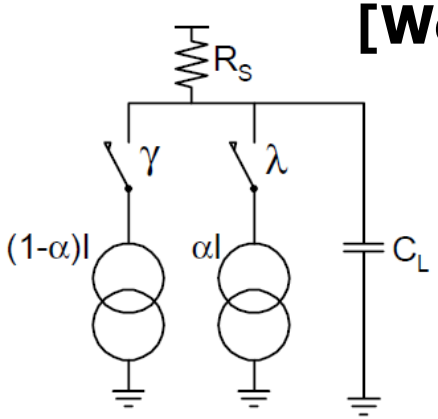
$$a_1 + a_2 = 1$$



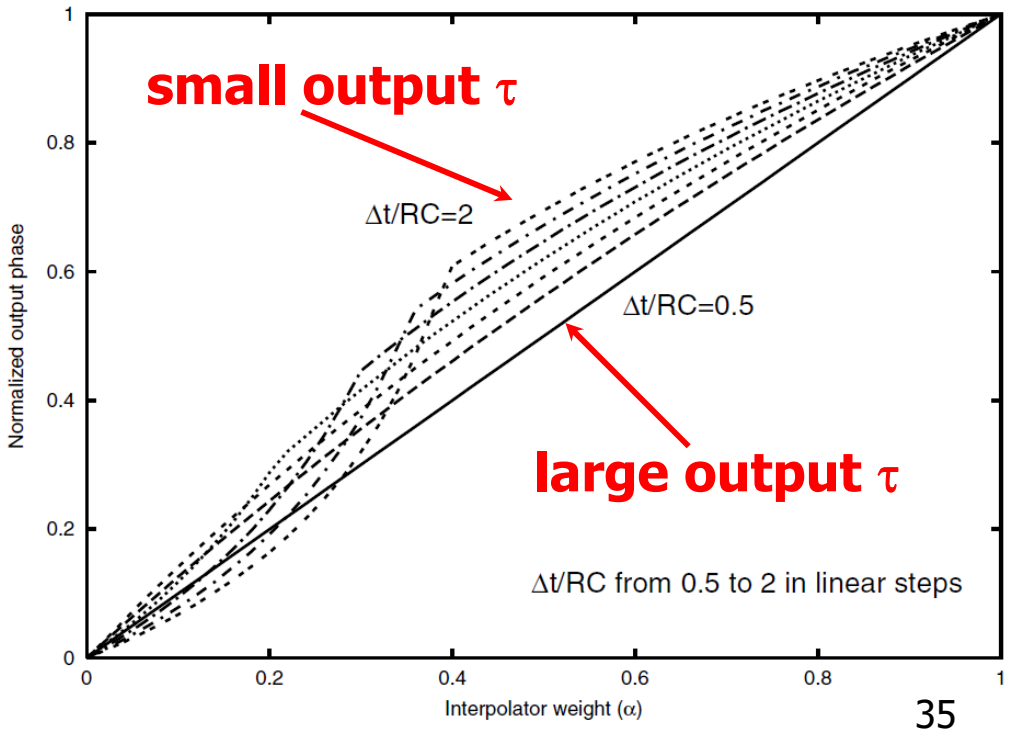
Phase Interpolator Model



[Weinlader]



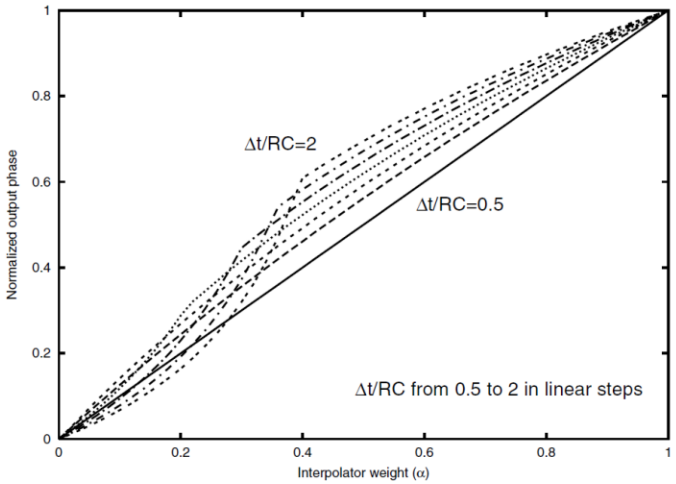
w/ ideal step inputs (worst case)



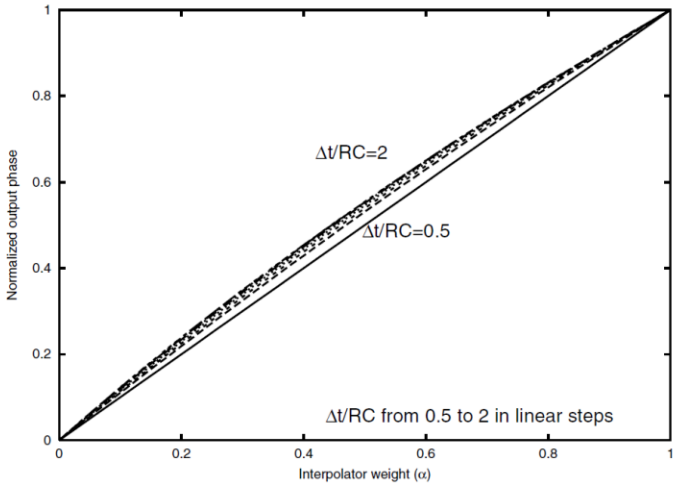
- Interpolation linearity is a function of the phase spacing, Δt, to output time constant, RC, ratio
- Important that interpolator output time constant is not too small (fast) for phase mixing quality

Phase Interpolator Model

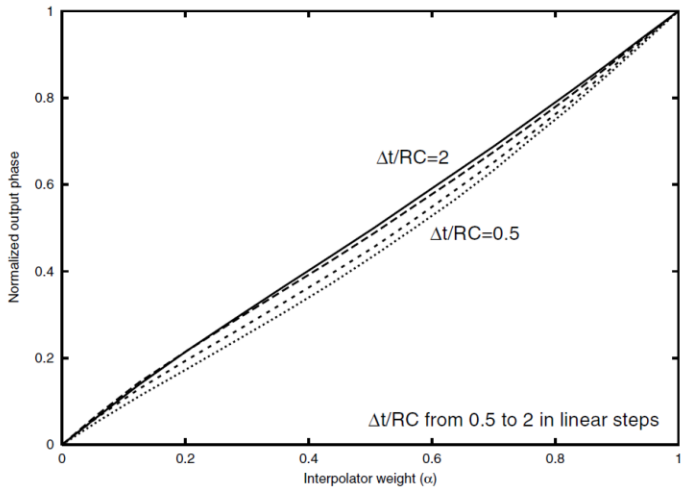
w/ ideal step inputs



w/ finite input transition time



Spice simulation



w/ ideal step inputs:

$$V_o(t) = V_{cc} + R \cdot I \cdot \left[(1-\alpha) \cdot u(t) \cdot \left(e^{-\frac{t}{RC}} - 1 \right) + \alpha \cdot u(t-\Delta t) \cdot \left(e^{-\frac{t-\Delta t}{RC}} - 1 \right) \right]$$

w/ finite input transition time:

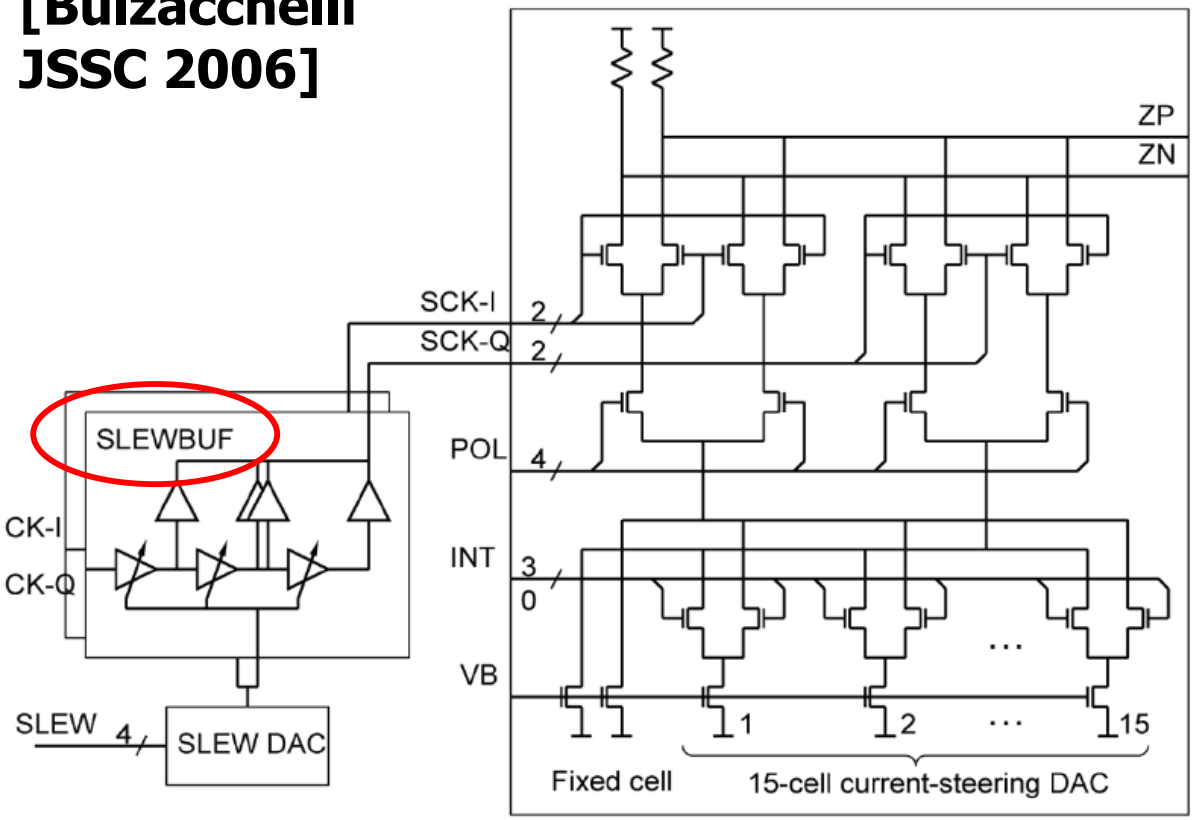
$$V_o(t) = V_{cc} + (1-\alpha) \cdot \frac{I_{max} \cdot t}{\Delta t} \cdot R \cdot \alpha \cdot [u(t) - u(t-\Delta t)] \cdot \left(e^{-\frac{t}{RC}} - 1 \right) +$$

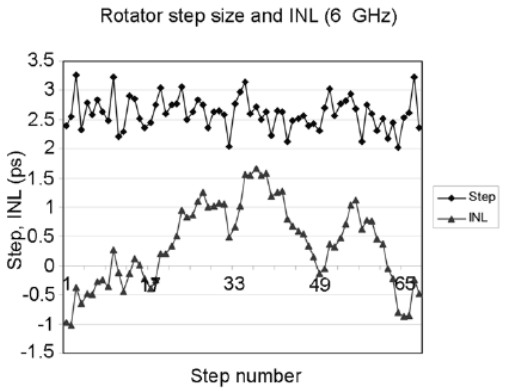
$$\alpha \cdot \frac{I_{max} \cdot t}{\tau_r} \cdot R \cdot [u(t-\Delta t) - u(t-3\Delta t)] \cdot \left(e^{-\frac{t-\Delta t}{RC}} - 1 \right).$$

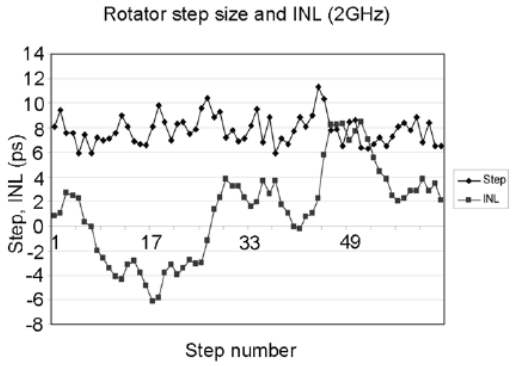
For more details see D. Weinlader's Stanford PhD thesis

Tail-Current Summation PI

[Bulzacchelli JSSC 2006]



