Noise in PLLs

Noise sources

Deterministic

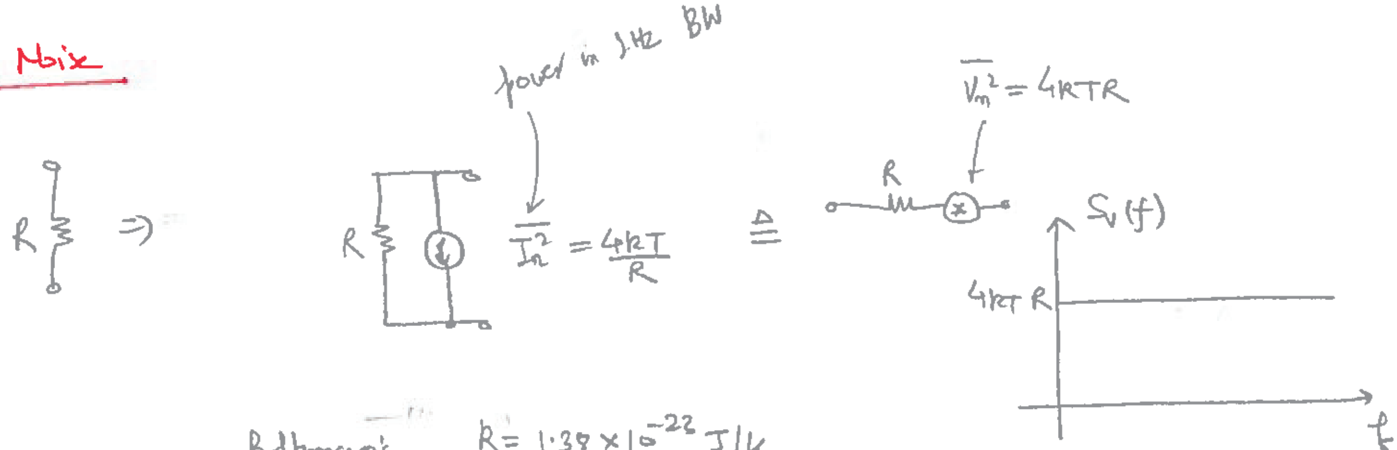
- Supply noise
- Coupling
- Substrate noise

