Sources of errors in digital communication

Intersymbol Interference (ISI)

Additive Noise

Jitter

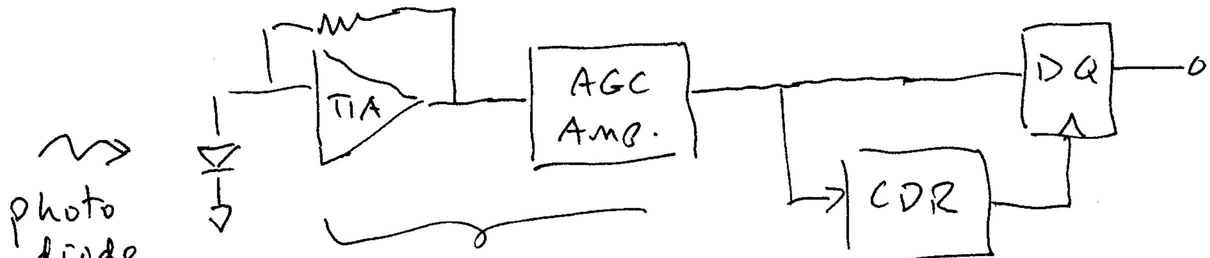
Data bits get corrupted and fail to produce a clean 0 or 1. This produces bit errors. A good digital transmission link should have a BER $< 10^{-12}$.

ISI. Data errors that are pattern dependent can be produced by bandwidth limitations. Periodic data does not experience this. AKA: DDJ, PDJ

Low Pass Filter. Reduced BW. This produces exponential rise/fall times. If these affect the next bit period, amplitude and threshold ~~errors~~ distortion will potentially produce errors.

$$V(t) = V_0 \left[1 - \exp\left(-t/\tau\right)\right]$$

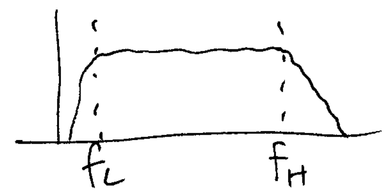
Ref. B. Razavi, Design of Integrated Circuits for Optical Communications, McGraw-Hill, 2003.



BW limitations

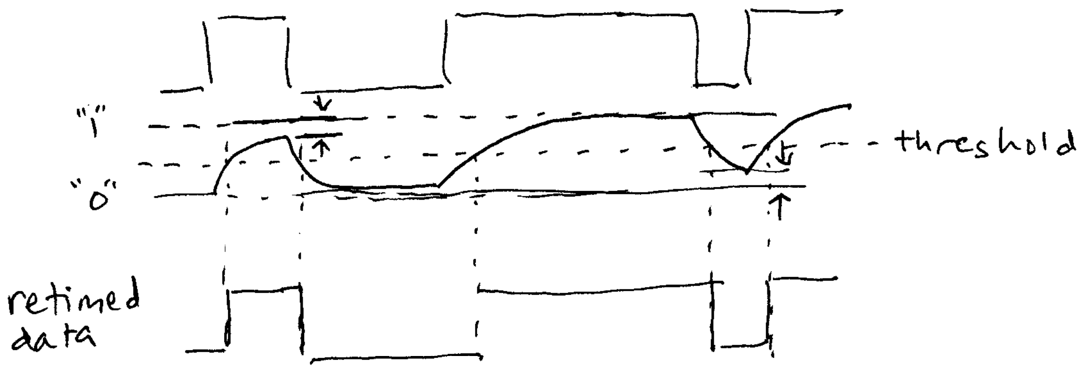
f_L , f_H

$$BW = f_H - f_L \cong f_H$$

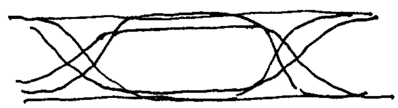


$$f_L = \frac{1}{2\pi R_L C_L}$$ High Pass

$$f_H = \frac{1}{2\pi R_H C_H}$$ Low Pass



pulsewidth distortion, weak 0 or 1



To predict amplitude reduction for given BW:

$$\ln\left(\frac{V(t)}{V_0} - 1\right) = -t/\tau$$

$$f_{3dB} = \frac{1}{2\pi\tau}$$

EX:

$T_b = 100ps$ $\qquad f_{3dB} = 3\ GHz$ $\qquad \tau = 53ps$

$$\frac{V(t)}{V_0} = 1 - \exp\left(-\frac{T_b}{\tau}\right) = 1 - 0.15 = 0.85$$

So 15% reduction in 1 bit period

2.3% in 2 bit periods

AC coupling to eliminate DC offsets also can produce bit errors through droop.

$$V(t) = V_0[\exp(-t/\tau)]$$

For long sequences of 0 or 1's, a very low HPF cutoff may be required.

