

# PLL Design Essentials for Wireless Systems

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# Overview

- In this talk, we will attempt to answer the following:
  - What types of system-level issues set wireless terminal performance requirements?
  - How are wireless terminals typically specified in standards-based systems?
  - Which specifications are germane to the frequency synthesizer?
  - How do I translate wireless terminal standards into a relevant set of synthesizer specifications?
  - What is a “toolkit” of useful modeling techniques and / or theorems that I can use to calculate expected performance and evaluate tradeoffs?

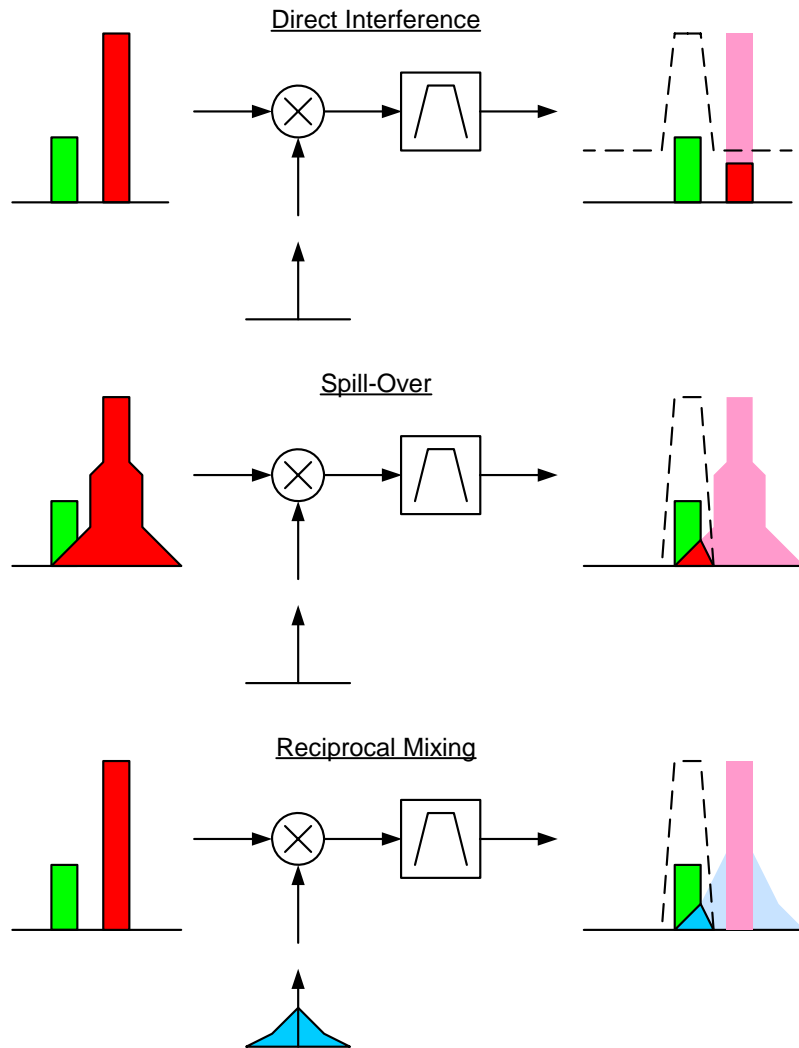
# Outline

- **Understanding wireless systems specifications**
  - The wireless channel and the issues it raises
  - Common performance specification types and techniques
- **Developing frequency synthesizer specifications**
  - Bandwidth, stability and settling behavior
  - Noise theorems and modeling techniques
  - Spectral impurity modeling and performance calculation
- **Summary**

# Wireless Channel Attributes

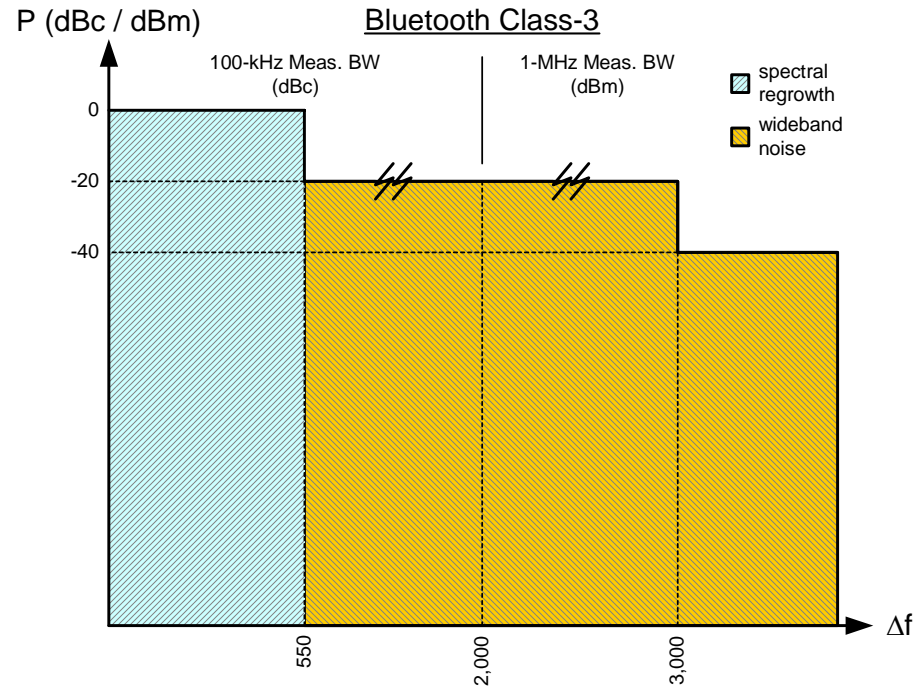
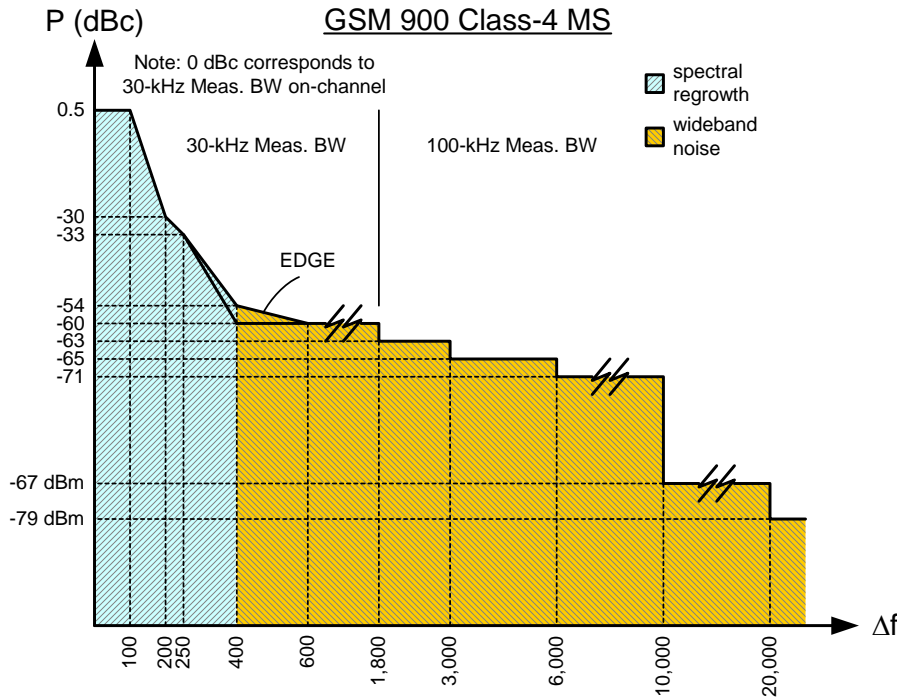
- The wireless channel is a fading multipath channel, producing:
  - Large-scale, slow signal fades (shadow fading)
  - Small-scale, rapid signal fades (Rayleigh fading)
  - A time-varying impulse response
  - Pulse spreading in time (Delay spread)
  - Spectral spreading in frequency (Doppler spread)
- Time-variance is present, *whether or not the mobile terminal is in motion*, due to inevitable motion of other objects
- Basically, it's a wonder that reliable communication is even possible on such a channel
- Bottom line
  - Your signal is often *weak*
  - The other guy's signal is often *strong*
  - Need to minimize interference potential and maximize link margin

# Some Important Interference Modes



- Direct interference due to finite filter stop-band attenuation
- Spill-over caused by TX spectral impurities
  - TX LO phase noise
  - TX spectral regrowth
- Reciprocal mixing caused by RX local oscillator spectral impurities
  - RX LO phase noise
  - RX LO spurious
- Also RX compression and IMD (not shown)

