Spur Reduction in Wideband PLLs by Random Positioning of Chargepump Current Pulses

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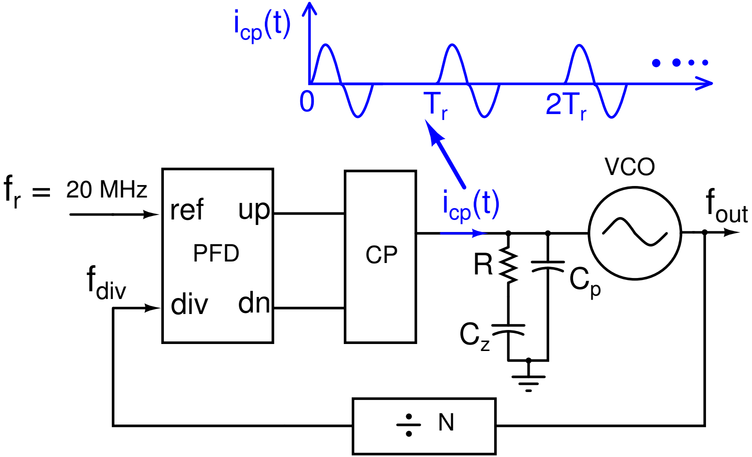
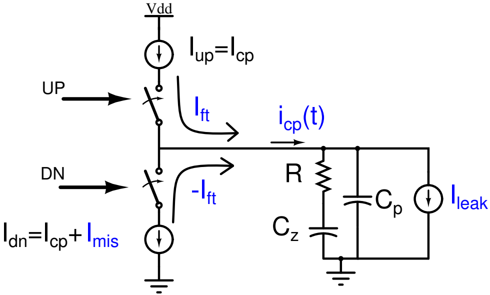
Outline

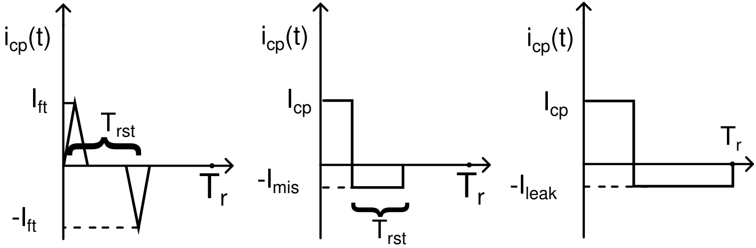
- Reference spur in chargepump PLLs
- Randomization of chargepump current pulses
- Implementation details
- Spectrum after randomization
- Effect of non-idealities
- Simulation results
- Conclusions

Reference spurs

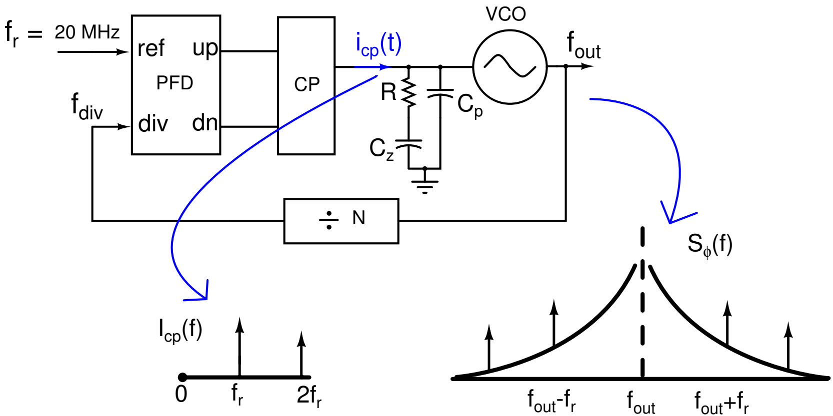


Chargepump non-idealities





Reference spurs



Spur vs bandwidth tradeoff

- The magnitude of the spur at a frequency offset f_r (dBc)

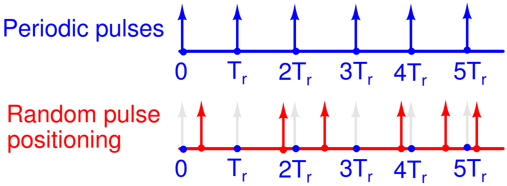
$$S_\phi(f_r) = 20\log\left(\frac{I_{cp}(f_r)\,|Z_{lp}(f_r)|\,K_{vco}}{2f_r}\right)$$