Random

- Thermal
- Flicker

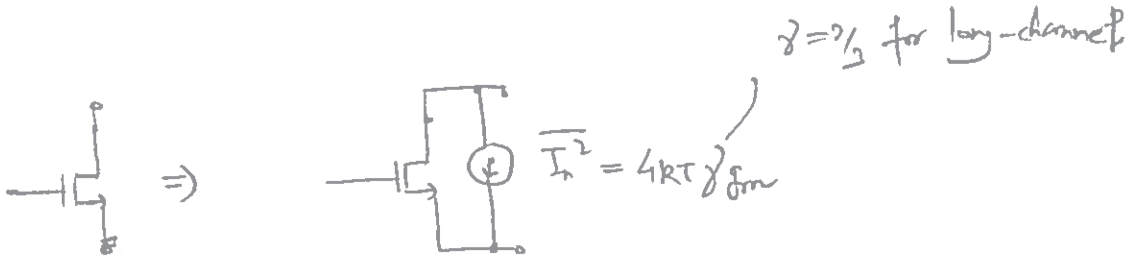
Also, we have reference feedthrough

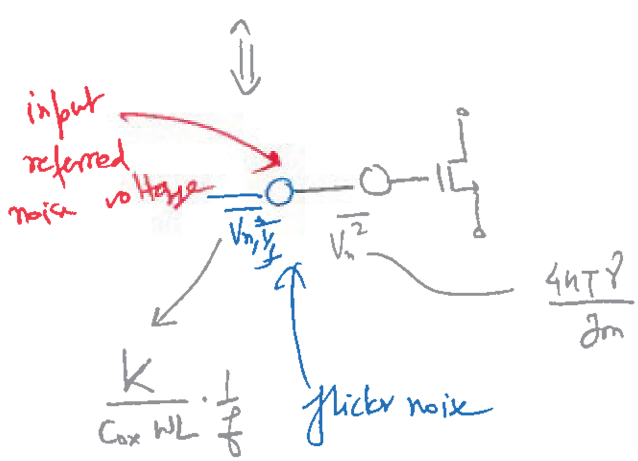
Thermal Noise

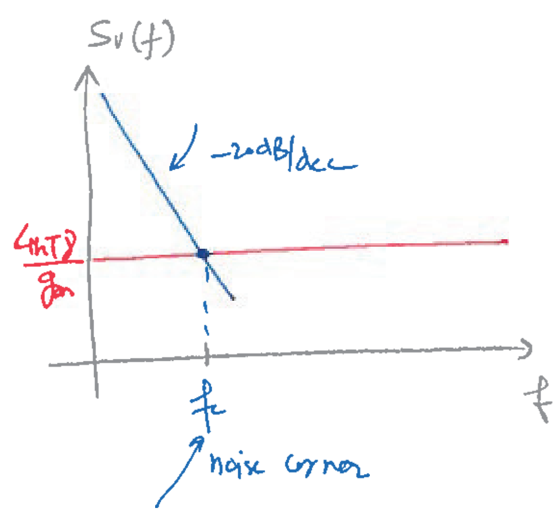


Boltzmann's constant $k = 1.38 \times 10^{-22}$ J/K

SAT







Generic Noise Analysis

* Small-signal analysis with several noise sources

Procedure:

① Identify all noise sources

② Calculate (estimate by simulation), PSD of each noise source $S_i(f)$

③ Evaluate TF from each of the noise sources to the output ($H_i(f)$)

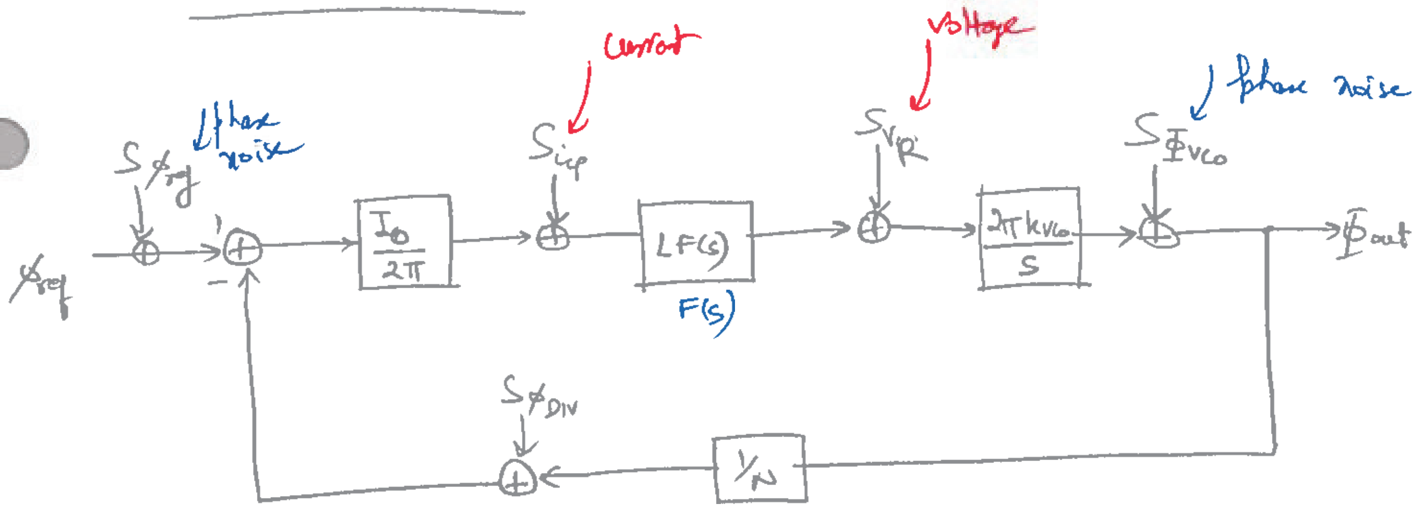
④ Determine the contribution of each noise source to the output $|H_i(f)|^2 S_i(f)$