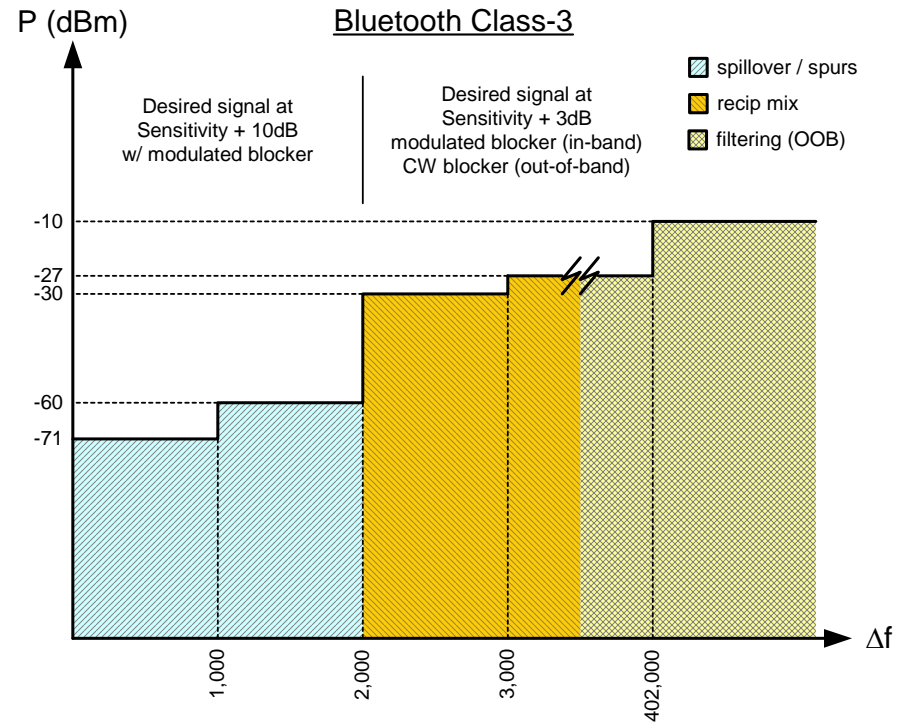
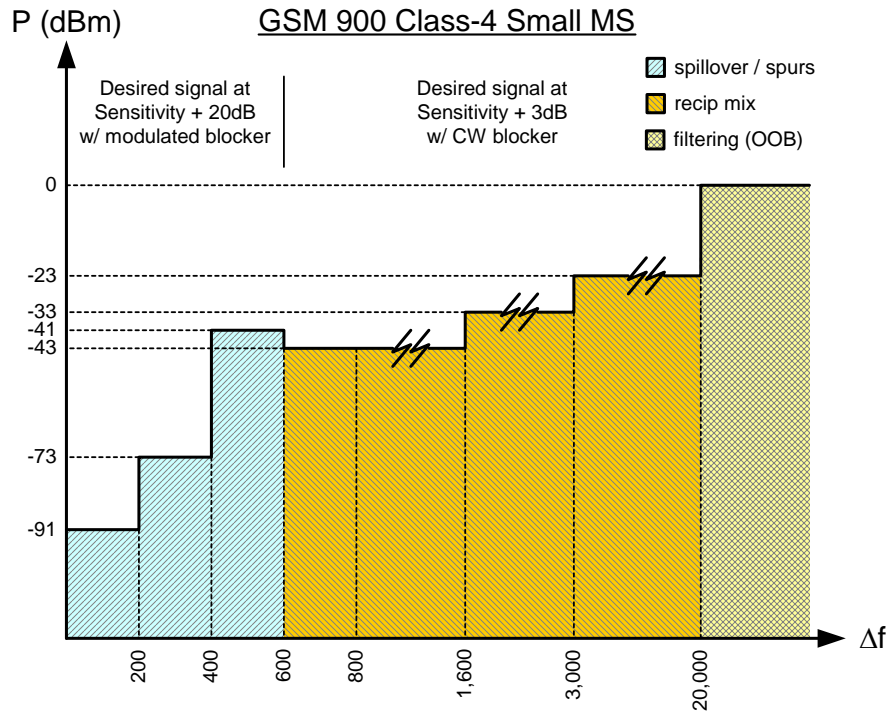
# Transmitter Spectral Purity



## Transmitter Spectral Purity Allowable Exceptions (Spurious)

Standard	Qty	Raster	Level	BW	Bands
GSM	5	200 kHz	< -36 dBm	100 kHz	MS Rx & BS Rx
Bluetooth	3	1 MHz	< -20 dBm	1 MHz	All

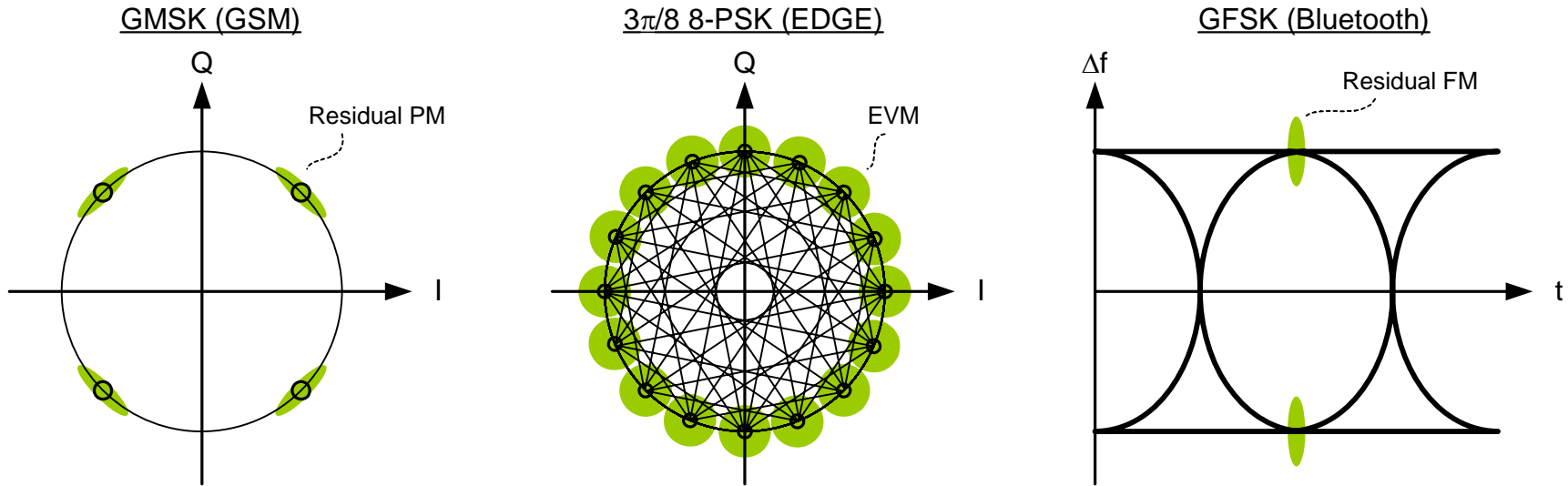
# Receiver Selectivity



## Receiver Selectivity Exceptions (Spurious Response)

Standard	Qty	Raster	Level	Bands
GSM	6 / 24	200 kHz	> -43 dBm	In-Band / OOB
Bluetooth	5 / 24	1 MHz	> 17 dBc / -50 dBm	IB (> 2MHz) / OOB

# Transmitter Modulation Accuracy



## Transmit / Receive Modulation Specifications

Standard	Rx Sens	SNRmin	Res. PM	EVM	Res. FM	Settling	Freq. Tol.
GSM	-102 dBm	9 dB	$5^\circ$	--	--	865 $\mu$ s	0.1 ppm*
EDGE	-102 dBm	--	--	9%	--	287 $\mu$ s	0.1 ppm*
Bluetooth	-70 dBm	11 dB	--	--	10 kHz	200 $\mu$ s	30 ppm

\* Requires AFC to correct crystal oscillator drift.

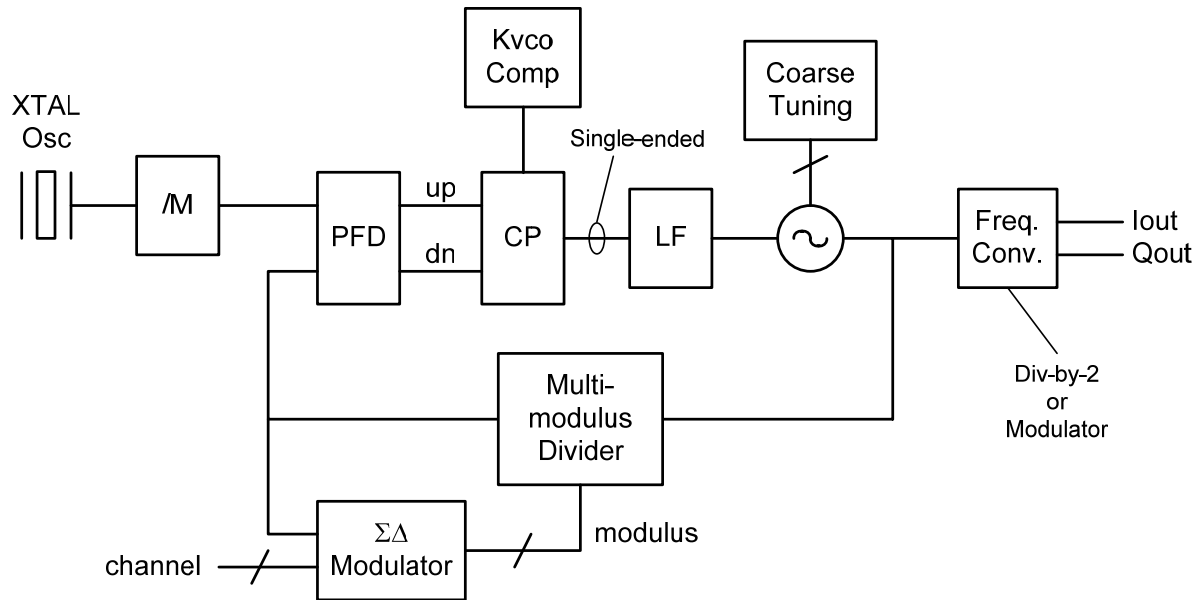
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# PLL Performance Specifications

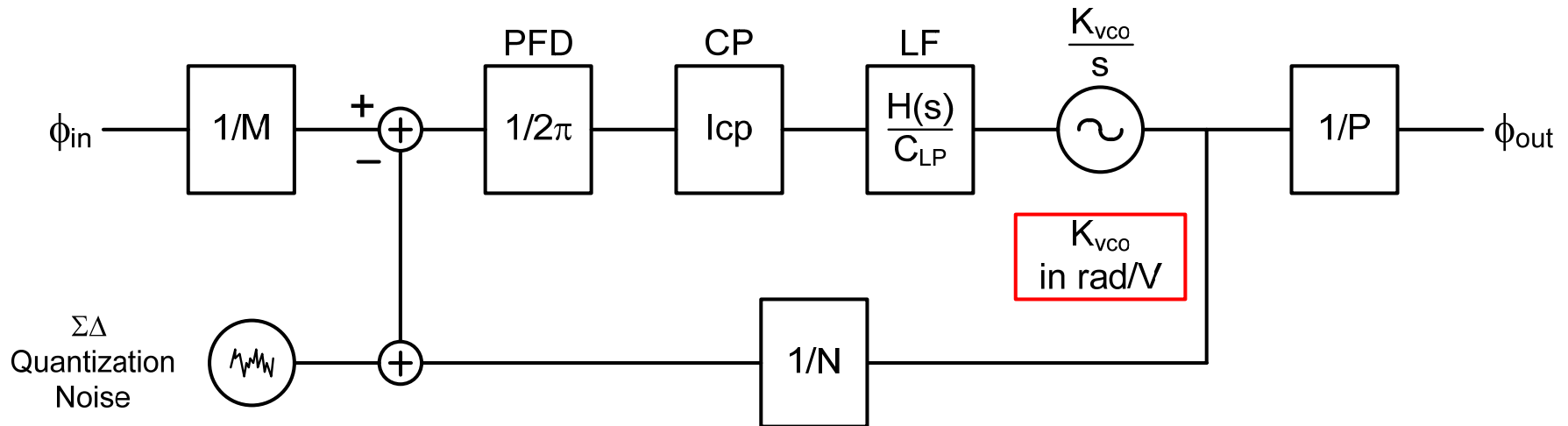
- A complete set of PLL specifications includes:
  - Dynamics
    - Bandwidth and settling time
    - Phase Margin
    - VCO gain
    - Charge pump current
    - Loop filter type and component values
    - Divider ratio and architecture (Int-N, Frac-N,  $\Sigma\Delta$ )
  - Spectral purity
    - Noise requirements for all blocks
      - VCO, dividers, reference, PFD, CP, etc...
    - CP offset and leakage limits
    - Permissible spurious levels
- The following slides provide an analytical “toolkit” for developing specifications from system requirements using hand estimates and / or simple MATLAB models.
- A complete GSM RX local oscillator numerical example is provided for reference at the end.