EX: $f_L = 1\,MHz$. $\tau = 159\,ns$

How many bit periods ($T_b = 100\,ps$) to get 1% error in V_0?

$$\frac{V}{V_0} = 0.99 = \exp(-t/159\,ns)$$

$$-159\,ns \cdot \ln(0.99) = t = \cancel{168\,ns}\ 1.6\,ns$$

~~or 1650 bits (highly unlikely)~~

16 bits

Pulse Width Distortion

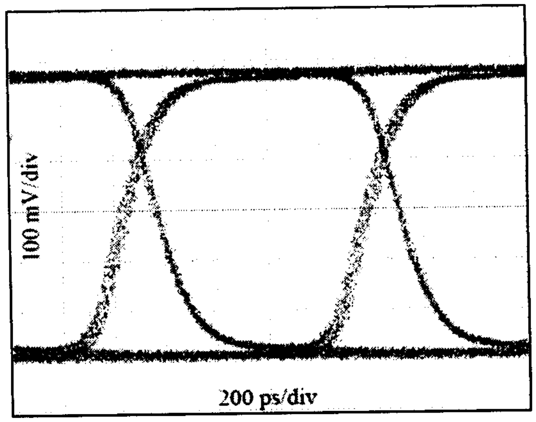


Figure 4. Eye diagram showing PWD

Intersymbol Interference (ISI)

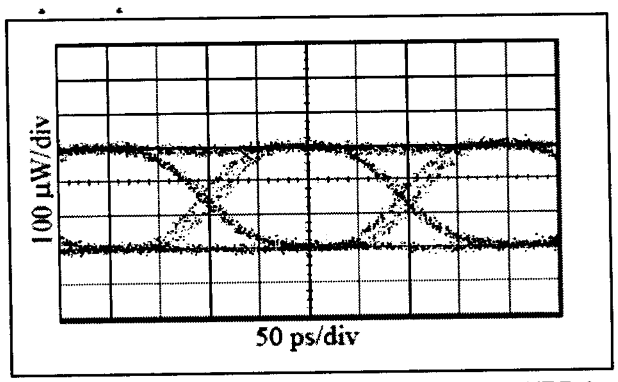
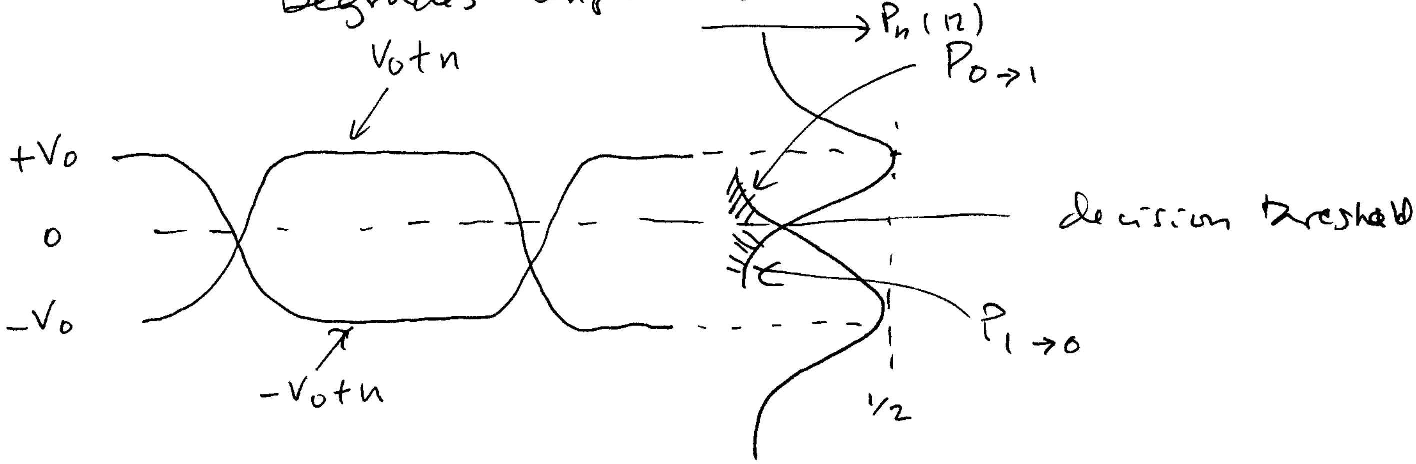


Figure 5. Eye diagram showing DDJ/ISI/PDJ

Jitter in Digital Communications Systems, Part 1, Maxim App. Note HFAN 4.0.3, Sept. 2001.

Additive Noise

Degrades amplitude and time resolution



Assume Gaussian noise PDF

$$P_n = \frac{1}{\sigma_n\sqrt{2\pi}} \exp\left(\frac{-n^2}{2\sigma_n^2}\right)$$

Assume 0 and 1 have equal probability.

$$P_{0\to1} = \frac{1}{2}\int_0^\infty \frac{1}{\sigma_n\sqrt{2\pi}} \exp\left(-\frac{(u+V_0)^2}{2\sigma_n^2}\right)du = P_{1\to0}$$

lets substitute $z = (u+V_0)/\sigma_n$

$$P_{0\to1} = \frac{1}{2}\int_{V_0/\sigma_n}^\infty \frac{1}{\sqrt{2\pi}} \exp\left(\frac{-z^2}{2}\right)dz \quad \left[\begin{array}{c}\text{error} \\ \text{function} \\ \text{erf}\left(\frac{V_0}{\sigma_n}\right)\end{array}\right]$$

$$= \frac{1}{2} Q\left(\frac{V_0}{\sigma_n}\right)$$

$$P_{TOTAL} = Q\left(\frac{V_0}{\sigma_n}\right)$$

$\frac{V_o}{\sigma_n}$ is essentially the SNR

σ_n requires knowledge of the BW. Noise must be integrated over signal BW.