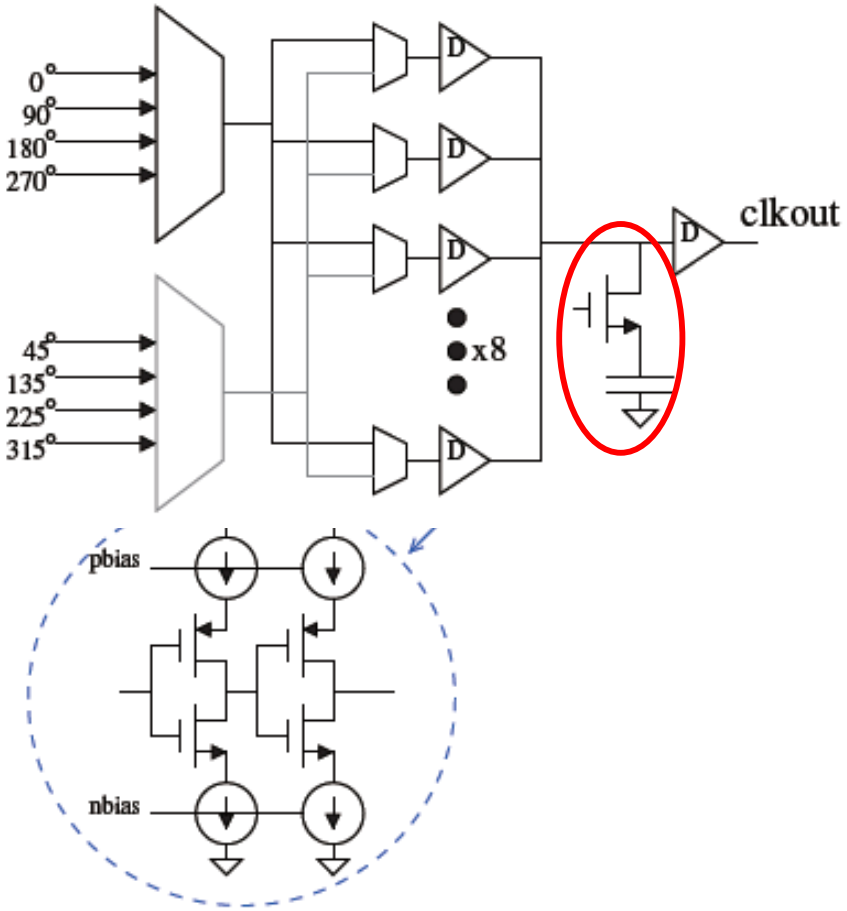


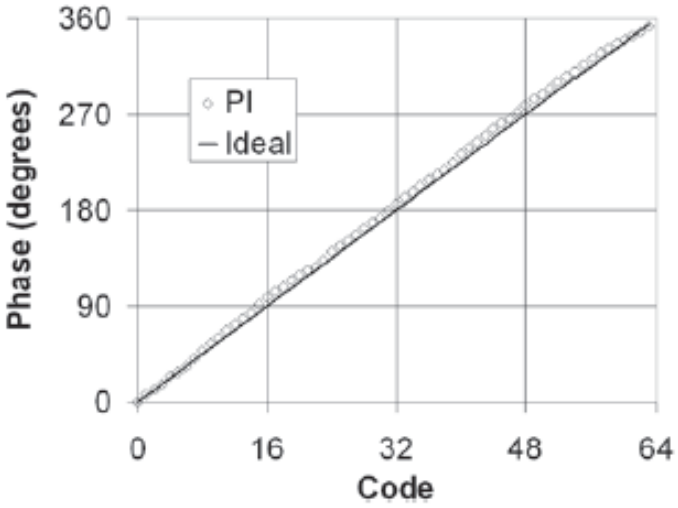


- Control of I/Q polarity allows for full 360° phase rotation with phase step determined by resolution of weighting DAC
- For linearity over a wide frequency range, important to control either input or output time constant (slew rate)

Voltage-Mode Summation PI

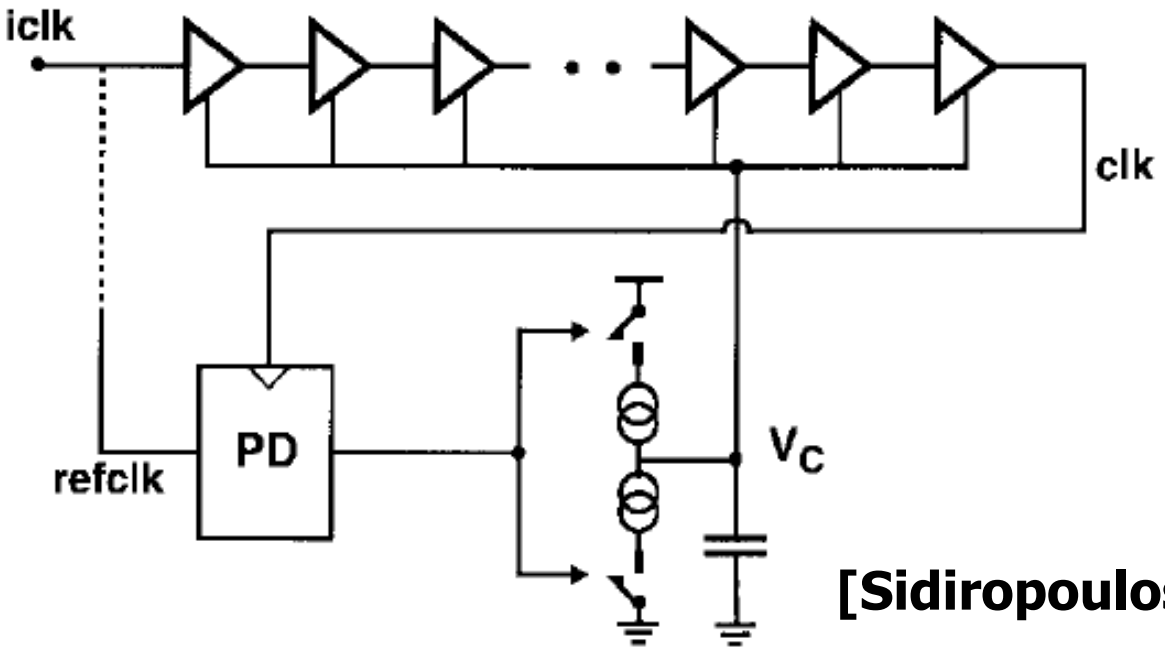
[Joshi VLSI Symp 2009]





- For linearity over a wide frequency range, important to control either input or output time constant (slew rate)

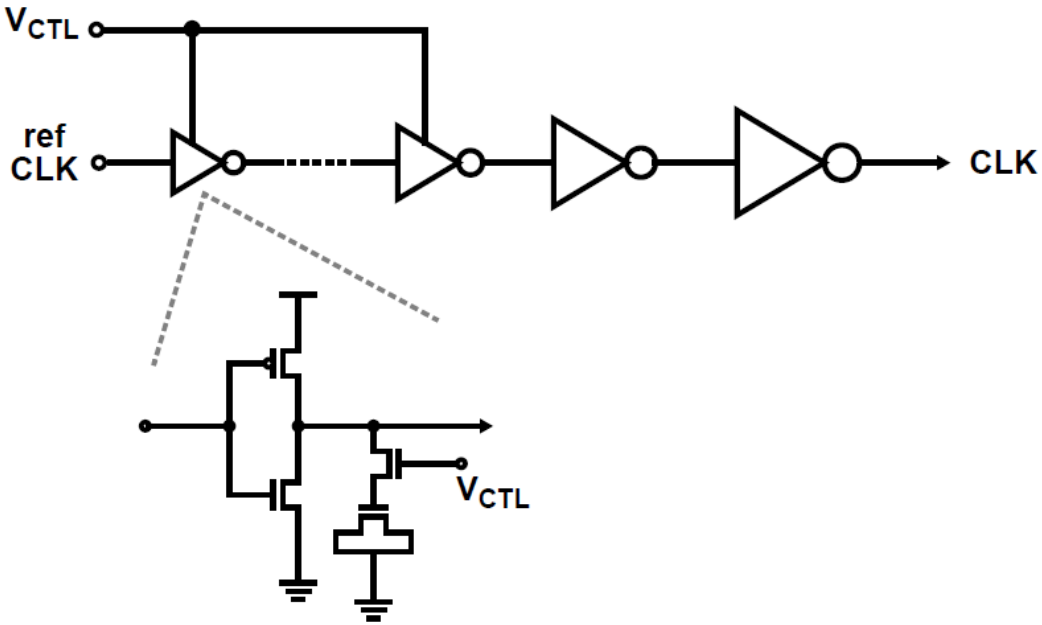
Delay-Locked Loop (DLL)

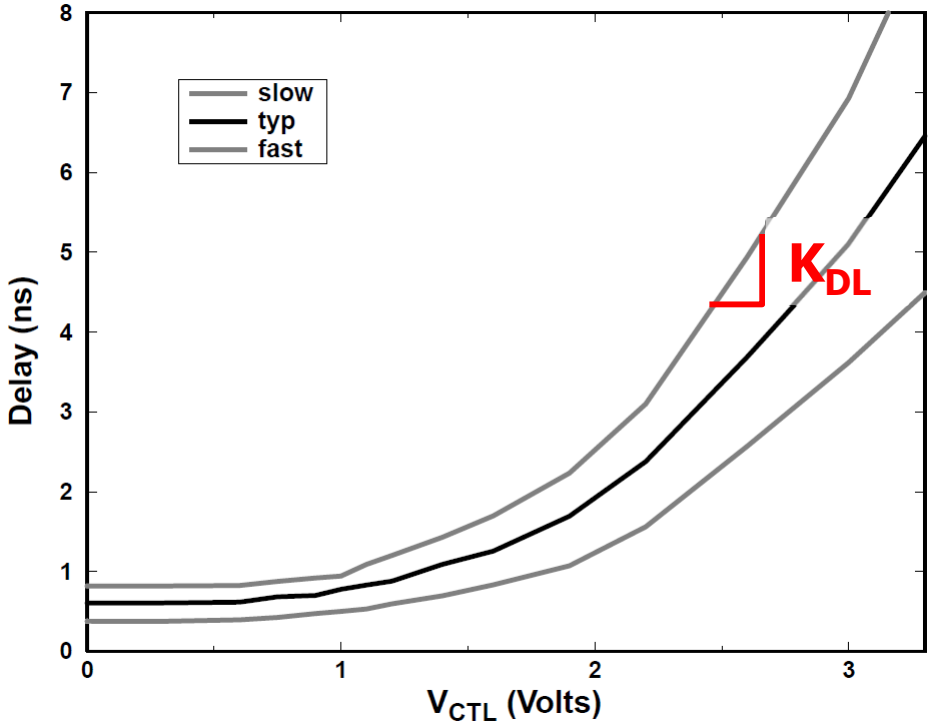


[Sidiropoulos JSSC 1997]