# A Typical Wireless PLL



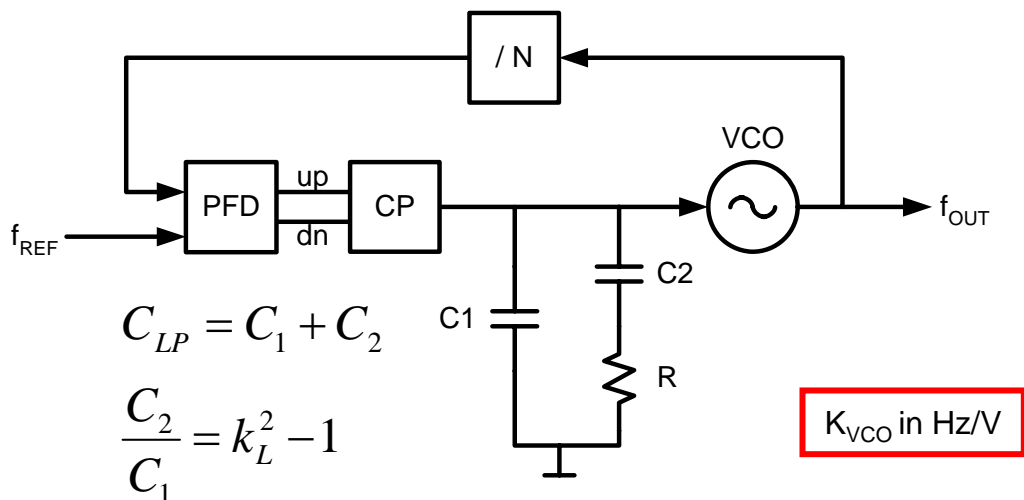
- **SD Fractional-N Loop**
  - Fine frequency resolution & support for multiple crystal frequencies
- **Coarse Tuning**
  - Minimize Kvco to keep spurious under control
- **Kvco Compensation**
  - Maintain loop dynamics over VCO fine-tuning range
- **Freq. Conversion**
  - For direct-conversion systems, VCO is off-frequency

# Phase-Domain Representation



- Linear model is approximately valid provided that  $f_C < f_{REF}/10$ .
- $N$  is the average divider modulus.
- The  $\Sigma\Delta$  modulator produces noise that is shaped away from DC.
  - This noise needs to be rejected by the loop filter  $H(s)$
- For a constant reference frequency,  $\phi_{in}$  is a ramp.

# 3<sup>rd</sup>-Order Type-II PLL Dynamics



## Loop Transmission Expressions

Specify:  $\omega_C$  and P.M.

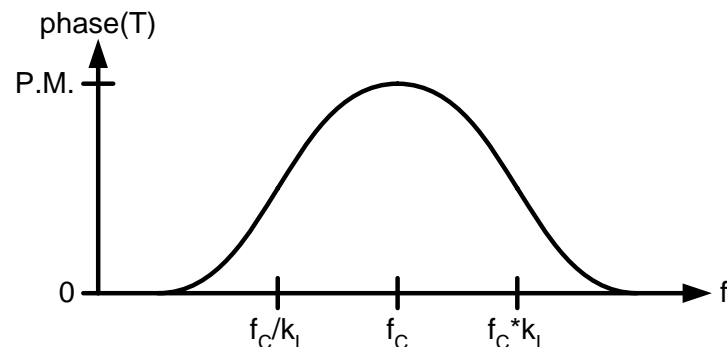
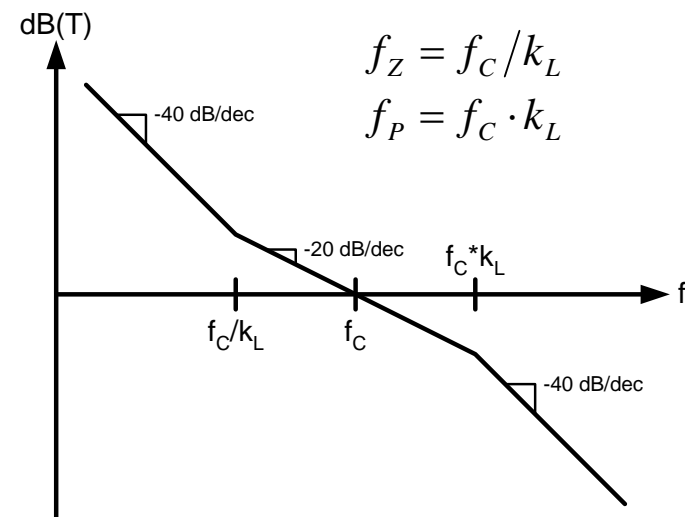
$$T(s) = \frac{I_{CP} K_{VCO}}{N C_{LP}} \frac{H(s)}{s}$$

$$\frac{H(s)}{s} = \frac{1 + \frac{s}{\omega_Z}}{s^2 \left( 1 + \frac{s}{\omega_P} \right)}$$

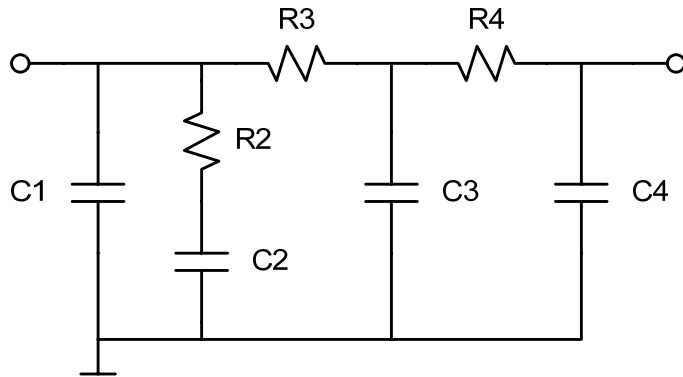
$$\frac{\omega_C^2}{k_L} = \frac{I_{CP} K_{VCO}}{N C_{LP}}$$

$$k_L = \left[ \frac{1 + \sin \text{P.M.}}{1 - \sin \text{P.M.}} \right]^{1/2}$$

## Bode Plots



# Working with High-Order Loop Filters

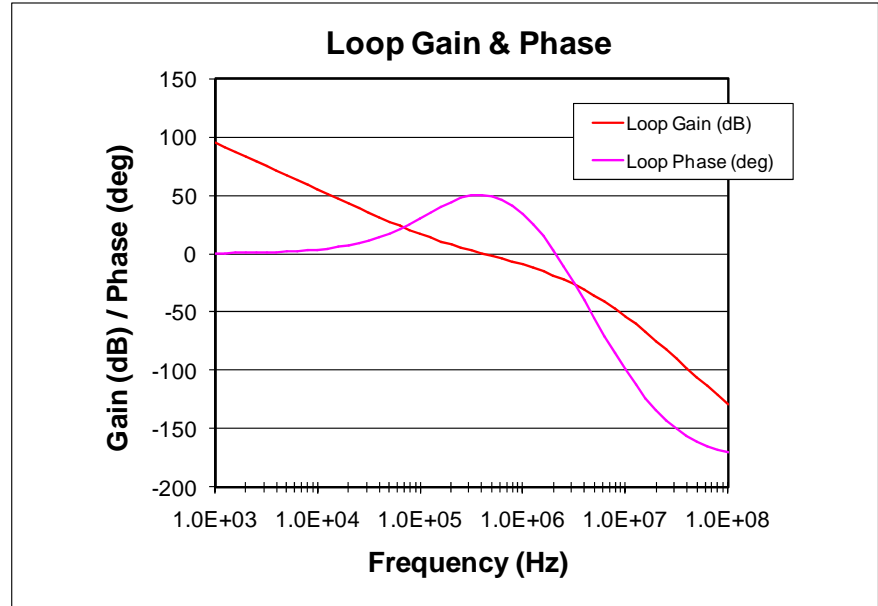


4 poles, 1 zero  
 $f_{p1}, f_{p2}, f_{p3}, f_z$

Where:

$$f_{p2} = k_2 * f_{p1}$$

$$f_{p3} = k_3 * f_{p1}$$



- High-order loop filters provide additional out-of-band filtering of noise and spurious.
- Use the same design procedure outlined on the previous slide, except:

$$f_{p1} = k_L * (1 + 1/k_2 + 1/k_3) * f_c$$

# Step Response & Settling Time

Approximate relationship between BW and settling time

$$t_{LOCK} = \frac{\ln(f_{STEP} / f_{ERROR})}{f_C \zeta_e (\text{P.M.})}$$

fastest  $\longrightarrow$

P.M. (deg)	$\zeta_e(\text{P.M.})$
30	2.25
40	3.4
<b>51</b>	<b>5.0</b>
60	2.6
70	1.5

Vaucher, "An Adaptive PLL Tuning System Architecture Combining High Spectral Purity and Fast Settling Time," JSSC, April 2000.

