PLL Fundamentals

Part 1: PLL Building Blocks

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Overview

- Oscillators
  - Crystal Oscillators
  - High Frequency Oscillators
  - Voltage Controlled Oscillators (VCO)
  - Silicon Voltage Controlled Oscillators
  - Oscillator Phase Noise
- Other PLL Building Blocks
  - Counters
  - Phase Detector/Charge Pump
  - Loop Filter
Reference Oscillator

• Typically a fixed frequency of operation = $f_{OSC}$
• Can come in many forms
  • Crystal
  • Crystal Oscillator (XO)
  • Temperature Compensated Crystal Oscillator (TCXO)
  • Oven Controlled Crystal Oscillator (OCXO)
  • Output from another device
  • Recovered clock
  • DDS Signal
The Traditional Oscillator

- Output of Inverter is fed back to the input
- Frequency of oscillation is determined by delay of inverter
The Traditional Oscillator

- Delay of $\tau$ can be added in feedback path to set the frequency
  - $f = 1/\tau$
- A filter can also be added for a sine wave. Note that it is impossible to filter without delay, so a filter and a delay are related.
Typical Crystal Oscillator

- **Crystal**
  - $L_m$ (Motional Inductance)
  - $C_m$ (Motional Capacitance)
  - $C_p$ (Parallel Capacitance)
The VCO (Voltage Controlled Oscillator)

- Converts voltage to frequency
- Generates frequencies over restricted frequency range
- Frequency drifts considerably over temperature, voltage and process
- Typically Much higher frequency than the reference oscillator
VCO Frequency Tuning

- **VCO Figures of Merit**
  - Tuning Range
  - Output Power
  - Tuning Sensitivity ($K_{VCO}$ in MHz/Volt)
  - Tuning Linearity (Want $K_{VCO}$ constant)
  - Pushing (Frequency shift over supply voltage)
  - Pulling (Frequency shift over load)
  - Harmonics (Undesired Multiples of intended frequency)
  - Power Consumption
  - Size
  - Phase Noise
Understanding How VCOs Work

• Crystals and VCOs are Not the Same
  – Crystals are typically limited to lower frequencies (<100 MHz)
  – Crystals typically have a frequency range that is too narrow for most applications

• Hard to Relate VCO Circuits to Crystal Circuits
  – Higher frequency oscillators like VCOs often contain transistors and MOS devices that deal with currents, not voltages
  – Trying to relate a VCO schematic to this traditional oscillator model takes a lot of imagination.
Neglecting the Impacts of Friction, the pendulum conserves energy. It just converts it between potential and kinetic energy.

In the real world, there is friction, so a small stimulus needs to be applied to keep the circuit going.
The Tank Circuit

- Tank circuit can be viewed as an electronic spring.
  - When voltage across the capacitor is maximum, current in the inductor is minimum, and vice versa.
- Assuming no parasitic resistances, circuit would go on forever, but wouldn’t that be nice?

\[ f = \frac{1}{2\pi\sqrt{L \cdot C}} \]

\[ \tau = 2\pi \sqrt{\frac{L}{g}} \]
The Real World Inductor

- $Q_L(f) = \frac{X_L}{R_L} = \frac{2\pi f L}{R}$

- $Q$ is the quality factor, measured at the frequency of interest.
- Parasitic resistances, such as the one in the inductor cause the circuit to eventually stop oscillating.
- Just as with the pendulum, it is necessary to provide some stimulus to keep the circuit going.
Now Add the Stimulus

- Amplified signal from emitter is lightly coupled into the circuit to sustain oscillation
- Above Circuit is Colpitts Oscillator
Typical Clapp (Clapp-Gouriet) Oscillator

- Very similar to the Colpitts oscillator, except ..
  - Series capacitance C3 (Often adjustable), is typically added
  - This is better than Colpitts with a variable capacitor because changing the C3 capacitance does not change the feedback at C1 and C2.
The Varactor Diode

To implement the variable capacitance for the VCO, a varactor diode is often used. As more voltage is applied to the diode, the capacitance decreases.