- Low spur level $\Rightarrow$ low bandwidth (large settling time)

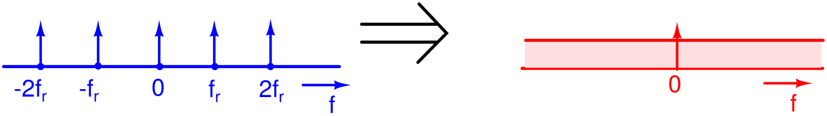
(Loop filter with one pole and one zero assumed here)

Random pulse position modulation

Time Domain

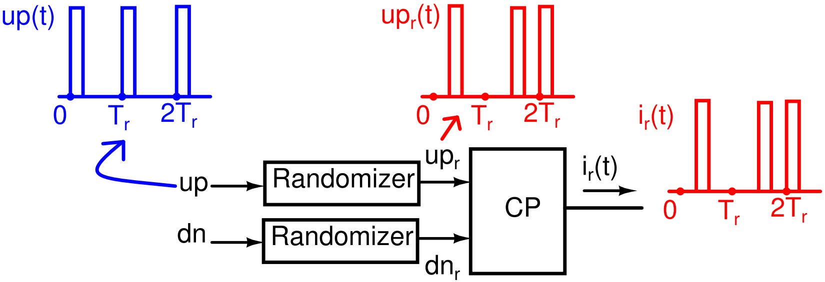


Frequency Domain



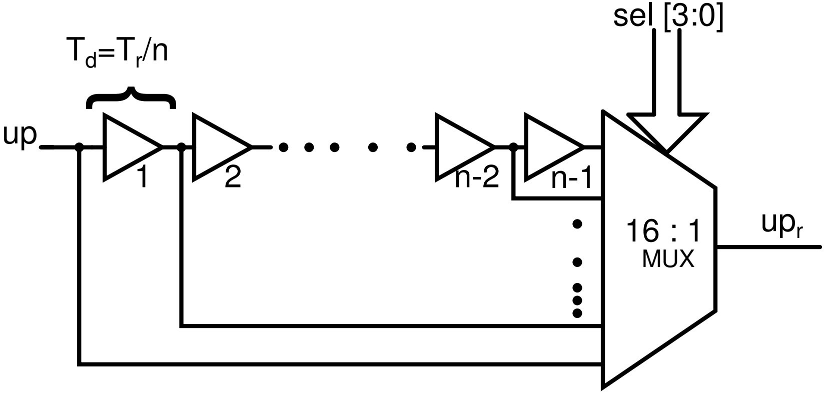
- Redistribute the spur energy to all frequencies.

Implementation



- Chargepump current pulse position has to be randomized.
- Accomplished by randomizing up/dn pulses.

Randomizer

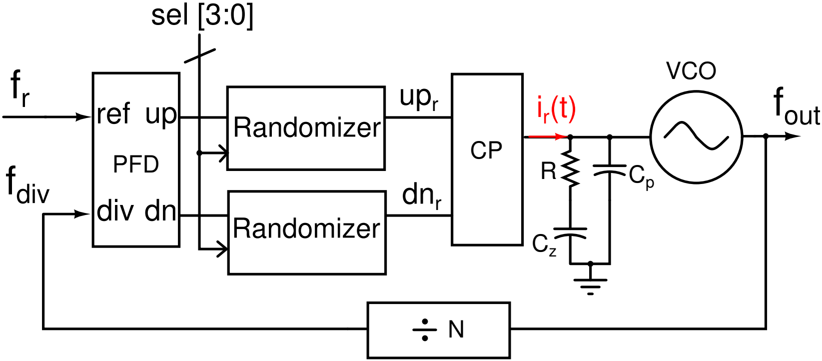


- Randomly choose 1 of *n* delayed pulses

Random number generator

- The randomizing sequence $sel\ [3:0]$ should have a uniform distribution.
- Generated using PRBS(Pseudo Random Bit Sequence) generator.
- A PRBS of longer length
    - produces low in-band noise.
    - guarantees near uniform distribution.
- Length of PRBS chosen based on tolerable in-band noise.