How to calculate the complete step response, given T(s)

$$\text{If: } G(s) = \frac{T(s)}{1+T(s)} = \underbrace{\sum_{k=1}^n \frac{r_k}{(s-p_k)^{a_k}}}$$

$$\text{Then: } v_{STEP}(t) = \sum_{k=1}^n r_k t^{a_k-1} e^{p_k t}$$

Partial fraction decomposition  
(see residue() function in MATLAB)

# Watch Out: Limits of Linear Analysis

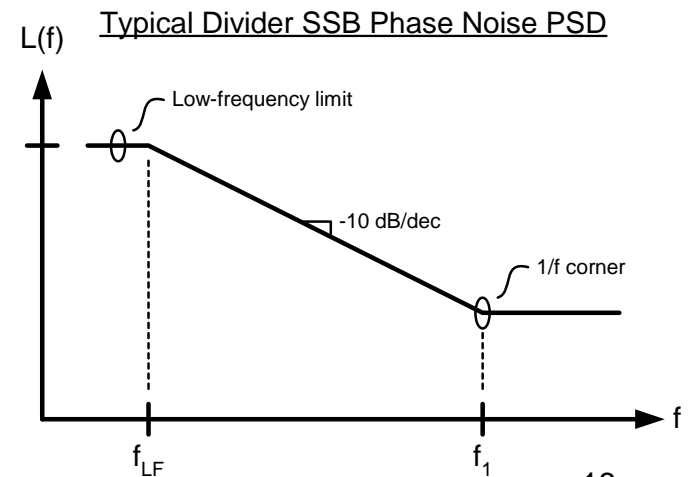
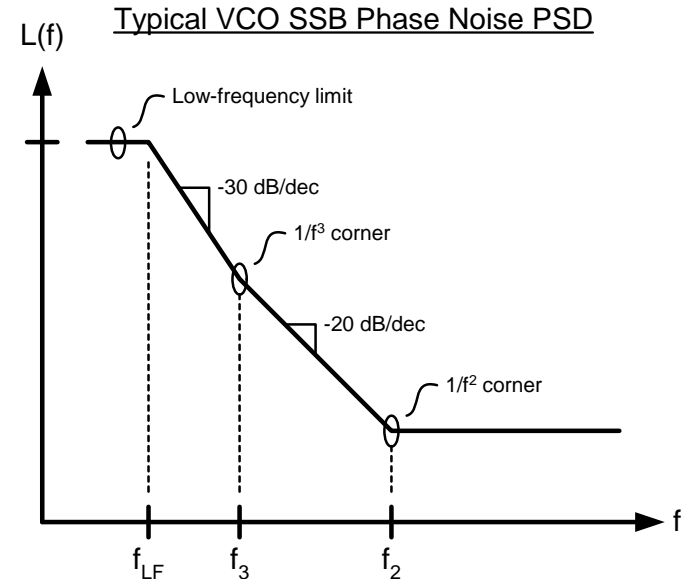
- Linear analysis should always be supplemented with time-domain simulations
- To minimize settling time, avoid:
  - Cycle slipping
    - Large frequency steps can over-range the PFD
  - VCO overload
    - AFC techniques are commonly used to reduce VCO gain
    - A low-gain VCO, desirable for noise immunity, may require high gain CP / LF
    - Loop filter transients can overload the tuning port of the VCO and / or saturate the CP output

# Sources of Spectral Impurity

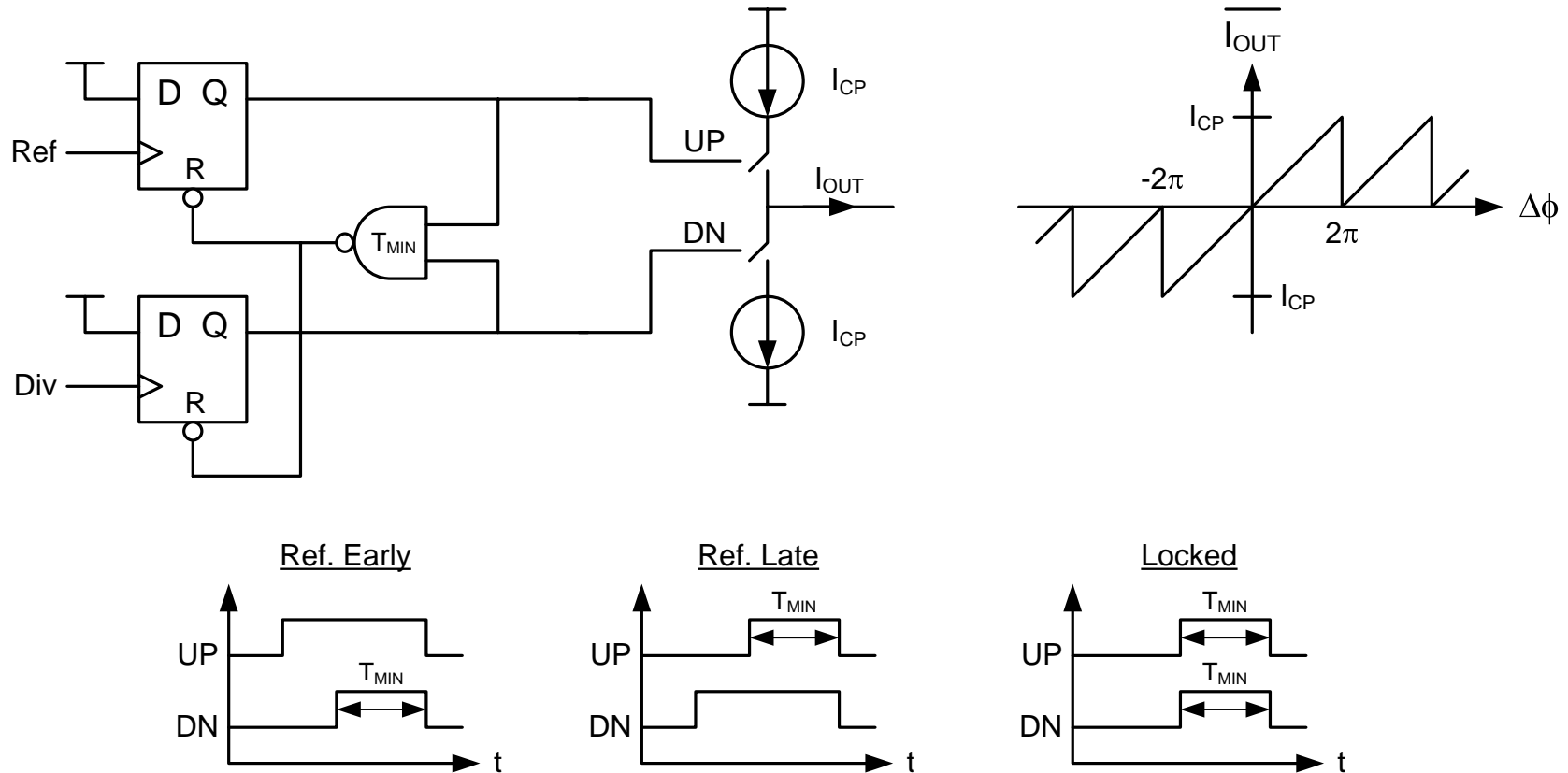
- Noise
  - VCO phase noise
  - Divider jitter
  - Noise coupling from other circuits
- Spurious
  - CP leakage
  - CP up / down current mismatch
  - Fractional divider spurs
- Noise and spurs refer to the PLL output via the *signal transfer function* (STF) and *noise transfer function* (NTF) of the loop.

# Modeling block-level noise contribs

- VCO
  - Typically have  $1/f^3$ ,  $1/f^2$  and flat noise asymptotes
  - $1/f^3$  corner not equal to process  $1/f$  corner
    - See Hajimiri & Lee reference
- Reference, dividers, etc...
  - Typically need to include  $1/f$  corner, esp. in CMOS
  - Dividers, PFD will require Spectre or HB simulation to estimate noise / power tradeoffs
- Low Frequency Limit
  - Spectral density levels off at low frequencies so that the total integrated power equals the carrier power.

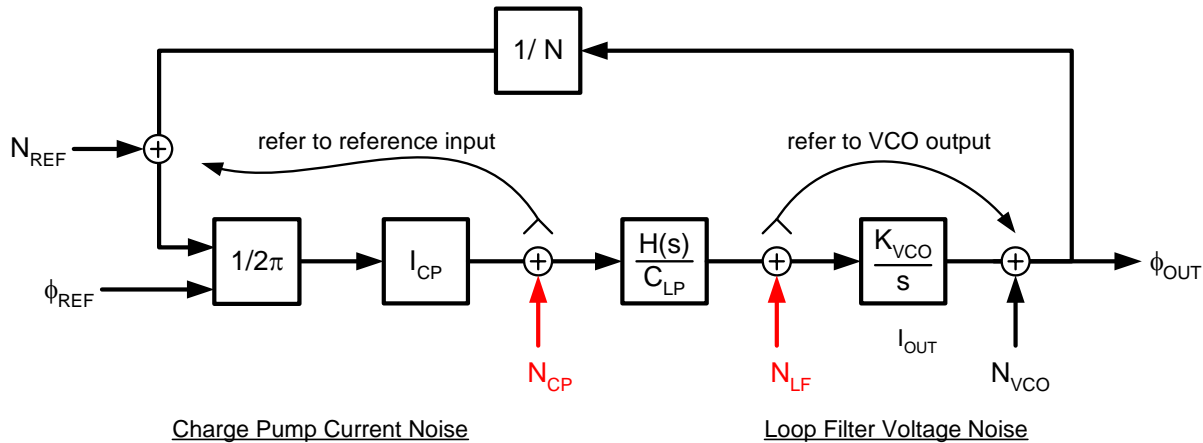


# Conventional PFD / CP Topology

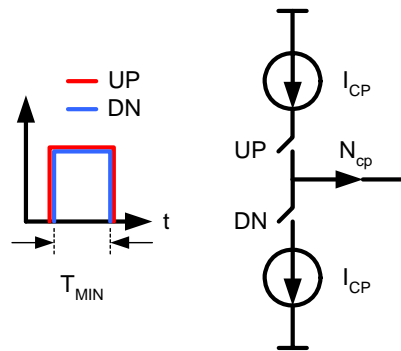


- PFD reset path incorporates a delay,  $T_{MIN}$ , which sets a minimum pulsewidth for the CP.
- This delay eliminates the 'dead-zone' due to runt CP pulses.