- DLLs lock delay of a voltage-controlled delay line (VCDL)
- Typically lock the delay to 1 or ½ input clock cycles
  - If locking to ½ clock cycle the DLL is sensitive to clock duty cycle
- DLL does not self-generate the output clock, only delays the input clock

Voltage-Controlled Delay Line

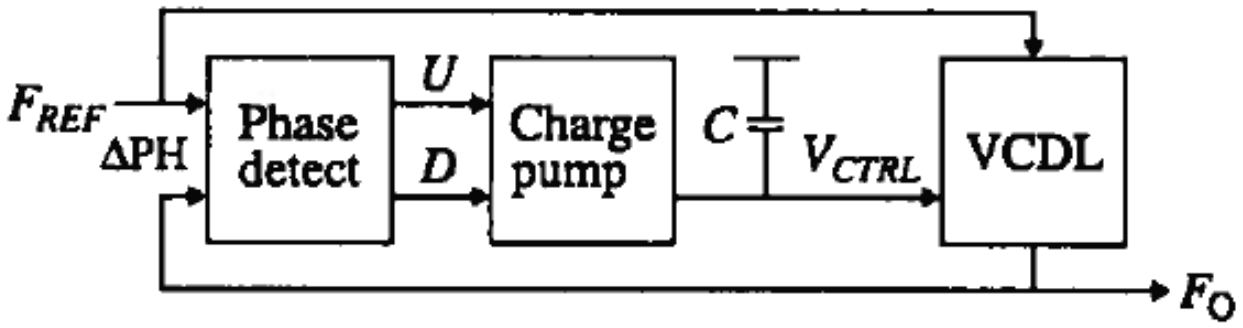




[Sidiropoulos]

DLL Delay Transfer Function

[Maneatis]



$$D_O(s) = (D_I(s) - D_O(s)) \cdot F_{\mathrm{REF}} \cdot \frac{I_{CH}}{sC_1} \cdot K_{DL}$$

$$\frac{D_O(s)}{D_I(s)} = \frac{1}{1 + s/\omega_N}$$

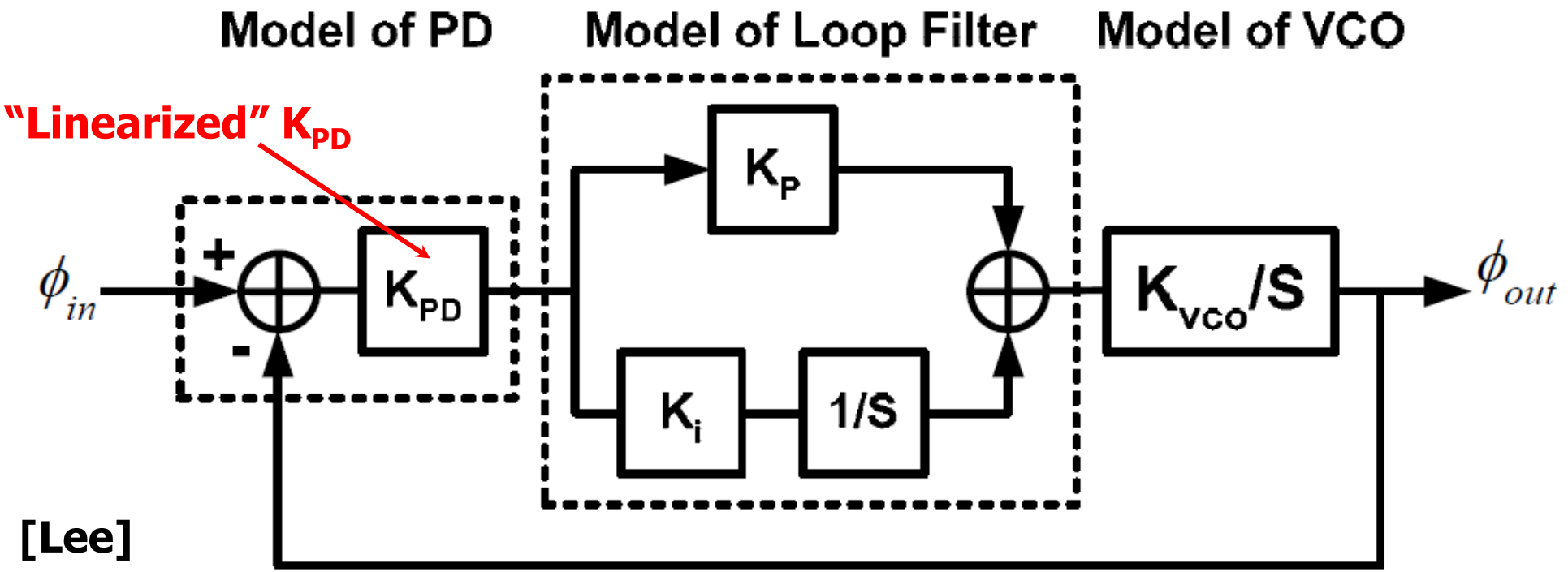
$$\omega_N = I_{CH} \cdot K_{DL} \cdot F_{\mathrm{REF}} \cdot \frac{1}{C_1}$$

- First-order loop as delay line doesn't introduce a (low-frequency) pole
- The delay between reference and feedback signal is low-pass filtered
- Unconditionally stable as long as continuous-time approximation holds, i.e. $\omega_n < \omega_{ref}/10$

Agenda

- CDR overview
- CDR phase detectors
- Single-loop analog PLL-based CDR
- Dual-loop CDRs
- Phase interpolators
- CDR jitter properties
  - Jitter transfer
  - Jitter generation
  - Jitter tolerance