\[ C_{\text{Varactor}}(V) = \frac{C_{\text{Varactor}}(0 \text{ volts})}{\sqrt{\phi + V}} \]

- 15-20 pF of capacitance is typical.
Complete VCO Circuit

- Varactor Diode Capacitance Adds to C3
  - Larger C3 => better Phase Noise, but less tuning range
- Resistor R5 isolates Tuning voltage from Loop Filter
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Integrating VCOs on Silicon

- **Inductance is Typically Formed by Bond Wires**
  - VCO frequencies tend to be higher due to low inductances
  - Can also do small inductors on silicon, but they are small
  - Can allow external inductors to be added for lower frequencies
  - Often easier to generate a higher frequency and divide it down
- **Capacitance is Formed by an Internal Bank of Capacitors**
  - Frequency calibration is typically necessary
Bank of Switched Capacitors

- Capacitors can be switched in and out to create multiple bands
  - The best phase noise and lowest tuning gain is often at the lowest frequency with all the capacitors switched in
- Logic is necessary to switch capacitors in and out to find the correct combination
  - On resistance of the switches is one source of phase noise
Silicon VCO Tuning Range

- VCO Range Divided into many bands
- These bands cover the whole frequency range and need
- Bands need to overlap to account for temperature drift
- Correct band is selected when frequency is changed
- This technique allows wider tuning range without sacrificing phase noise
Things to Watch for with Silicon VCOs

• Temperature Drift
  – If temperature changes without the VCO doing it’s frequency calibration, tuning voltage drifts towards a rail
  – Typically bands overlap to accommodate for this
  – National has a proprietary method to deal with this issue

• Calibration Time
  – Faster for higher OSCin frequencies
  – Improves lock time if bandwidth is narrow or if there are large cycle slipping issues
  – Hurts lock time if loop filter is fast (i.e. <400 us)
Phase Noise vs Mystery Parameter at 10 kHz Offset

-95 -90 -85 -80 -75

Mystery Parameter

Fout = 2120 MHz  Fout = 2210 MHz  Fout = 2290 MHz
Traditional vs. Silicon VCOs

- **Traditional VCO Advantages**
  - Potentially better performance (tuning range and/or phase noise) if there is a large tuning voltage supplied
  - Can be customized to frequency

- **Silicon VCO Advantages**
  - Lower Cost
  - Smaller Size
  - Higher Reliability
  - VCO to PLL mismatch issues eliminated
  - Wider tuning range for a given supply voltage
  - Extra bells and whistles
    - Programmable Output Power
    - Switchable Dividers
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Classical Oscillator Phase Noise Model

Phase Noise vs. Offset from Carrier, f

- **Total Oscillator Noise**
- **1/f² Region** (20 dB/decade)
- **1/f³ Region** (30 dB/decade)
- **Flat Region**
Lesson’s Equation

\[ L(f) = 10 \cdot \log \left( N3 \cdot \left( \frac{f_{default}}{f} \right)^3 + N2 \cdot \left( \frac{f_{default}}{f} \right)^2 + N0 \right) \]

- **Parameters**
  - \( N3, N2, N0 \) are constants to be discussed later
  - \( f_{default} \) is the default frequency where these constants are defined, and is constant
  - \( f \) is the offset frequency
1/f³ Region

- Noise Coefficient

\[ N3 = \frac{1}{f^3} \text{ Noise Coefficient} = \frac{F \cdot k \cdot T}{P} \cdot \frac{f_{vco}}{8 \cdot Q_L^2 \cdot f_{\text{default}}} \]

- Phase noise goes down by 30 dB/decade in this region
- Phase Noise is caused by the flicker noise of the transistor
- \( Q_L \) is the loaded Q of the inductor, and is the most important term and the one with the greatest influence
1/\(f^2\) Region

- **N2 Noise Coefficient**

\[
N2 = \frac{1}{f^2} \text{ Noise Coefficient} = \frac{F \cdot k \cdot T}{P} \cdot \frac{f_{vco}^2}{8 \cdot Q_L^2 \cdot f_{default}^2} + \frac{2 \cdot k \cdot T \cdot R_{var} \cdot K_{vco}^2}{f_{default}^2}
\]