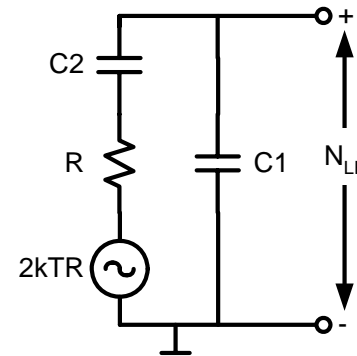
# Charge Pump / Loop Filter Noise



Charge Pump Current Noise



Loop Filter Voltage Noise



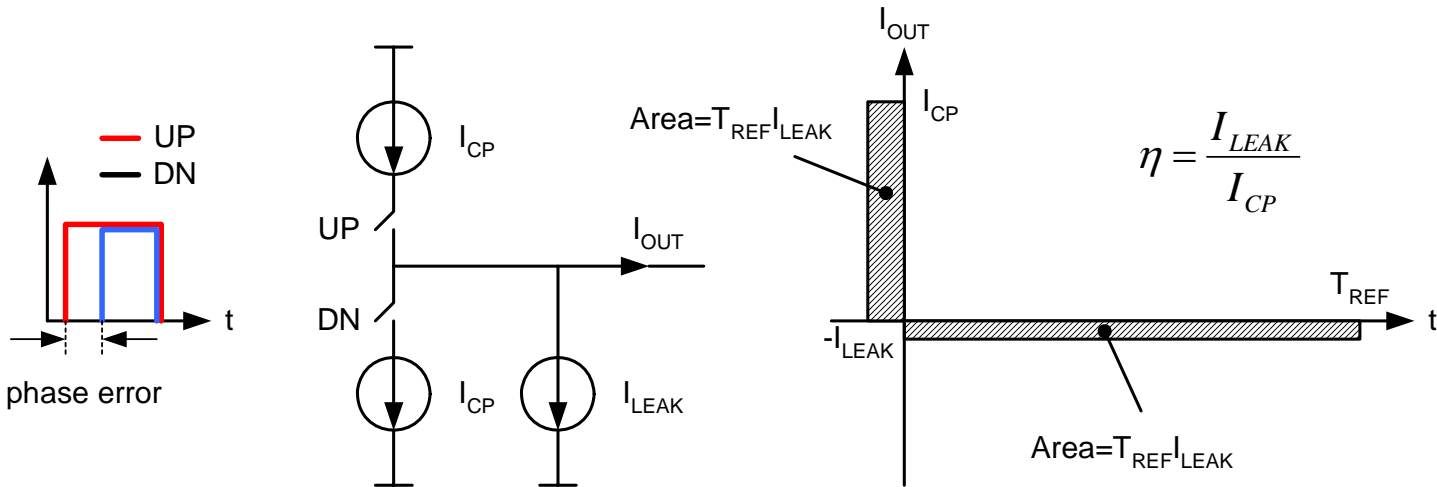
CP SSB noise density referred to reference input

$$S_{ICP} = 2\pi^2 \frac{T_{MIN}}{T_{REF}} \cdot \frac{\bar{i}_{CP}^2}{I_{CP}^2}$$

LF SSB noise density referred to VCO output

$$S_{LF}(\Delta f) \leq \frac{K_{VCO}^2}{\Delta f^2 \left( 1 + \frac{\Delta f^2}{f_Z^2} \right)} \cdot 2kTR$$

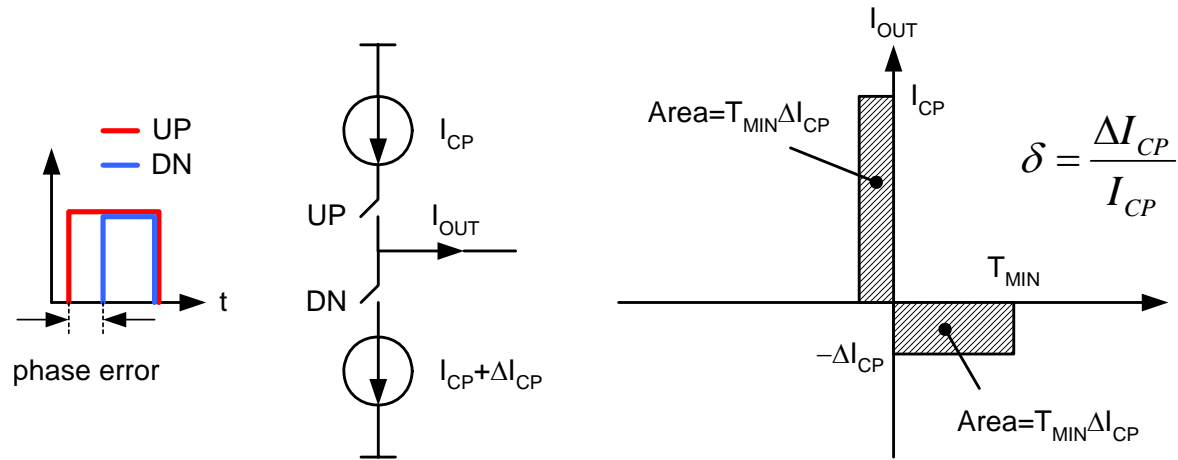
# Spurious Tones: CP Leakage



$$S(\Delta f) = 20 \log_{10} \left[ \frac{I_{LEAK} |Z_H(\Delta f)| K_{VCO}}{\Delta f} \right] = 20 \log_{10} \left[ \frac{2\pi\eta N \left(\frac{f_C}{\Delta f}\right)^2}{k_L} \sqrt{\frac{1 + \left(\frac{k_L \Delta f}{f_C}\right)^2}{1 + \left(\frac{\Delta f}{k_L f_C}\right)^2}} \right]$$

- Reference spurious level (dBc) at offset  $\Delta f$  from carrier is partly determined by charge pump leakage current as a percentage of the charge pump current ( $\eta$ ).

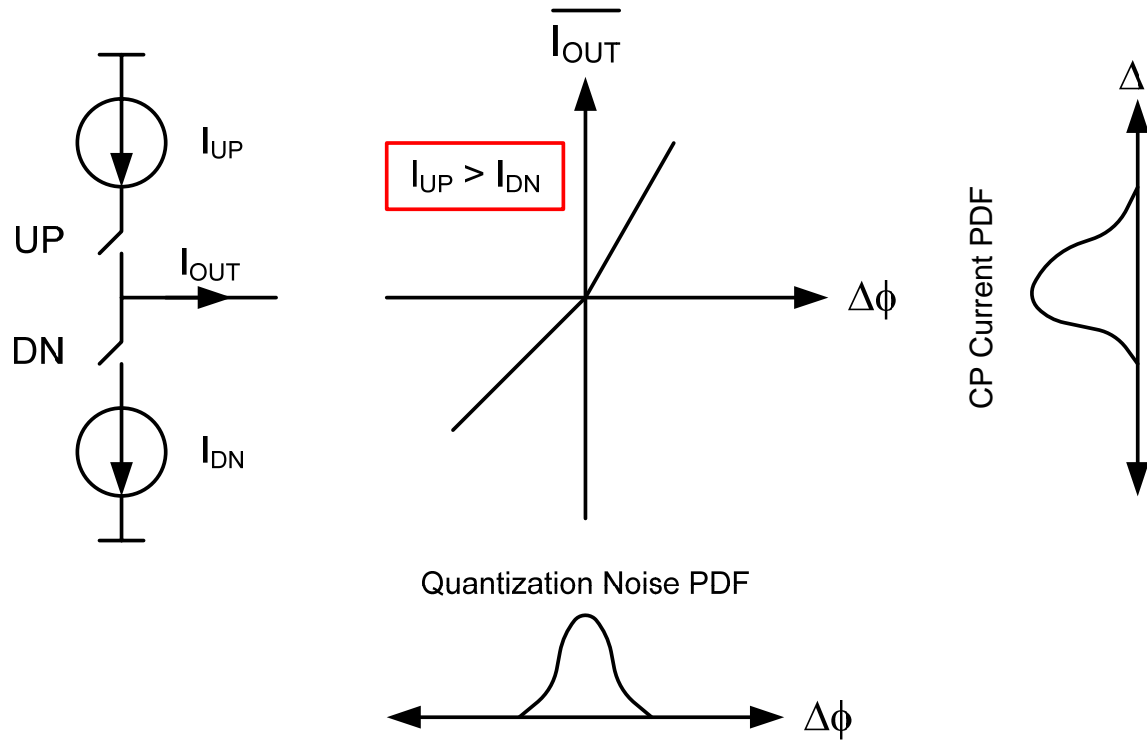
# Spurious Tones: CP Mismatch



$$S(\Delta f) = 20 \log_{10} \left[ \pi \cdot \Delta I_{CP} \frac{T_{MIN}^2}{T_{REF}^2} \cdot \frac{|Z_H(\Delta f)| K_{VCO}}{\Delta f} \right] = 20 \log_{10} \left[ \frac{2\pi^2 \delta N}{k_L} \frac{T_{MIN}^2}{T_{REF}^2} \left( \frac{f_C}{\Delta f} \right)^2 \sqrt{\frac{1 + \left( \frac{k_L \Delta f}{f_C} \right)^2}{1 + \left( \frac{\Delta f}{k_L f_C} \right)^2}} \right]$$

- Reference spurious due to CP mismatch is in quadrature with leakage spur, depending mainly on the UP / DN current mismatch ( $\delta$ ) and the minimum UP / DN pulsewidth ( $T_{MIN}$ ).

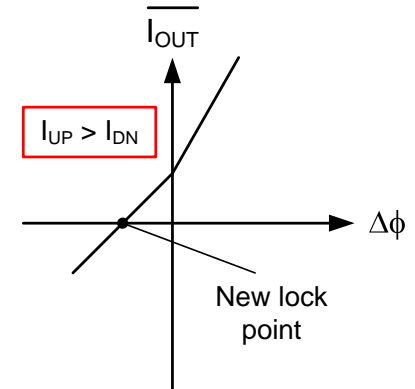
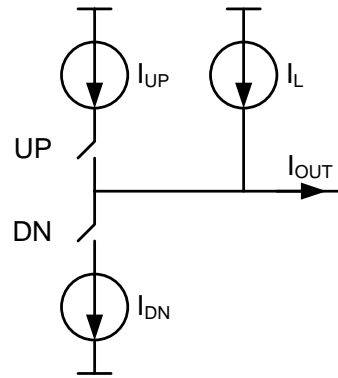
# CP Nonlinearity – Noise Folding



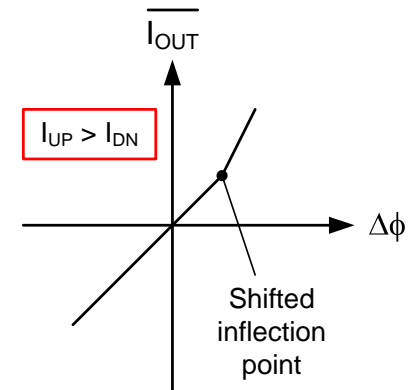
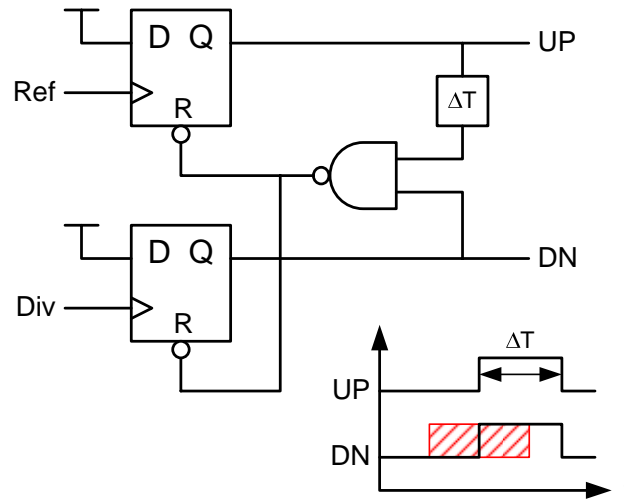
- CP Nonlinearity causes SD quantization noise to fall in-band.
  - Note the non-zero mean of CP current PDF.
  - Implies degraded residual P.M. due to noise folding to low frequencies.
- After folding, this noise cannot be rejected by the loop filter.