This probability gives us the BER.

for $x > 3$, $Q(x) \approx \frac{1}{x\sqrt{2\pi}} \exp\left(\frac{-x^2}{2}\right)$

so, $\frac{V_o}{\sigma_n} = 5$ gives us $Q(5) \cong 3 \times 10^{-7}$

3 bits per 10^7 in error

$Q(6) \approx 10^{-9}$

$Q(7) \approx 10^{-12}$

since $\sigma_n \propto \sqrt{BW}$, we must avoid excessive BW.

On the other hand, ISI requires sufficient BW

$BW \cong 0.7 \times$ Data Rate

is good compromize for NRZ data.

Jitter.

Many definitions, but all refer to a time difference between the ideal time for an event to occur and the actual time it occurred.

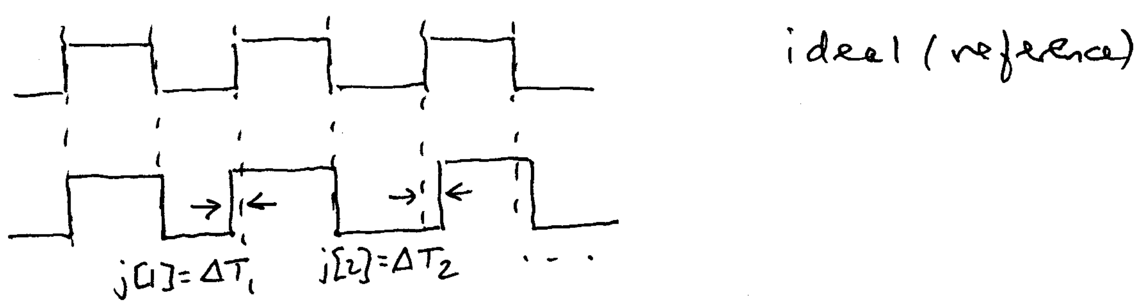
The event could be

sampling instant of data (NRZ)
zero crossing of differential signal
rising or falling clock edge

Instantaneous or Absolute Jitter.

Deviation of event from ideal

$$j[n] = t_{Ideal} - t_{Actual}$$



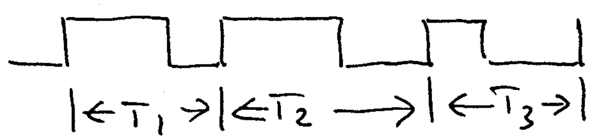
Average jitter. (rms method)

$$\mu = \frac{1}{N} \sum_{n=1}^{N} j[n]$$

$$\sigma = \sqrt{\frac{1}{N-1} \sum_{n=1}^{N} (j[n]-\mu)^2}$$

peak-to-peak jitter $= \max\{j[n]\} - \min\{j[n]\}$

Cycle-to-cycle jitter



$$\Delta T_{cc} \cong \lim_{N\to\infty} \frac{1}{N} \sqrt{(T_2-T_1)^2+(T_3-T_2)^2+\cdots}$$

no reference (ideal) is required.

Two types of Jitter:

Random (RJ)

- Gaussian PDF describes jitter
- unbounded

Deterministic (DJ)

- caused by periodic interferences
- Power/Ground noise
- Oscillator cross-coupling
- ISI, duty cycle distortion
- bounded

RJ comes from phase noise of oscillators and the effects of additive noise on the data threshold.

Deterministic Jitter (DJ)

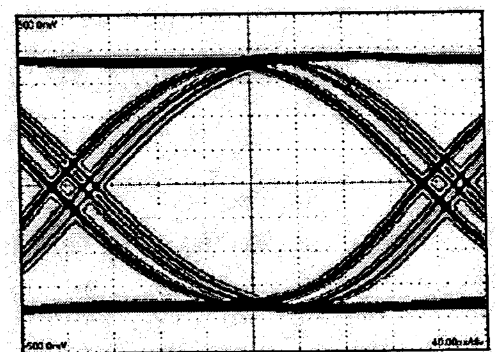


Figure 3. Eye diagram showing DJ

Random Jitter (RJ)

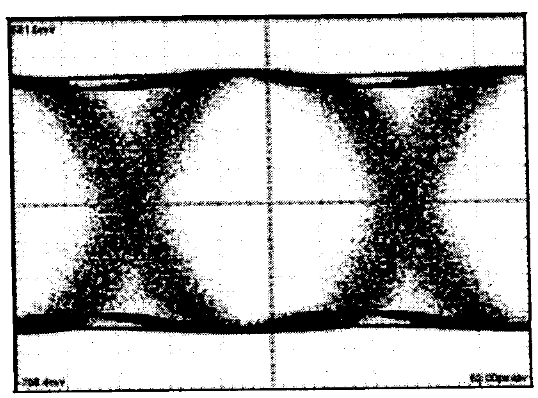


Figure 2. Eye diagram showing RJ

Jitter in Digital Communications Systems, Part 1, Maxim App. Note HFAN 4.0.3, Sept. 2001.