CDR Jitter Model

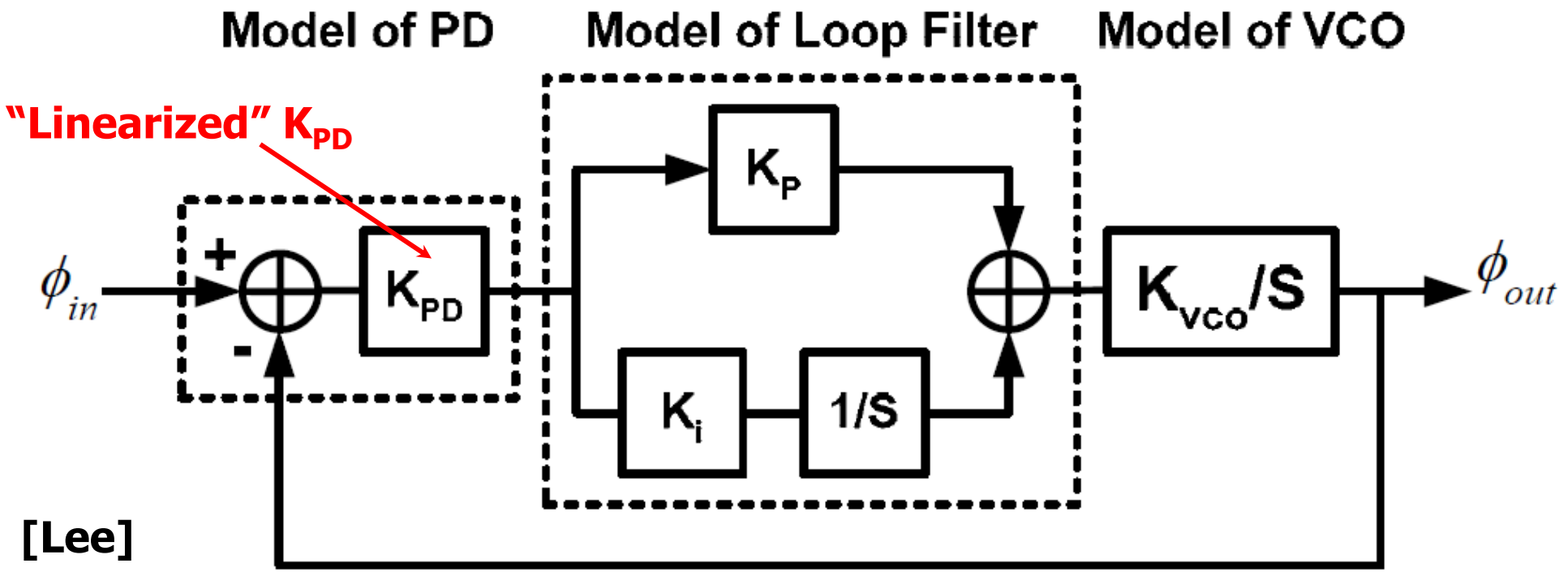


[Lee]

$$\frac{\phi_{out}}{\phi_{in}} = \frac{s \cdot K_P \cdot K_{PD} \cdot K_{VCO} + K_i \cdot K_{PD} \cdot K_{VCO}}{s^2 + s \cdot K_P \cdot K_{PD} \cdot K_{VCO} + K_i \cdot K_{PD} \cdot K_{VCO}}$$

$$K_P = I_C \cdot R \qquad K_i = \frac{I_C}{C} \qquad \omega_n = \sqrt{K_i \cdot K_{PD} \cdot K_{VCO}} \qquad \zeta = \frac{K_P}{K_i} \cdot \frac{\omega_n}{2}$$

Jitter Transfer

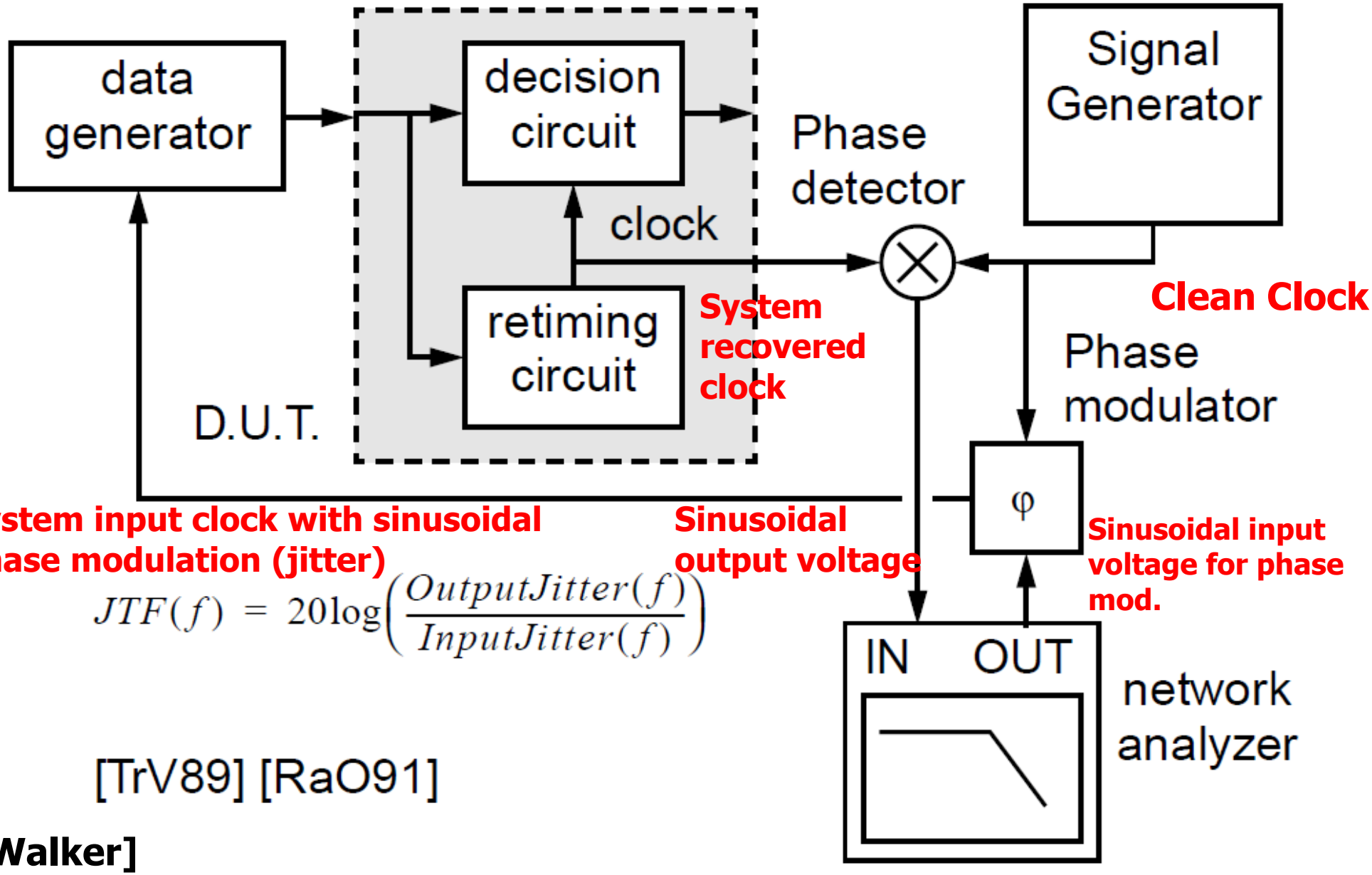


[Lee]

- Jitter transfer is how much input jitter "transfers" to the output
  - If the PLL has any peaking in the phase transfer function, this jitter can actually be amplified

$$\frac{\phi_{out}}{\phi_{in}} = \frac{s \cdot K_P \cdot K_{PD} \cdot K_{VCO} + K_i \cdot K_{PD} \cdot K_{VCO}}{s^2 + s \cdot K_P \cdot K_{PD} \cdot K_{VCO} + K_i \cdot K_{PD} \cdot K_{VCO}}$$