# Mitigating CP Nonlinearity

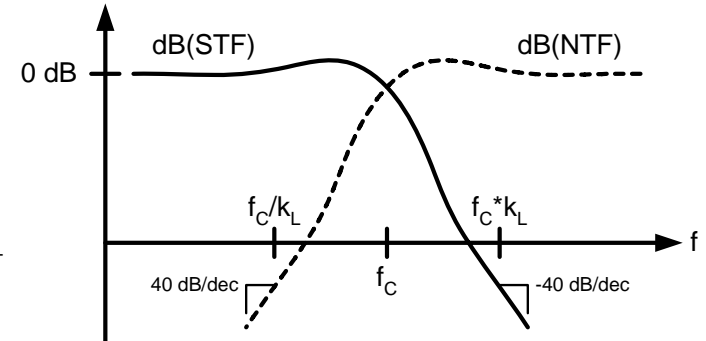
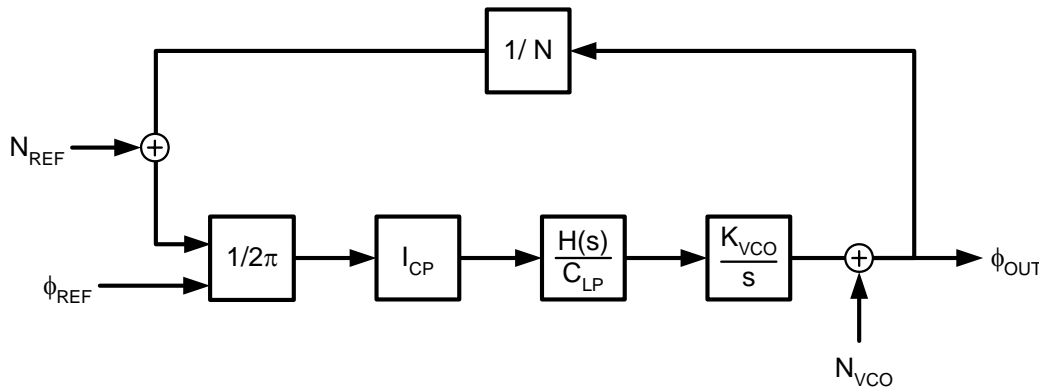
- CP offset current
  - Increased noise
  - Reference spur



- PFD delay offset
  - Longer  $T_{MIN}$
  - No reference spur



# 3<sup>rd</sup>-Order Type-II PLL NTF / STF



$$STF(s) = \frac{NT(s)}{1+T(s)}$$

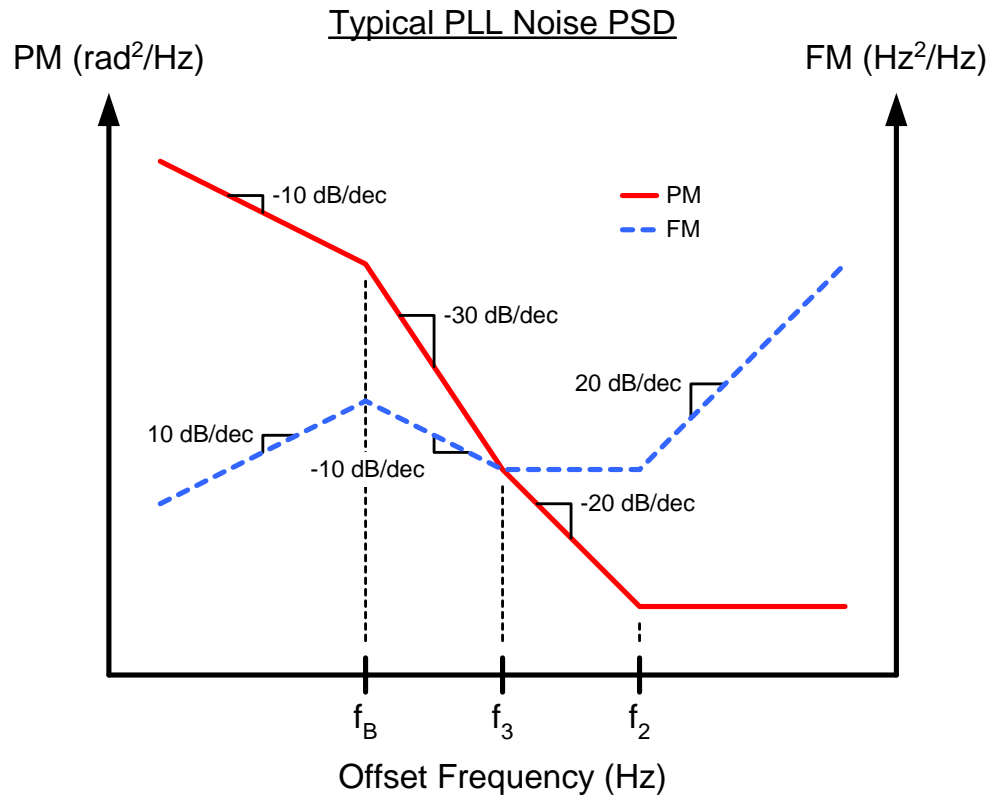
$$N_{OUT}(s) = N_{REF}(s) \cdot |STF(s)|^2 + N_{VCO}(s) \cdot |NTF(s)|^2$$

$$NTF(s) = \frac{1}{1+T(s)}$$

...where  $T(s)$  is the *PLL loop transmission*

- Noise sources can be referred to two points in the loop:
  - VCO output (VCO noise)
  - Reference input (Reference, PFD, CP, Divider)
- VCO noise is high-pass filtered by the loop noise transfer function
- Reference noise is low-pass filtered by the loop signal transfer function

# Residual PM and Residual FM



## Residual P.M.

$$\sigma_{\phi}^2 = 2 \int_{f_L}^{f_H} L(\Delta f) d\Delta f$$

## Residual F.M.

$$\sigma_f^2 = 2 \int_{f_L}^{f_H} \Delta f^2 L(\Delta f) d\Delta f$$

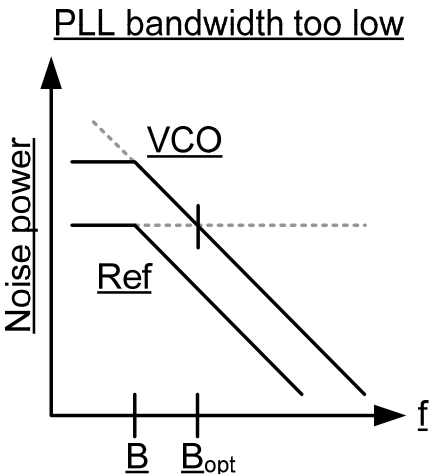
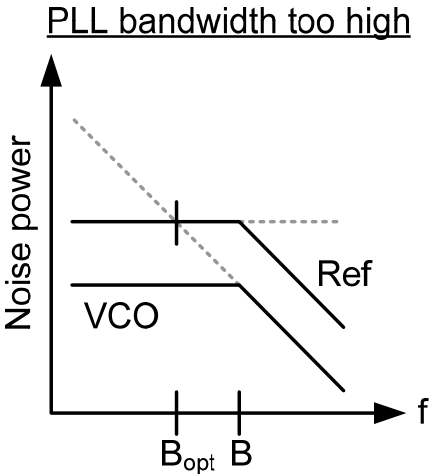
- For many systems, residual phase modulation contributes to RX SNR reduction
  - Reference noise tends to dominate
- For FM systems (incl. Bluetooth), residual frequency modulation is more relevant
  - Broadband (VCO) noise is much more important
- Low-frequency integration limit is determined by the carrier recovery loop bandwidth

# Useful Noise Integration Theorems

Noise Type	L(f)	Integrated MS Phase from $f_L$ to $f_H$	$f_0$ at which L(f) equals equivalent white noise
White	$S_0$	$2S_0(f_H - f_L)$	$f_0 = \frac{(f_H + f_L)}{2}$
1/f	$\frac{S_0 f_0}{f}$	$2S_0 f_0 \ln\left(\frac{f_H}{f_L}\right)$	$f_0 = \frac{(f_H - f_L)}{\ln(f_H/f_L)}$
1/f <sup>2</sup>	$\frac{S_0 f_0^2}{f^2}$	$2S_0 f_0^2 \left(\frac{f_H - f_L}{f_H f_L}\right)$	$f_0 = \sqrt{f_H f_L}$
1/f <sup>3</sup>	$\frac{S_0 f_0^3}{f^3}$	$2S_0 f_0^3 \left(\frac{f_H^2 - f_L^2}{2f_H^2 f_L^2}\right)$	$f_0 = \sqrt[3]{\frac{f_H^2 f_L^2}{f}}$

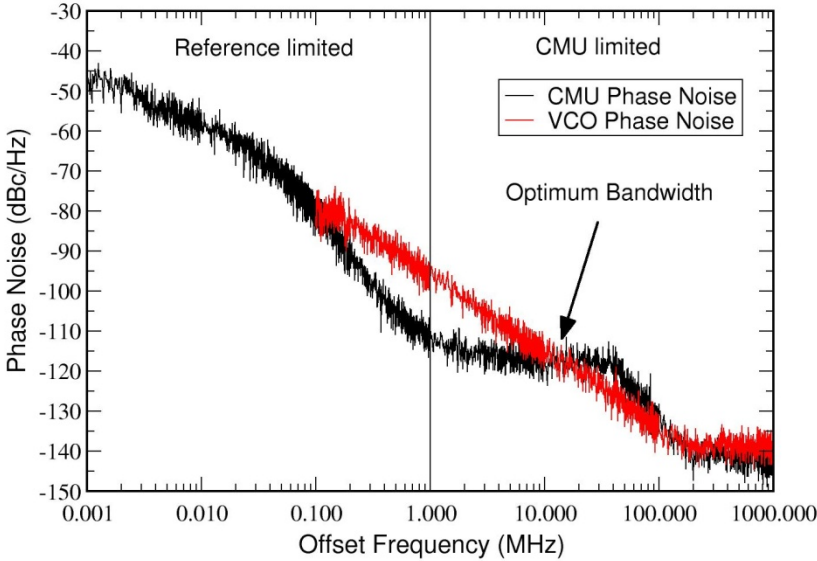
For  $f_0$  given in last column:  $\sigma_\phi^2 = 2L(f_0)(f_H - f_L)$  for all cases.