DJ

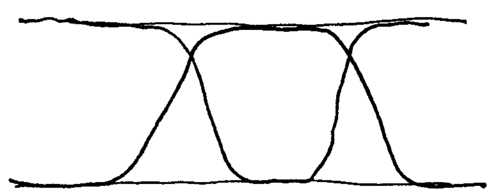
Duty Cycle or Pulse Width Distortion

unequal width of 0 and 1

unequal rise / fall times can cause this.

voltage offsets on differential inputs

crossover is shifted up or down



0 is shorter than 1

Data Dependent Jitter (DDJ)

same as ISI

or also known as Pattern Dependent J.
(PDJ)

Sinusoidal Jitter

$$j[n] = A \sin\left[2\pi f \frac{n}{r} + \phi\right]$$

r = data rate f = jitter freq.

n = cycle #

This can be caused by oscillator coupling through power/gnd or substrate.

RJ. peak-to-peak measurements are not meaningful because in theory Gaussian tail is infinite.

Limits based on the required BER can be used to convert from rms to pk-pk jitter.

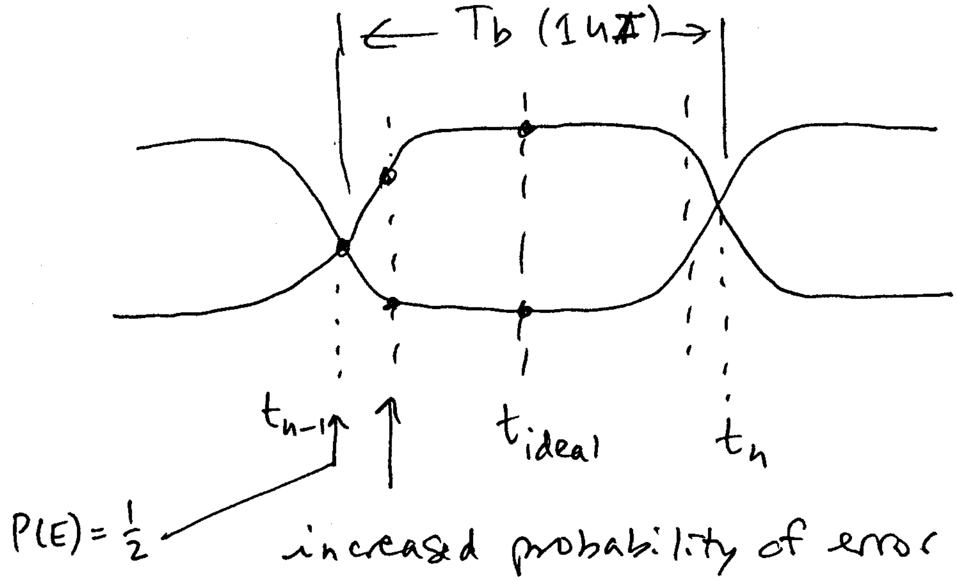
Since DJ *is* bounded, it typically is expressed as pk-pk.

Total Rms jitter $= \sqrt{\sigma_1^2 + \sigma_2^2 + \cdots}$

where each σ_i comes from an individual system component.

How will jitter affect BER?

→ Timing of sampling instant is uncertain.



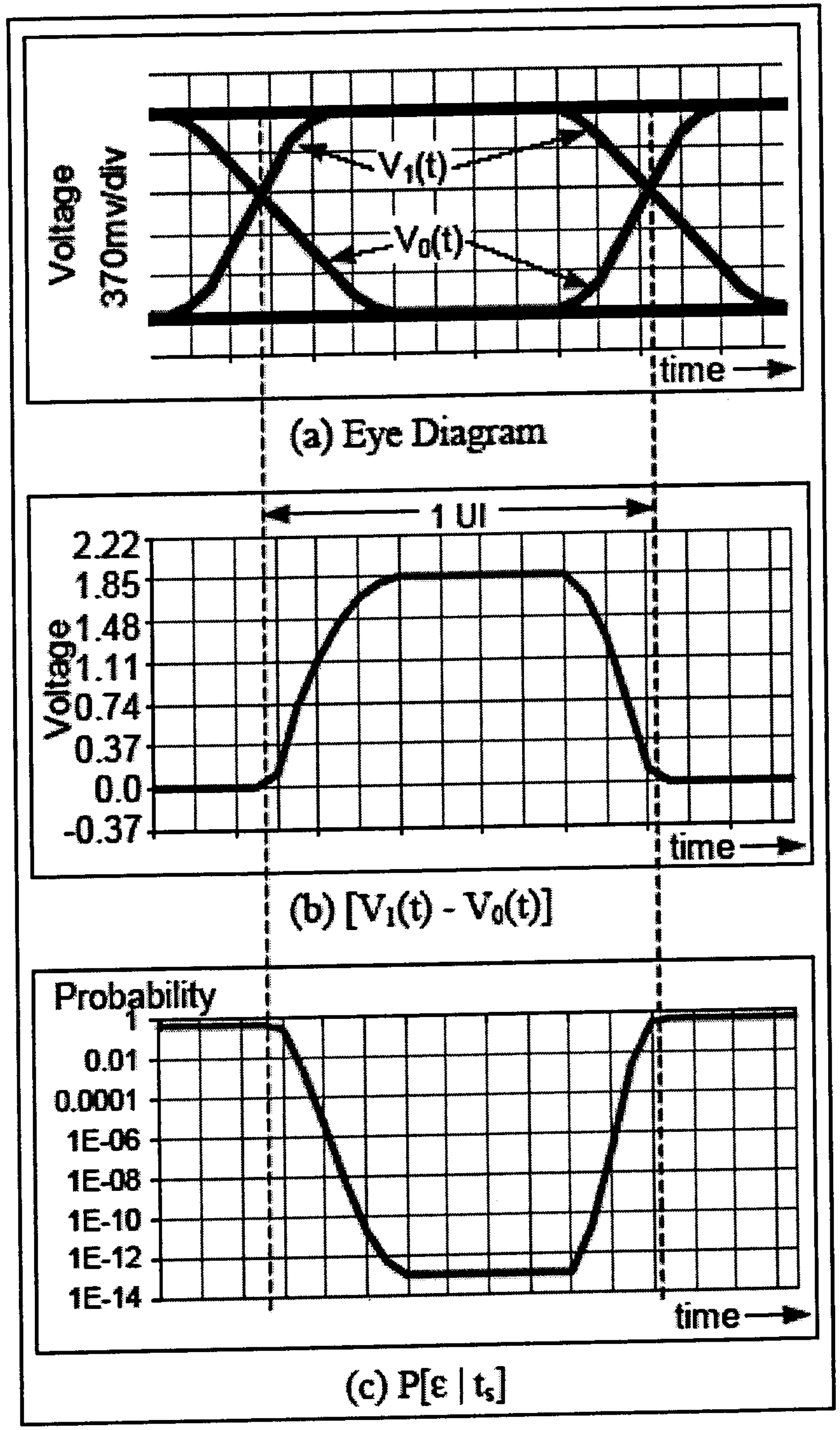
Now P(E) must take into account the probability of bit error at each sampling instant:

$$P[E \mid t_s]$$

as well as the probability that sampling instant t_s actually occurs $P[t_s]$.

consider jitter to be on clock edge, not data edge.

Assume noise on on both 0 and 1, Gaussian RJ



(a) Eye Diagram

averages: $\overline{V_1} - \overline{V_0}$

(b) $[V_1(t) - V_0(t)]$

probability of bit error at each t_s

"Bathtub" Plot

(c) $P[\varepsilon \mid t_s]$

Jitter in Digital Communication Systems, Part 1, Maxim App. Note HFAN-4.0.3, Sept. 2001

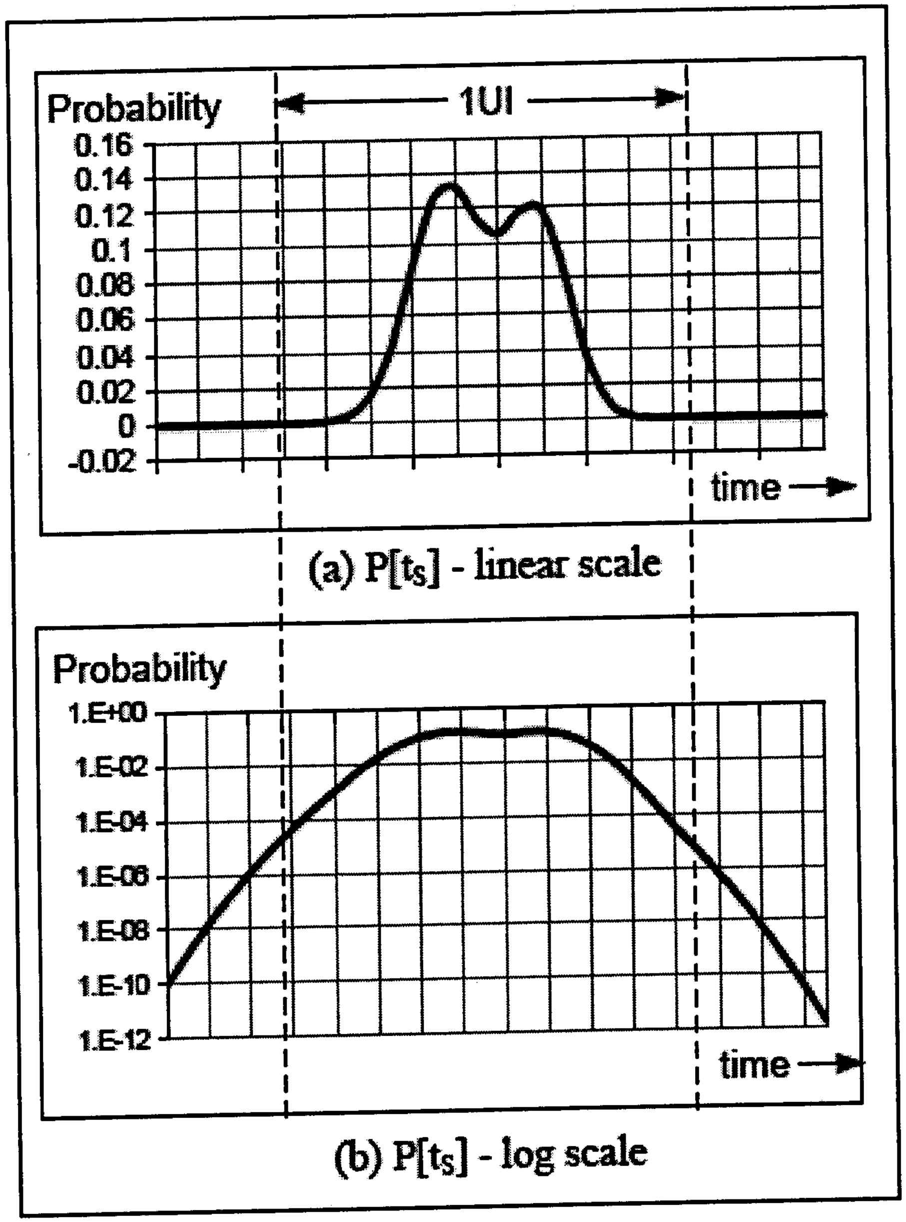


Figure 7. Sampling instant probability density function (PDF)

Timing probability of bit clock relative to data