PLL with random pulse positioning



- Control voltage not periodic

Mathematical analysis

- The periodic impulse train

$$x(t) = \sum_{k=-\infty}^{\infty} \delta(t - kT_r)$$

- The randomized impulse train

$$r(t) = \sum_{k=-\infty}^{\infty} \delta(t - kT_r - \frac{a_k T_r}{n})$$

(n: Number of possible pulse positions in a period)

Spectrum before and after randomization

- Power spectrum of a periodic impulse train

$$S_x(f) = \frac{1}{{T_r}^2} \sum_{k=-\infty}^{\infty} \delta(f - \frac{k}{T_r})$$

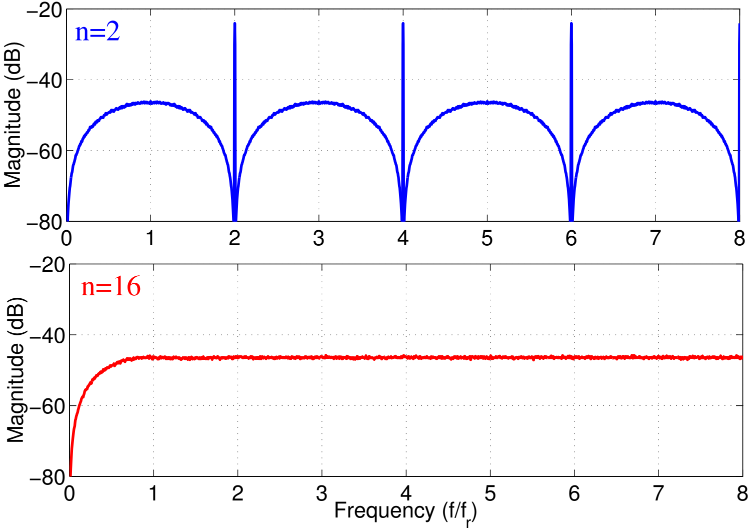
- Power spectrum of the randomized signal

$$S_r(f) = S_{rd}(f) + \frac{1}{{T_r}^2} \sum_{k=-\infty}^{\infty} \delta(f - k\frac{n}{T_r})$$

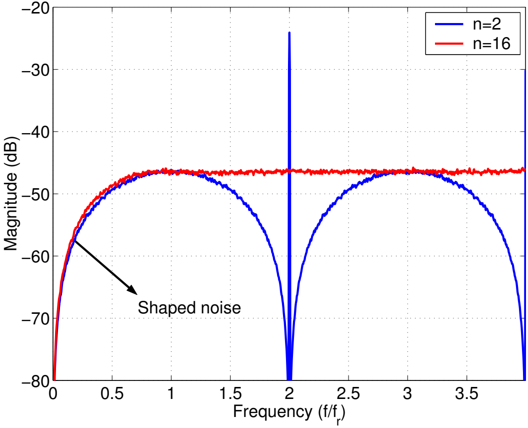
- $S_{rd}(f)$ is the “redistributed noise”

$$S_{rd}(f) = \frac{1}{nT_r} \left[(n-1) - \frac{2}{n} \sum_{k=1}^{n-1} (n-k) \cos(\frac{2\pi k f T_r}{n}) \right]$$

Simulated spectrum after randomization



Noise shaping in the redistributed noise



- The ‘redistributed noise’ is not white.
- For n=2 we can see that

$$S_{rd}(f) = \frac{1}{T_r}\sin^2(\frac{\pi f T_r}{2})$$

- Close-in phase noise remains unaffected.