Jitter Transfer Measurement

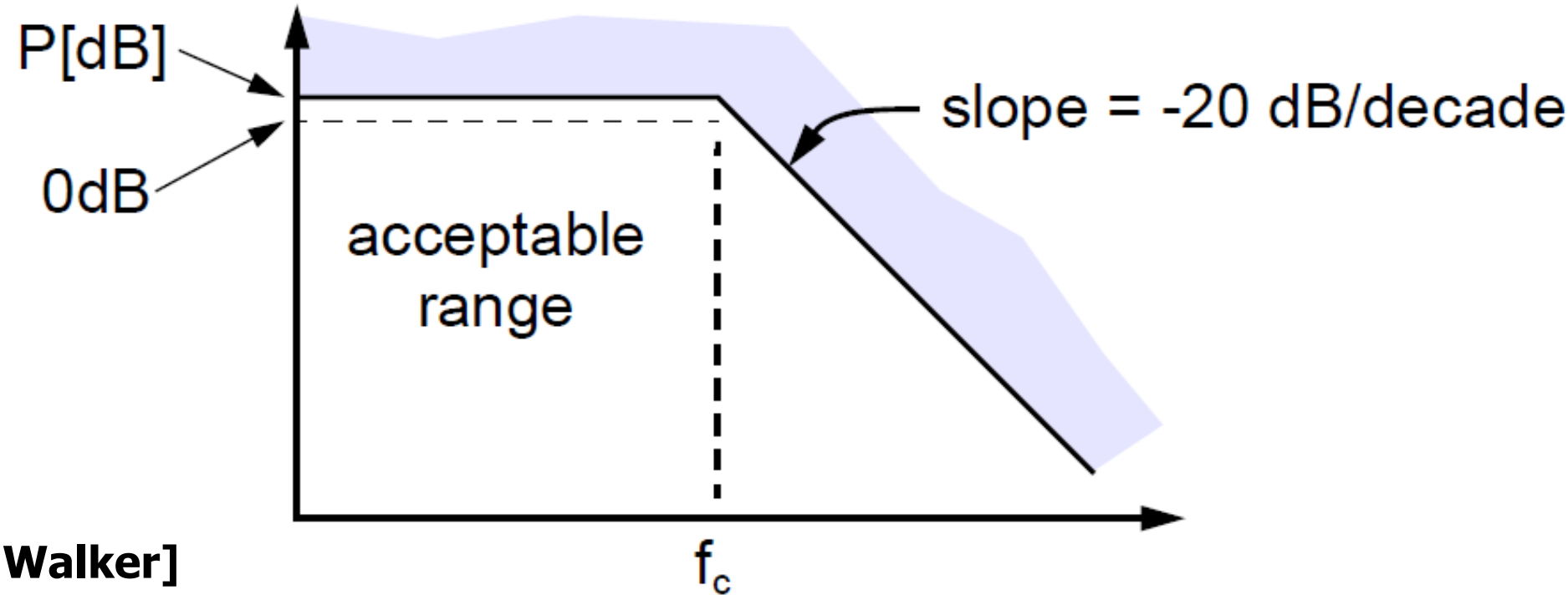


$$JTF(f) = 20\log\left(\frac{OutputJitter(f)}{InputJitter(f)}\right)$$

[TrV89] [RaO91]

[Walker]

Jitter Transfer Specification



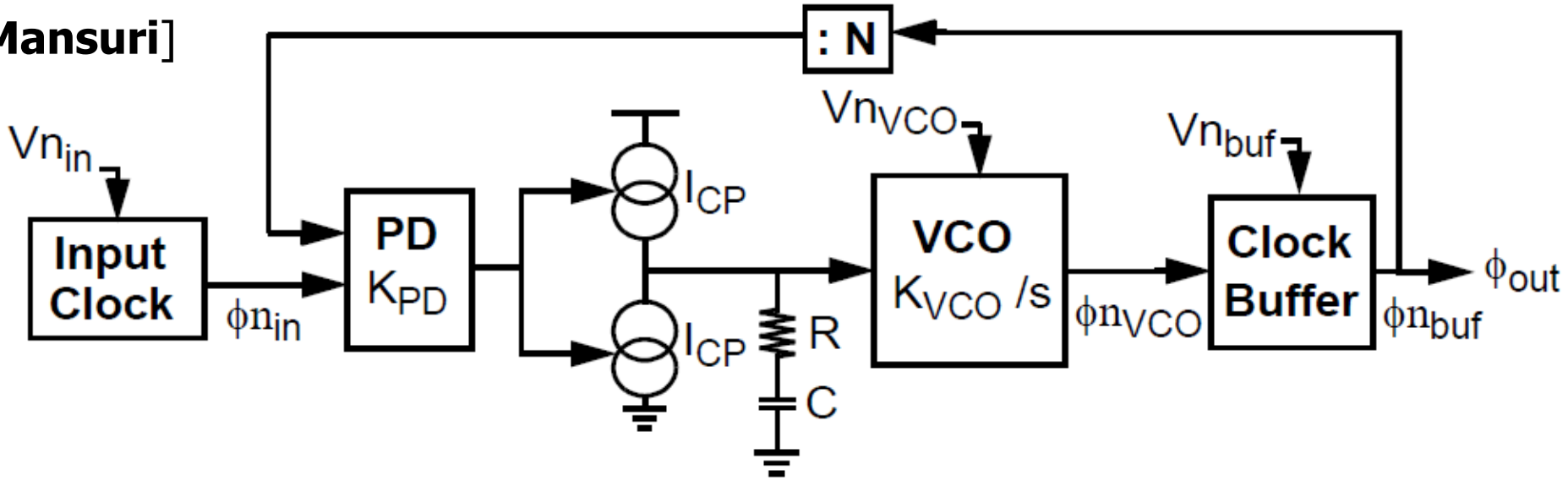
[Walker]

Data Rate	f_c[kHz]	P[dB]
155 Mb	130	0.1
622 Mb	500	0.1
2.488 Gb	2000	0.1

This specification is intended to control jitter peaking in long repeater chains

Jitter Generation

[**Mansuri**]



- Jitter generation is how much jitter the CDR "generates"
  - Assumed to be dominated by VCO
- Assumes jitter-free serial data input

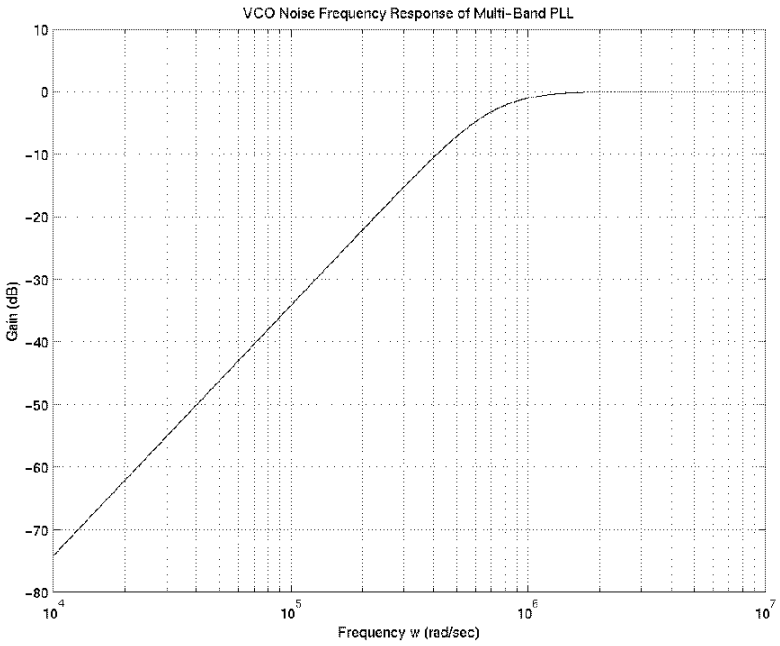
VCO Phase Noise: $$H_{n_{VCO}}(s) = \frac{\phi_{out}}{\phi_{n_{VCO}}} = \frac{s^2}{s^2 + \left(\frac{K_{Loop}}{N}\right)RCs + \frac{K_{Loop}}{N}} = \frac{s^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