maxim, op. cit

Maxim, op. cit.

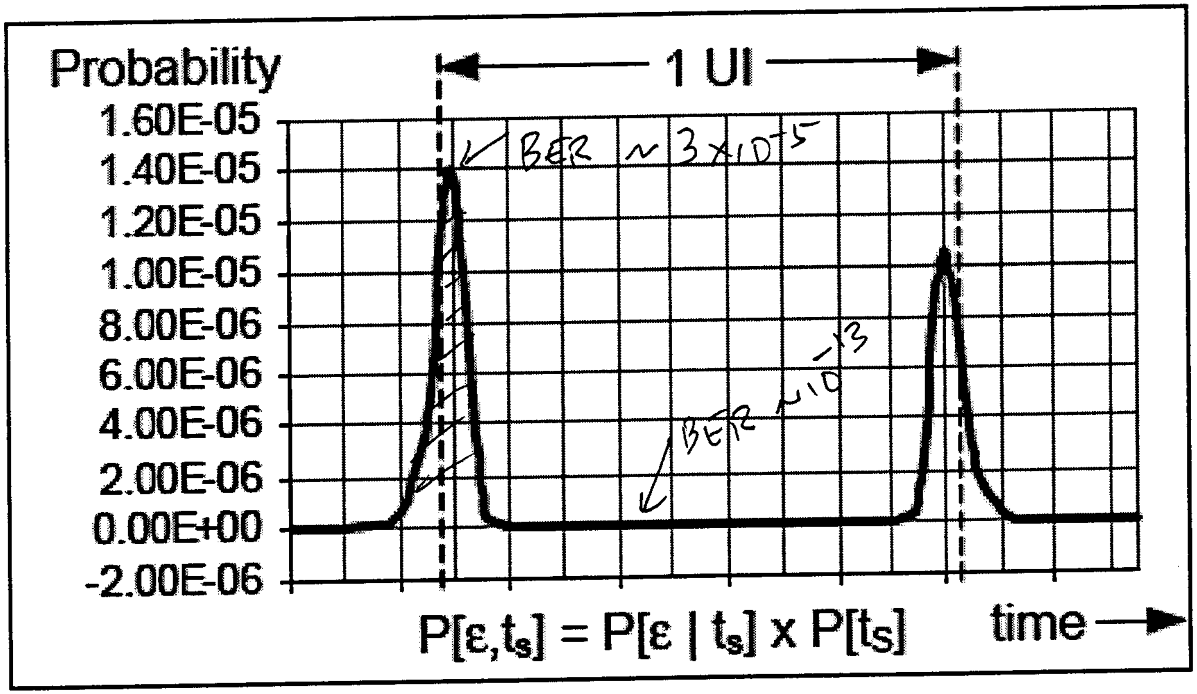


Figure 8. Probability of bit error over the range of possible sampling instants

Multiply bathtub plot with P[ts].

$$BER = \int_{-\infty}^{\infty} P[\epsilon, t_s]\, dt$$

<u>Jitter Peaking</u>

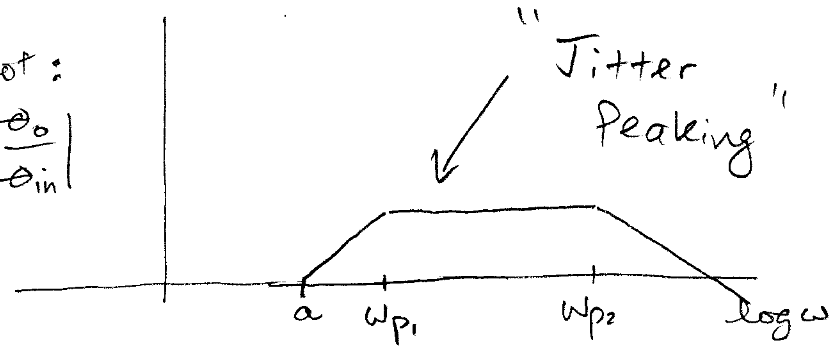
The TYPE 2 loop filter with the ideal integrator gives

- zero steady state phase error for a $\Delta\omega$
- loop BW independent of phase error
- damping improves as ω_z is reduced for fixed ω_n
- crossover frequency is increased

$$T(s) = \frac{K(s+a)}{s^2}$$ see Bode Plot.