Delay sensitivity

- Delays prone to process variations ($T_d \neq T_r/n$).
- Delay line may span more or less than a reference period
- The current after randomization ($i_r(t)$) on an average can be expressed as

$$i_r(t) = \frac{1}{n}[i_{cp}(t) + i_{cp}(t - T_d) + ... + i_{cp}(t - (n-1)T_d)]$$

$$|I_r(f)| = \frac{\sin(n\pi f T_d)}{\sin(\pi f T_d)}|I_{cp}(f)|$$

Delay sensitivity

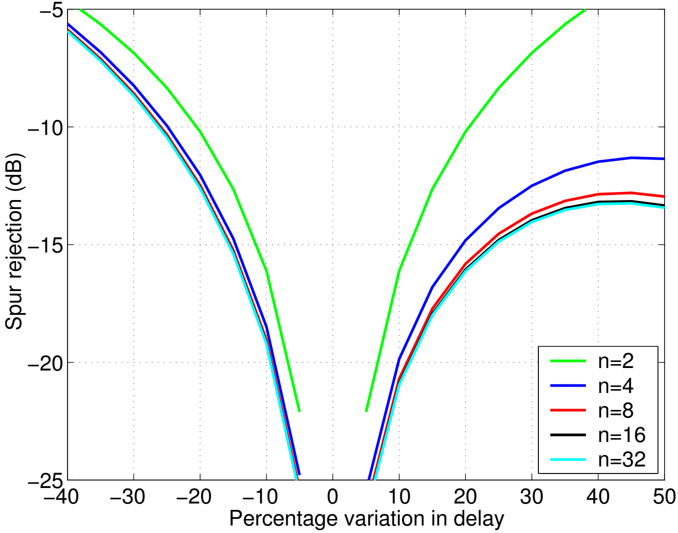
- Thus the randomization behaves as a moving average filter with frequency nulls at

$$f_z = \frac{k}{nT_d}$$

$k \in [1, (n-1)]$

- If $T_d = \frac{T_r}{n}$; nulls occur at reference harmonics.
- If $T_d \neq \frac{T_r}{n}$; nulls do not occur at reference harmonics and spurs appear at PLL output