# Optimal BW for Integrated Noise



$$\sigma_J^2 = K \left( \frac{B}{B_{opt}} + \frac{B_{opt}}{B} \right)$$

↑ Reference      ↑ VCO



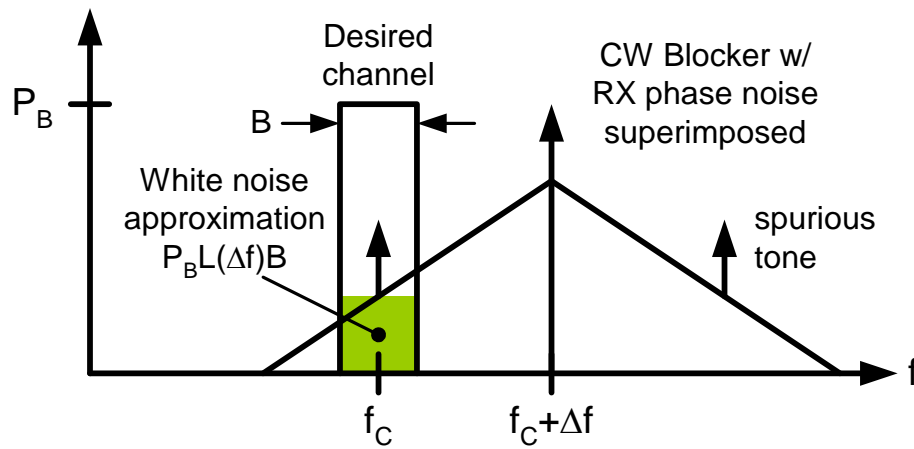
Shaeffer, et al., "A 40 / 43-Gb/s SONET OC-768 SiGe 4:1 MUX / CMU," ISSCC 2003

# Blocker Modeling

- Blocker specifications contemplate different types of interferers
  - CW (un-modulated) blockers
  - Modulated blockers within the same system
  - Modulated blockers from other systems
    - Especially true in ISM bands, where different types of systems have to co-exist, sharing the same spectrum
- Need to generate PSD for each blocker type that is required for evaluating PLL performance
  - Use MATLAB to generate power spectra using random data
  - Fit the power spectrum to a piecewise linear or simple functional representation for subsequent simulations
  - This is a good job for the systems guru in your group

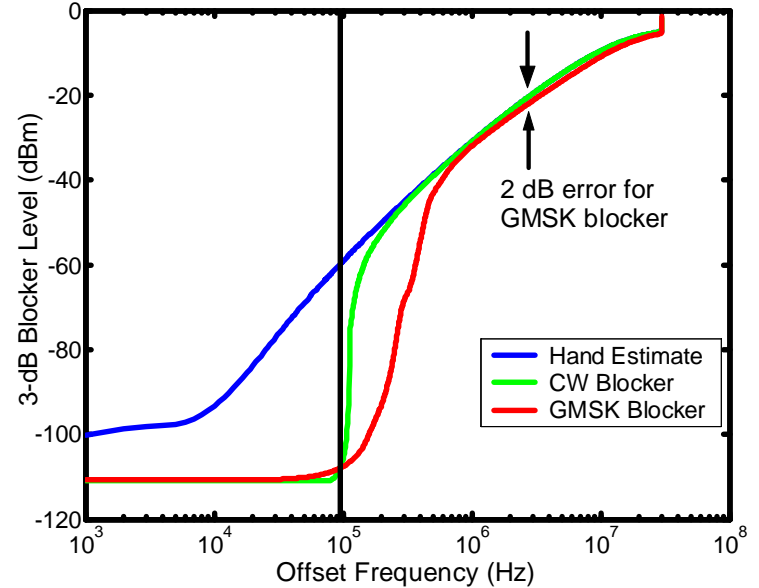
# Blocking Estimates and Phase Noise

Approximate phase noise required for a given 3-dB CW blocker desensitization



$$L(\Delta f)B + S(\Delta f) = \frac{P_{SENS}}{P_B(\Delta f)SNR_{MIN}} = \frac{F_{RX} kTB}{P_B(\Delta f)}$$

Accuracy of Simple Blocker Hand Calculations

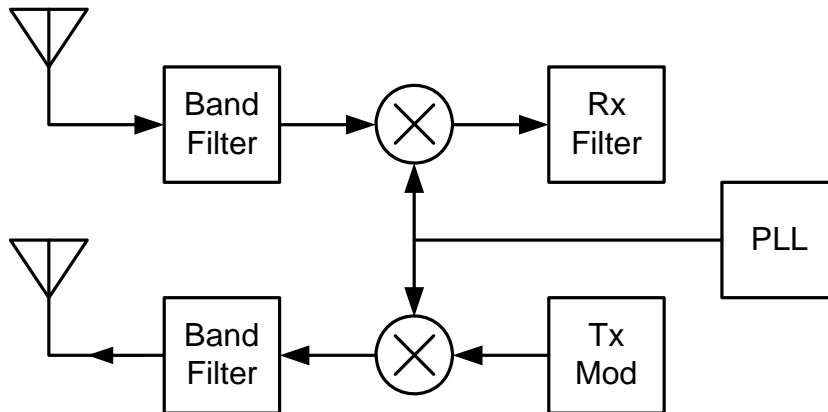


Expression includes phase noise and spurious tones (relative to carrier)

Shaeffer and Lee, "The Design and Implementation of Low-Power CMOS Radio Receivers," Kluwer, 1999.

# Putting it all together: TX / RX Model

Simple TX / RX MATLAB Model



## Received Blocker Power

$$P_B(\Delta f) = [S_B(\Delta f) \cdot S_{BAND}(\Delta f)] * S_{PLL}(\Delta f) * S_{RXFLT}(\Delta f)$$

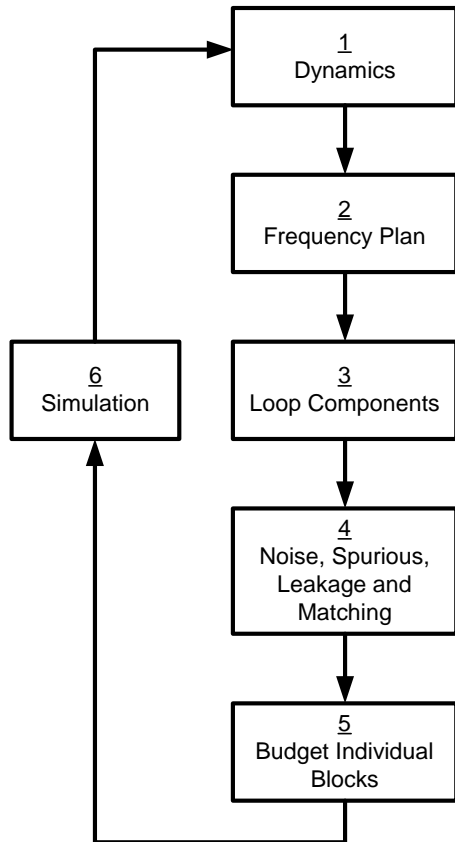
## Transmit Spectrum

$$P_{TX}(\Delta f) = [S_{MOD}(\Delta f) * S_{PLL}(\Delta f)] \cdot S_{BAND}(\Delta f)$$

- Bottoms-up model in MATLAB:
  - Assemble a complete PLL spectral model derived from block level specifications using the analytical techniques presented here
  - Assemble a transceiver model incorporating reasonable filter profiles
  - Calculate
    - Settling behavior (include reasonable variation for process!)
    - TX spectral profile
    - RX blocking profile
    - Residual PM / FM, as appropriate

# Example Calculations: GSM Rx

Specification Flow

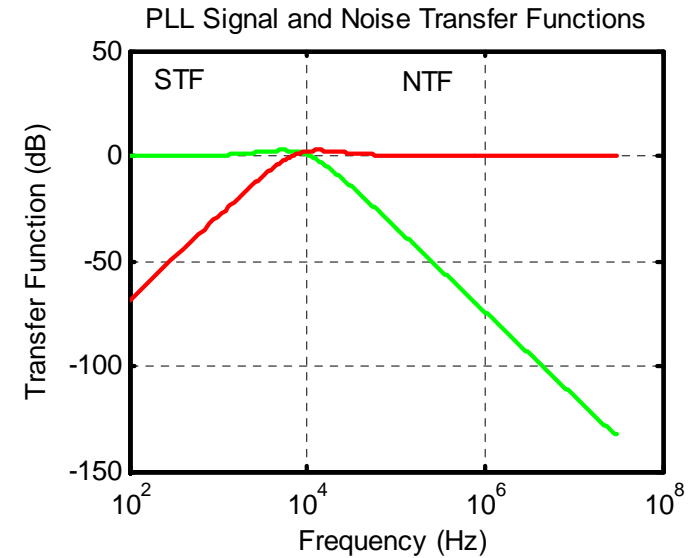
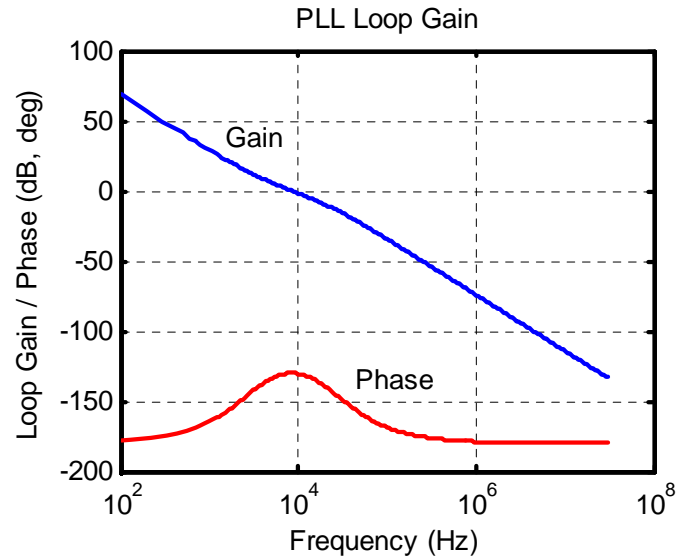