<u>Root Locus</u>. when heavily damped, zero is always to the right of the poles

Closed Loop Bode Plot: $\log\left|\frac{\theta_o}{\theta_{in}}\right|$



need $\zeta > 4$ to meet jitter transfer spec of 0.1dB

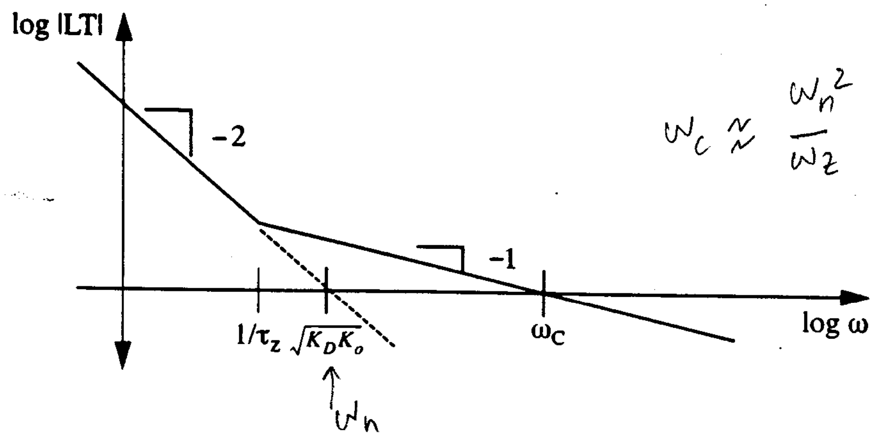
Here is where DLL is more effective.

No jitter peaking by nature -
single pole CL TF

But, also requires a frequency reference with exact frequency.

Combined PLL/DLL systems can do this,

see Lee and Bulzacchelli,
JSSC, 27, pp1736-1746, Dec 1992.



$\omega_c \approx \frac{\omega_n^2}{\omega_z}$ if $\omega_c >> \omega_n$

FIGURE 15.4. Loop transmission of second-order PLL.

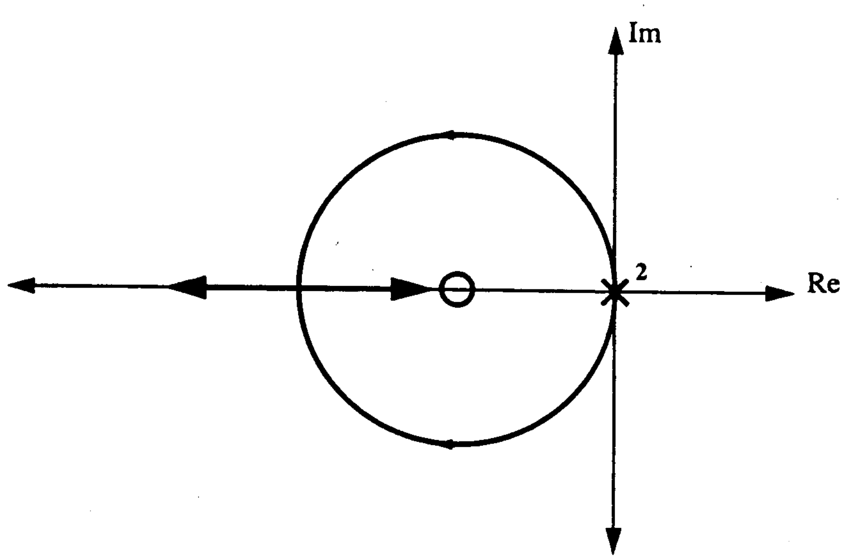
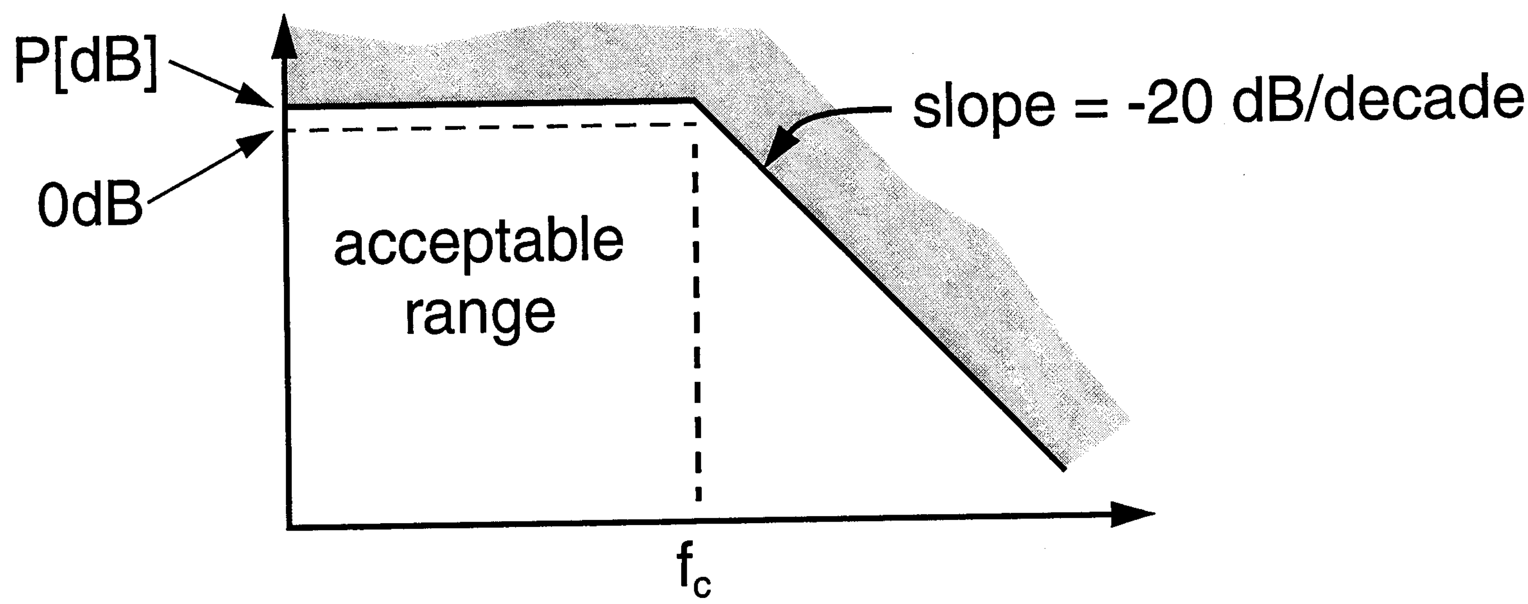