For CDR, N should be 1

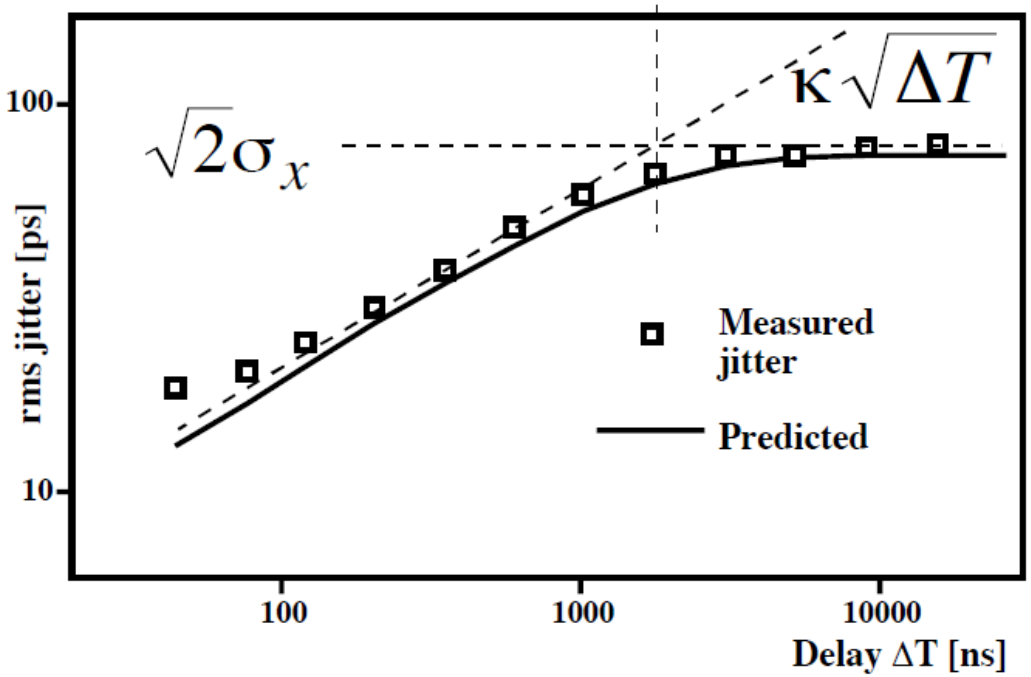
Jitter Generation

High-Pass Transfer Function

$$20\log_{10}\left|\frac{\theta_{out}(s)}{\theta_{vcon}(s)}\right|$$



Jitter accumulates up to time ∝ 1/PLL bandwidth



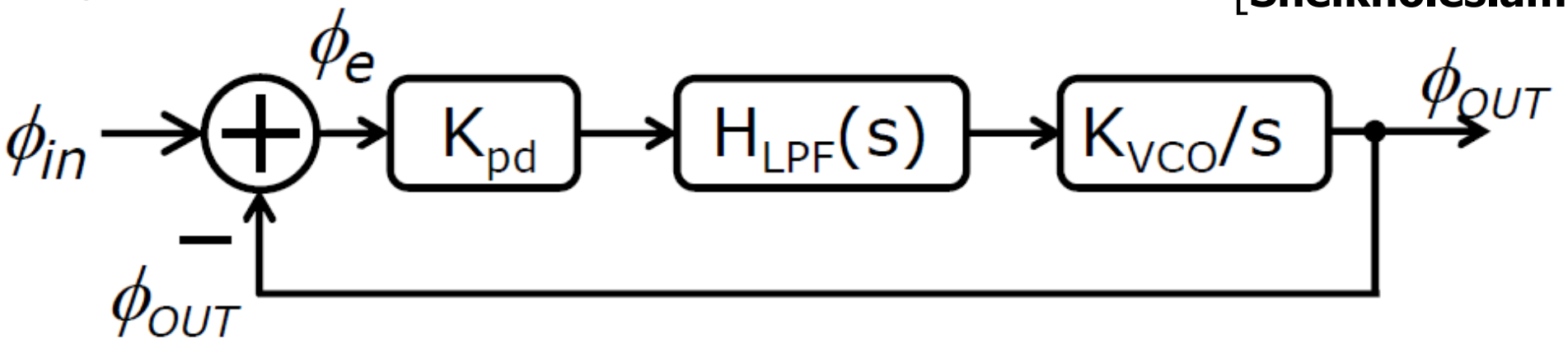
[**McNeill**]

- SONET specification:
  - rms output jitter ≤ 0.01 UI

Jitter Tolerance

- How much sinusoidal jitter can the CDR "tolerate" and still achieve a given BER?

[**Sheikholeslami**]