- **Phase Noise goes down by 20 db/decade in this region**
- **\(R_{var}\)** is the noise resistance of the varactor diode. Note that for a larger VCO gain, \(K_{vco}\), this noise is multiplied.
  - Putting multiple varactor diodes in parallel helps reduce this noise.
- **Loaded \(Q_L\)** is also important
Flat Region

• Noise Coefficient

\[ N0 = VCO \text{ Noise Floor} = \frac{F \cdot k \cdot T}{P} \]

• Terms here
  – F is the noise figure
  – T is the temperature in Kelvin
  – k is Boltzmann’s constant
  – P is the output power

• Output buffer dominates here. High output power is good for phase noise because of the thermal noise floor

• Theoretically, the best VCO phase noise is at cold temperature and worse at hot temperature in all three regions
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Basic PLL Operation

\[
\frac{f_{\text{OSC}}}{R} = f_{\text{PD}} = f_{N} = f_{\text{VCO}}/N
\]

\[
f_{\text{VCO}} = f_{\text{OSC}} \cdot (N/R)
\]
Reference Oscillator and R Counter

- **Phase Detector Frequency**
  - Fixed frequency of operation = $f_{PD}$
  - Equal to the channel spacing for an integer PLL

- **R Counter Value**
  - $R = \frac{f_{OSC}}{f_{PD}}$
N Counter

- N Counter Value
  - $N = \frac{f_{VCO}}{f_N} = \frac{f_{VCO}}{f_{PD}}$
- Because the input to this counter can be high frequency, prescalers are typically inside this counter
Dual Modulus Prescalers

- VCO Frequency is divided by prescaler
  - Only the Prescaler has high frequency requirements
- After the prescaler and the 1-pulse swallow circuit, each cycle decreases the A counter by 1 cycle
  - This takes \( a \cdot (P+1) \) cycles
  - B Counter is also decreased with the A counter
• **After the A counter reaches zero ..**
  – Pulse Swallow circuitry is disabled
  – B counter counts down to zero
  – This takes \((b-a)P\) cycles
• **Total N Count**
  – \(N = a \cdot (P+1) + (b-a) \cdot P = P \cdot B + A\)
  – \(b \geq a\) is a consequence of this architecture
Quadruple Modulus Prescaler

Advantage Allows lower divide ratios.

\[ N = P \cdot C + 4 \cdot B + A \]
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Phase Frequency Detector/Charge Pump

- **Phase Frequency Detector (PFD)**
  - Detects Frequency Error Between N and R Counter
- **Charge Pump**
  - Converts this frequency Error to a Correction Current
- **Usually, the PFD and Charge Pump are Integrated Together**
Phase Frequency Detector/Charge Pump

- Detects differences in input signals
  - Detects phase error between 2 input signals
  - Detects frequency error between 2 input signals
- Outputs a voltage to the charge pump
  - The average value of this voltage is proportional to the phase/frequency error.
  - Along with the rest of the system, ensures the 2 input signals are the same frequency and phase
Phase Frequency Detector/Charge Pump

- **Charge Pump/Phase-Frequency Detector**
  - Sources Current if output frequency/phase is too low
  - Sinks Current if output frequency/phase is too high
  - High Impedance (tri-state) if output frequency/phase is correct (within tolerances)

- **Spurs Can Originate from the Charge Pump**
  - Want source and sink currents closely equal
  - Want tri-state to be very low leakage current

- Period = $1/F_{PD}$

- Tri-State (High Impedance)
  - Sourcing Current
  - Sinking Current
Charge Pump Current

![Charge Pump Current Graph](image)

- Charge Pump Voltage (V):
  - Vp=3V
  - Vp=5V

- Charge Pump Current (mA):
  - Kφ
• The loop filter is a low pass filter
  – Accumulates correction currents from the Charge pump into a voltage
• The loop filter has a dramatic effect on performance
  – Determines the loop bandwidth
  – Impacts switching speed
  – Impacts spurs
  – Can impact phase noise
  – Many Design trade-offs involved
  – National has tools for this
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