FIGURE 15.5. Root locus of second-order PLL.

T. H. Lee, Design of CMOS Radio Frequency ICs, 2nd Ed., Cambridge Press, 2004.

Jitter Transfer Specification



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

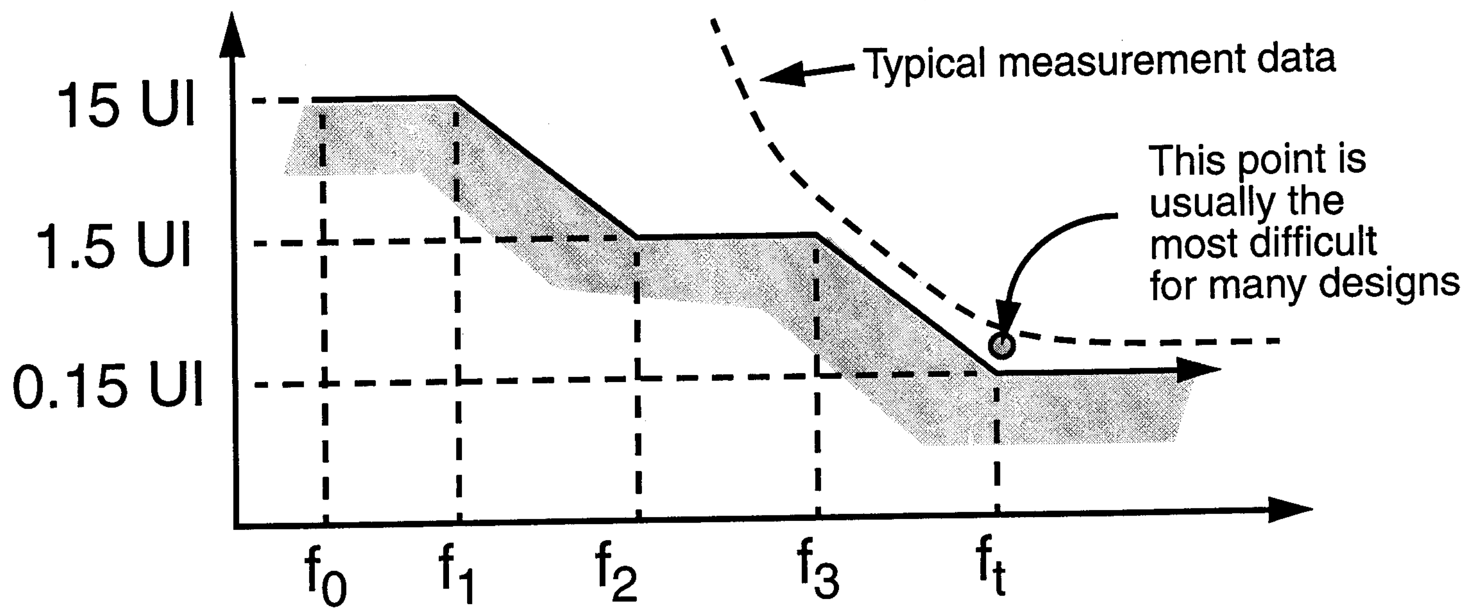
Walker, op. cit.

Jitter Tolerance.

ability of PLL to track jitter on incoming data signal. Phase modulation

PLL must follow this jitter to enable accurate retiming.

SONET Jitter Tolerance Mask



Data Rate		f_0[Hz]	f_1[Hz]	f_2 [Hz]	f_3 [kHz]	f_t [kHz]
OC-3	155 Mb	10	30	300	6.5	65
OC-12	622 Mb	10	30	300	25	250
OC-48	2.488 Gb	10	600	6000	100	1000
OC-192	10 Gb	10	2400	24000	400	4000

from SONET SPEC: TA-NWT-000253 Issue 6, Sept. 1990, fig 5-13