Step	System Requirements		Resulting PLL Specifications	
1	Settling Time	577 $\mu$ s	Max. Frequency Error	89 Hz
	W/C Frequency Step	25 MHz	Loop Bandwidth	8.7 kHz
	Carrier Frequency	890 MHz	Phase Margin	50 deg
	Frequency Tolerance	0.1 ppm	kL	2.747
	Loop Param. Manufact. Margin	+/- 15%	Zero Frequency	3.166 kHz
2			Pole Frequency	23.895 kHz
	Channel Spacing	200 kHz	Divider Range	4450 – 4575
	Tuning Range	25 MHz	Divider Type	Int-N
	VCO Frequency / LO Frequency	1	Reference Frequency	200 kHz
	Tuning Manufacturing Margin	30%	VCO Tuning Range	32.5 MHz
3			VCO Gain Slope	16.25 MHz/V
	Loop Capacitor Die Area	0.2 mm <sup>2</sup>	C1	26.5 pF
	CP Current Consumption	< 100 $\mu$ A	C2	173.5 pF
	Loop Resistor Noise Contrib.	< 10% of VCO	R	290 k $\Omega$
4			Icp	60 $\mu$ A
	Rx Sensitivity	-102 dBm	Spurious @ 600-kHz	< -74 dBc/Hz
	SNRmin	9 dB	VCO PN @ 600-kHz	< -127 dBc/Hz
	Channel Occupied Bandwidth	190 kHz	VCO PN @ 3-MHz	< -144 dBc/Hz
	Carrier Recovery Loop Bandwidth	100 Hz	1/f Corner Frequency	< 1.2-MHz
	Residual PM	5-deg, RMS	CP Leakage	< 12.35 ppm
	GSM Rx Blocker Mask	See 05.05	CP Offset	Not Critical
	Desired Mask Margin	3 dB	Ref. Chain PN @ 10-kHz	< -147 dBc/Hz

# Example Calculations: GSM Rx

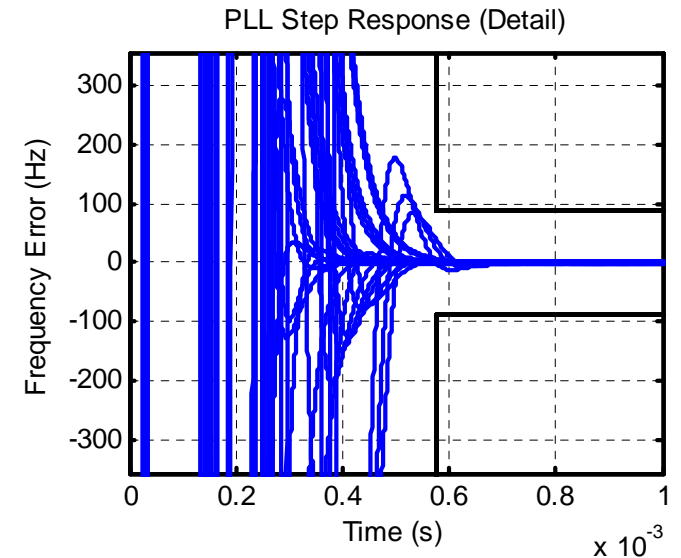
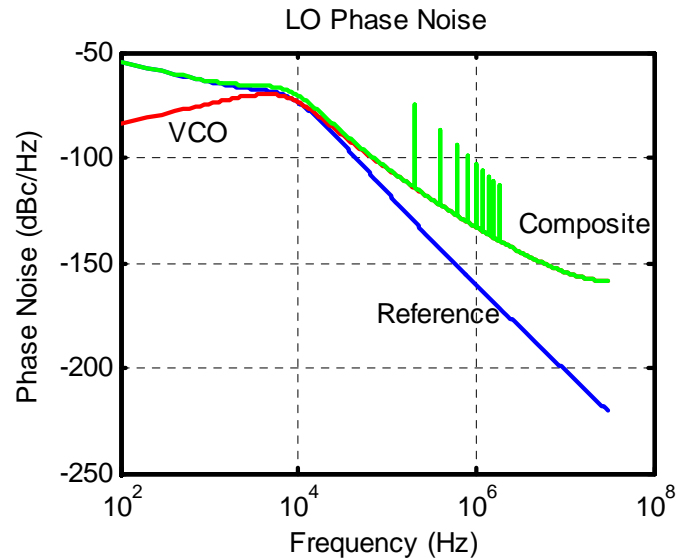
## PM / Jitter Performance

Residual PM	4.64 deg
Ref. Jitter	12.1 ps
VCO Jitter	7.9 ps



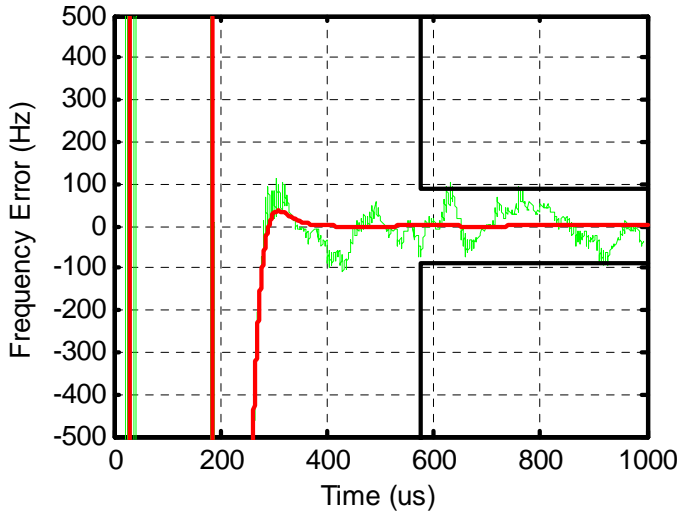
## Reference Spurious Table

Offset	Calc	CppSim
200 kHz	-55	-54
400 kHz	-67	-66
600 kHz	-74	-73
800 kHz	-79	-78
1000 kHz	-83	-82
1200 kHz	-86	-87
1400 kHz	-89	-89
1600 kHz	-91	-90
1800 kHz	-93	-92

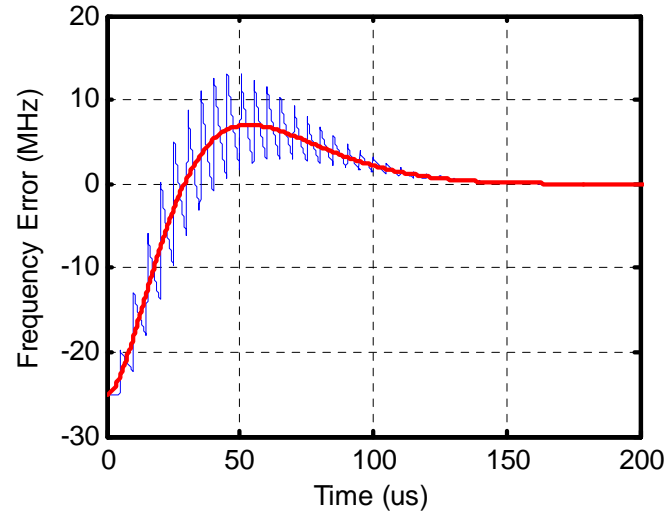


# Example Calculations: GSM Rx

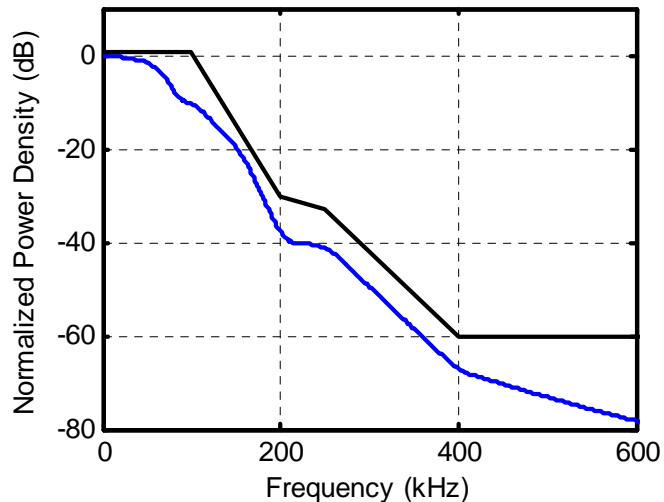
PLL Step Response (Detail) : CppSim vs. Linear Calculation



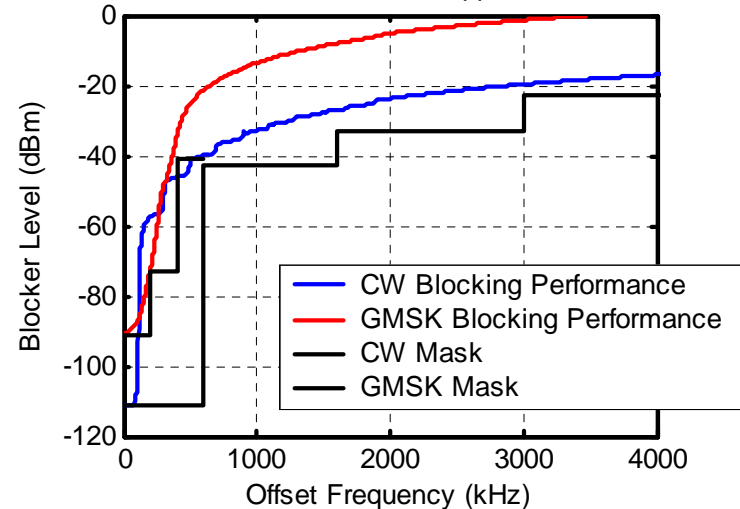
PLL Step Response : CppSim vs. Linear Calculation



GMSK Blocker Spectral Mask



Simulated Blocker Suppression



# Outline

- Understanding wireless systems specifications
  - The wireless channel and the issues it raises
  - Common performance specification types and techniques
- Developing frequency synthesizer specifications
  - Bandwidth, stability and settling behavior
  - Noise theorems and modeling techniques
  - Spectral impurity modeling and performance calculation
- **Summary**

# Summary

- Wireless standards typically seek to maximize link margin and minimize interference potential through four major specification categories:
  - TX spectral purity
  - RX selectivity
  - TX modulation accuracy
  - RX sensitivity
- Metrics in these categories relating to PLL performance were identified and discussed.
- A “tool-kit” for bottoms-up evaluation of PLL spectral performance and settling behavior was presented.
- A numerical example for GSM Rx applications was presented to illustrate the use of these techniques.

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