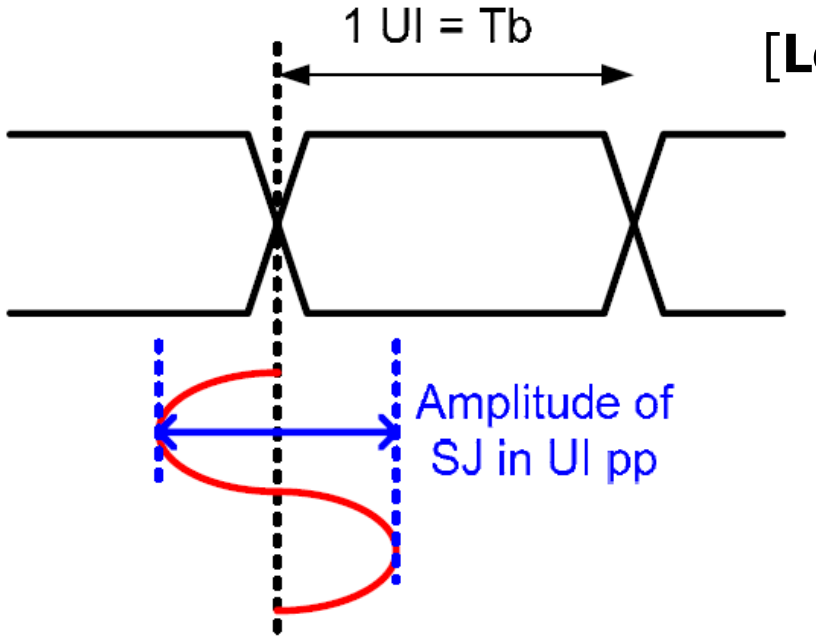


Maximum tolerable ϕ_e

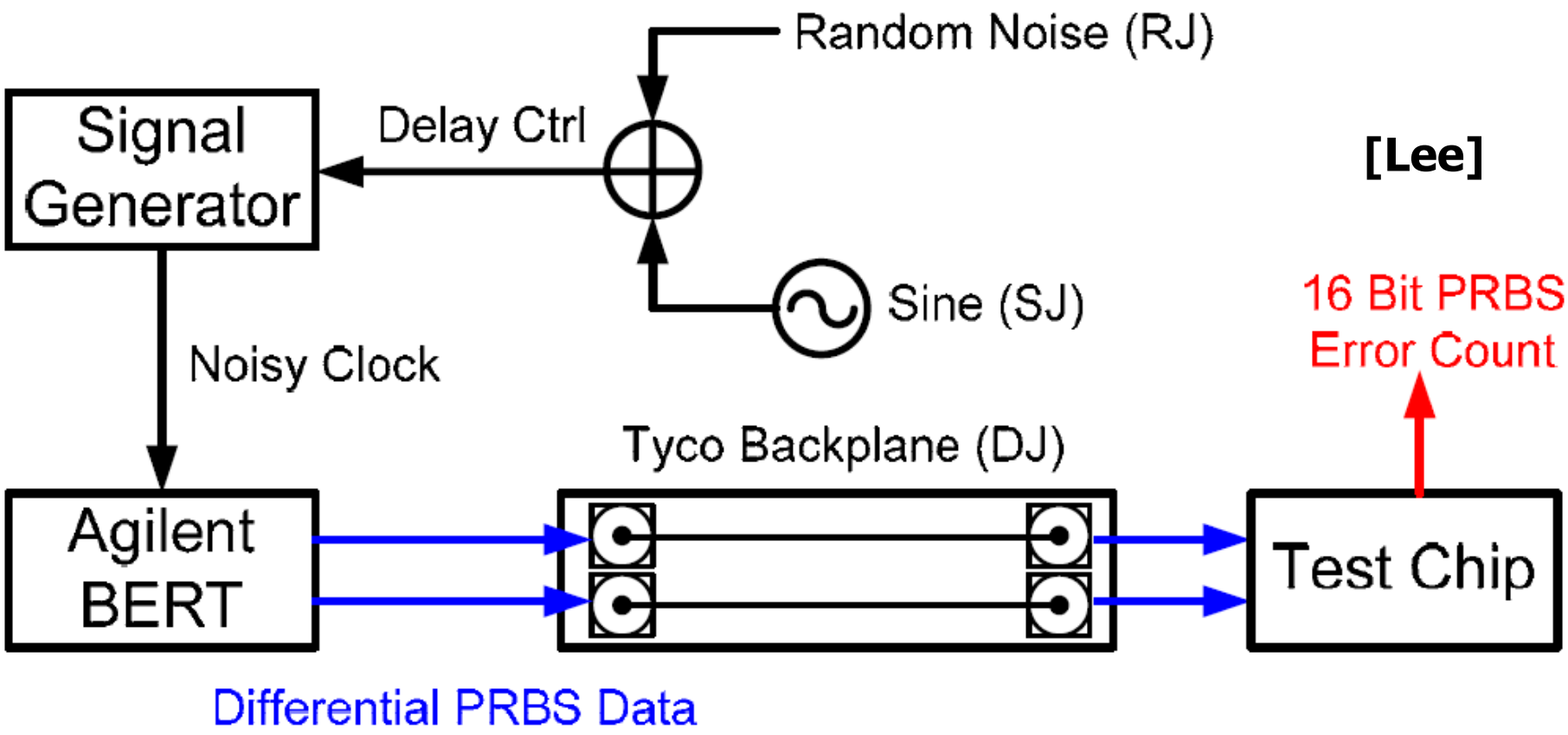
$$\phi_e(s) = \left(1 - \frac{\phi_{out}(s)}{\phi_{in}(s)}\right)\phi_{n.in}(s) \le \frac{\text{Timing Margin}}{2}$$

$$JTOL(s) = 2\phi_{n.in}(s) = \frac{TM}{\left(1 - \frac{\phi_{out}(s)}{\phi_{in}(s)}\right)}$$

[**Lee**]

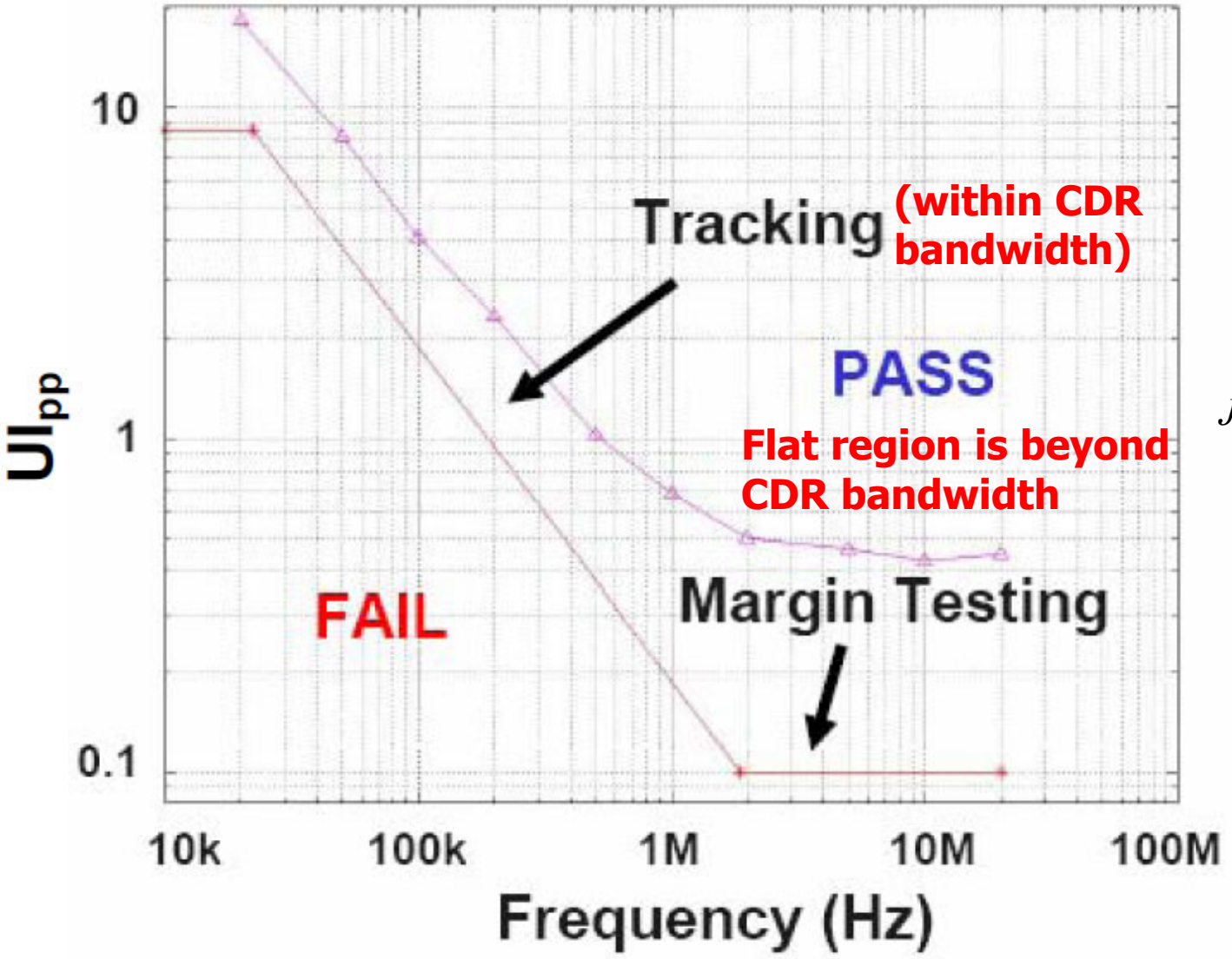


Jitter Tolerance Measurement



- Random and sinusoidal jitter are added by modulating the BERT clock
- Deterministic jitter is added by passing the data through the channel
- For a given frequency, sinusoidal jitter amplitude is increased until the minimum acceptable BER (10^{-12}) is recorded

Jitter Tolerance Measurement



[Lee]

$$JTOL(s) = 2\phi_{n.in}(s) = \frac{TM}{\left(1 - \frac{\phi_{out}(s)}{\phi_{in}(s)}\right)}$$

CDR Take-Away Points

- CDRs extract the proper clock frequency and phase position to sample the incoming data symbols
- Specialized phase detectors suited for random data symbols are required
- Dual-loop CDRs are often used to both optimize jitter performance and provide robust frequency acquisition
- Jitter tolerance is an important CDR metric that is improved with increased loop bandwidth

Next Time

- Forwarded-Clock Deskew Circuits
- Clock Distribution Techniques