Sensitivity to delay variations



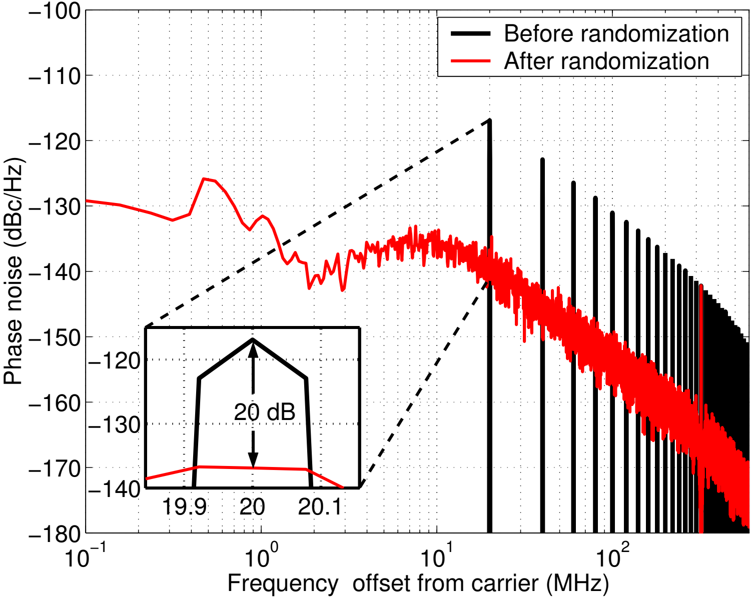
Simulated PLL parameters

f_{ref}	20 MHz
f_{out}	1 GHz
f_{BW}	1 MHz

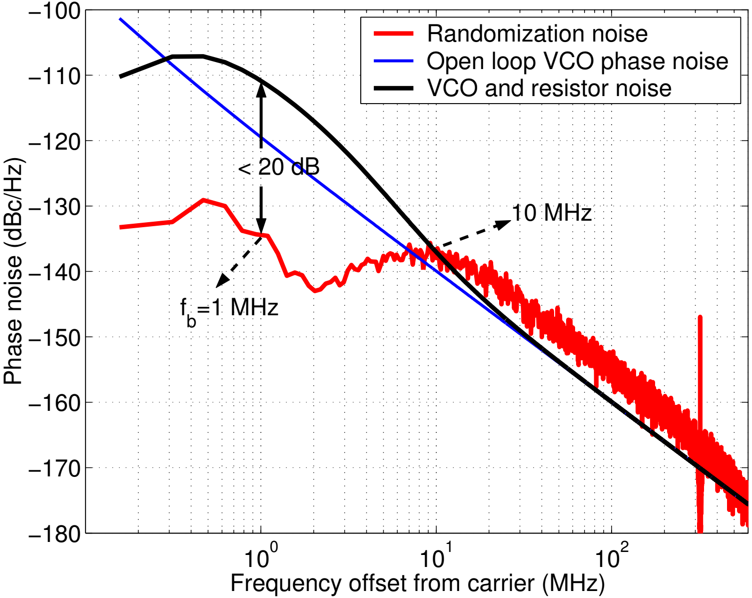
PFD	Tri-state PFD
Charge-pump	$I_{cp} = 50\,\mu\mathrm{A}$
Loop-filter	$\mathrm{R} = 21.7\,\mathrm{k}^{\cdot}, \mathrm{C_z} = 37.25\ \mathrm{pF}, \mathrm{C_p} = 1.99\ \mathrm{pF}$
VCO	$f_{vco} = 1\,\mathrm{GHz},\ K_{vco} = 200\,\mathrm{MHz/V}$
Divider	N=50

- 3-dB bandwidth of the PLL is $\approx$ 1 MHz.
- Charge pump current mismatch 10 %
- Charge pump and PFD: transistor level
- Other components: ideal

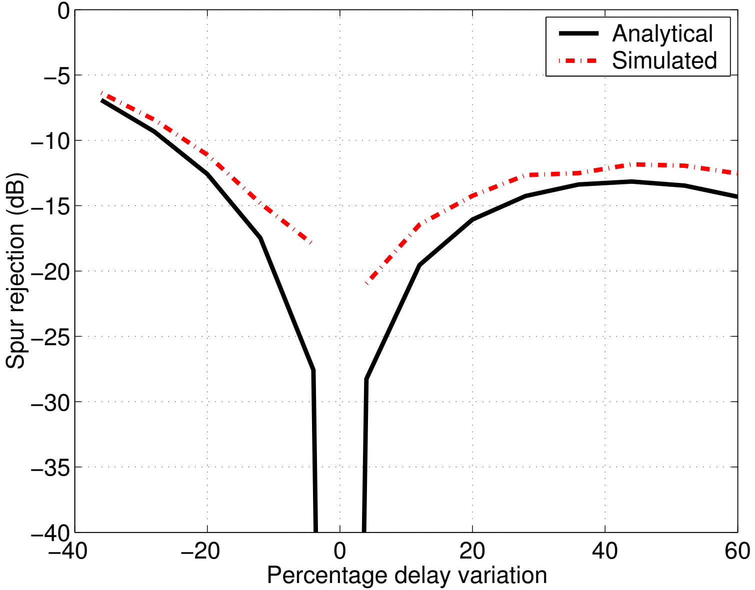
Simulation results



Effect of randomization at high frequencies



Simulated sensitivity to delay variations



Conclusions

- Pulse position randomization eliminates reference spur.
- Resulting spectrum shaped to high frequencies.
- Close-in phase noise remains unaffected.
- $>$ 11.5 dB spur rejection for ±20% delay variation.
- Simple implementation.

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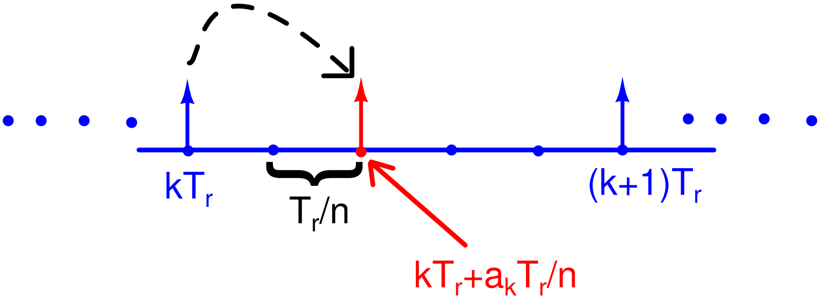
Mathematical representation



- The reference period (T_r) is divided into equal time intervals of T_r/n.
- The k^{th} current pulse will appear at $kT_r + a_k T_r/n$ instead of kT_r.
- a_k is a uniform random integer $\in \ [0, \ n-1]$

Random pulse positioning illustrated for n=4