Result: from Comm Theory

$S_{out}(f) = S_{in}(f)\,|H(f)|^2$

⑤ Sum all the contributions $\sum_i |H_i(f)|^2 \times S_i(f)$ to find the total output noise

Noise in PLLs



$S_{\phi_{ref}} \Rightarrow$ Reference clock noise PSD

$S_{i_{cp}} \Rightarrow$ PFD/CP noise PSD (CP dominates)

$S_{V_R} \Rightarrow$ Loop filter resistor noise PSD

$S_{\Phi_{VCO}} \Rightarrow$ VCO phase noise PSD

$S_{\phi_{DIV}} \Rightarrow$ Divider noise PSD

Noise Transfer function:

loop gain $\Rightarrow$ $L(s) = \frac{I_o k_{VCO}}{N} \cdot \frac{F(s)}{s}$

$$NTF_{ref}(s) = \frac{\phi_{out}(s)}{\phi_{ref}(s)} = \frac{N \cdot L(s)}{1 + L(s)}$$ LPF

LPF: $NTF_{DIV}(s) = NTF_{ref}(s)$ ← Same entry point as ϕ_{ref}

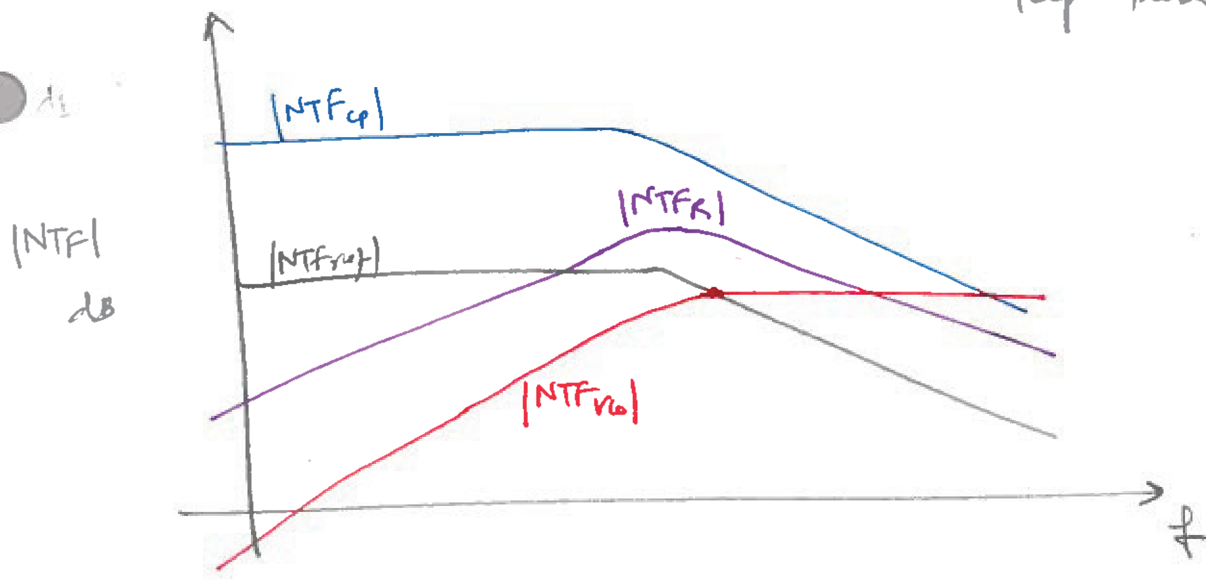
LPF: $NTF_{cp}(s) = \frac{\phi_{out}(s)}{i_{cp}(s)} = \frac{2\pi}{I_{cp}} \cdot NTF_{ref}(s)$ ← divide by the gain of CP to refer to the input

BPF: $NTF_R(s) = \frac{\phi_{out}(s)}{V_R(s)} = \frac{\left(\frac{2\pi k_{VCO}}{s}\right)}{1 + L(s)}$

"Notice same Denominator" → feedback system TF property

HPF: $NTF_{VCO}(s) = \frac{\phi_{out}(s)}{\phi_{VCO}(s)} = \frac{1}{1 + L(s)}$

* Note, these are closed loop transfer functions ④



Output Phase Noise Contribution

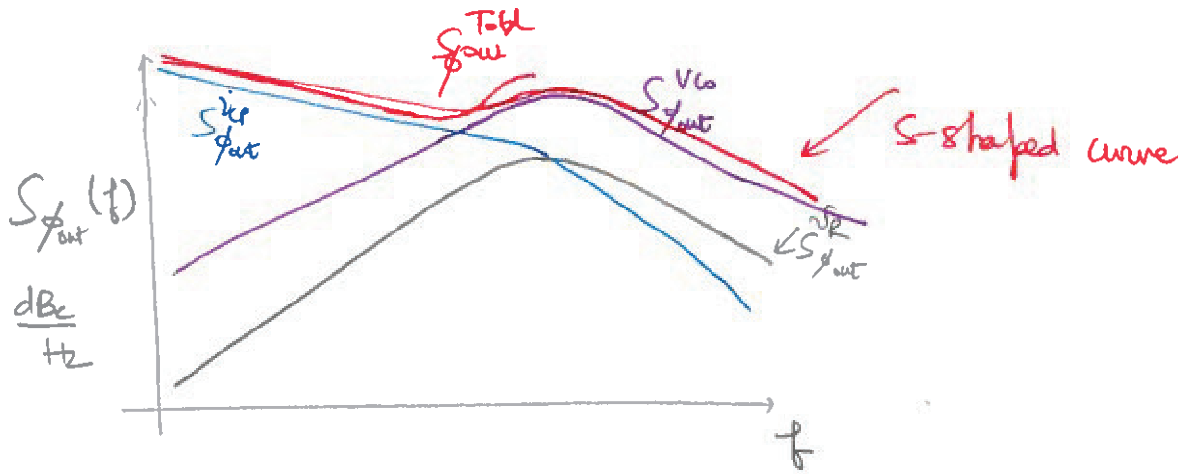
$$S_{\phi_{out}}^{\phi_{ref}} = S_{\phi_{ref}} \cdot |NTF_{iref}(j\omega)|^2$$

$$S_{\phi_{out}}^{i_{cp}} = S_{i_{cp}} \, |NTF_{cp}(j\omega)|^2$$

$$S_{\phi_{out}}^{V_R} = S_{V_R} \, |NTF_R(j\omega)|^2$$

$$S_{\phi_{out}}^{\phi_{vco}} = S_{\phi_{vco}} \cdot |NTF_{vco}(j\omega)|^2$$

$$S_{\phi_{out}}^{Total} = S_{\phi_{out}}^{\phi_{ref}} + S_{\phi_{out}}^{i_{cp}} + S_{\phi_{out}}^{V_R} + S_{\phi_{out}}^{\phi_{vco}} + S_{\phi_{out}}^{\phi_{div}}$$



Calculating Jitter from Phase Noise :

$$\text{Total phase noise} = \sigma_{\Delta\phi}^2 = \int_0^\infty S_{\phi out}^{Total}(f)\,df$$

↑ variance of phase noise (in radians)

$$\sigma_{\Delta\phi} = \sqrt{\int_0^\infty S_{\phi out}^{Total}(f)} \cdot \frac{360^\circ}{2\pi} \quad \text{(degrees)}$$

$$\sigma_{\Delta T} = \sqrt{\int_0^\infty S_{\phi out}^{Total}(f)} \cdot \frac{T_{vco}}{2\pi} \quad \text{(sec)}$$

* Use trapz function in MATLAB to evaluate discrete integration

Jitter usually represented as some ps rms

Noise Optimization :

* optimal PLL bandwidth to minimize overall noise

Procedure :

1. Start with an estimate of PLL BW (ω_{3dB})

   $\omega_{3dB} \leq \frac{\omega_{ref}}{10}$

2. find loop parameters
3. Simulate / Calculate PSD of all the noise sources.
4. find the total output phase noise
5. If the output phase noise doesn't meet the specification, adjust ω_{3dB} or lower noise
6. If spec met, check if power can be reduced further
7. Repeat 1-6 until you achieve phase noise spec with lowest power.

Use Matlab or PLL assistant from cppsim.com