Towards Single Tapeout Crystal Free IoT Mote Design: Investigating Free Running Oscillator Simulation Inaccuracies

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Abstract

Crystal-free communication is the next step towards low-power sustainable Internet of Things (IoT) devices. Local Oscillator (LO) stability is paramount for optimal performance in RF communication systems. Frequency fluctuations in the LO can result in problems such as reciprocal mixing and carrier mismatches, resulting in higher Bit Error Rates (BER) and receiver guard time. While traditional communication systems rely on crystal oscillators and Phase-Locked Loops (PLLs) to maintain frequency stability, the power and area constraints, and sometimes battery-less nature of IoT motes necessitate their elimination. The solution is to use low-power free-running oscillators that can meet the stability requirements of communication standards such as IEEE 802.15.4 and Bluetooth Low-Energy (BLE). However, the design of free-running oscillators is especially challenging due to the long simulation times, and the number of tapeout iterations required to meet the specifications. Not only does the oscillator have a non-linear large signal behavior, but the effects of flicker noise at frequencies close to the carrier are often masked in the simulations due to the Lorentzian tappering; primarily because this region is traditionally expected to be dealt with by the PLL. By investigating the simulation inaccuracies involved in the early stages of free-running oscillator design, we aim to assist designers in getting their first tapeout to meet the desired specifications, thereby reducing the number of tapeouts required as well as the environmental impact that they may have.

Crystal Free IoT

Visual Illustration of various devices connected together in Internet of Things (IoT). Image generated using Pixlr AI tool [1].

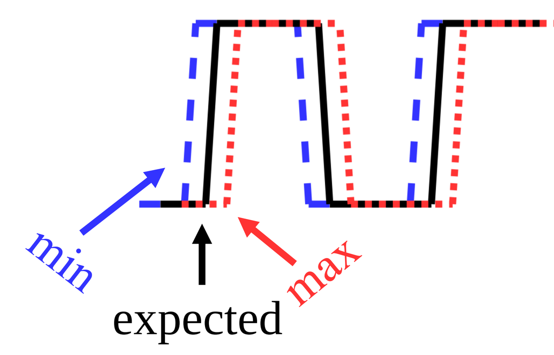
- IoT (Internet of Things) devices are sensors or everyday objects connected together
- They gather data, or perform everyday tasks, and communicate with a server (or your computer/phone)
- The goal of crystal free IoT is to reduce the power consumption required by these devices

Problem Statement

- Oscillator phase noise simulations are tricky, especially in the low offset close to carrier regime that is flicker dominated
- This region is typically expected to be controlled by the PLL and crystal reference
- Fast (AC) simulation methods tapper off this region (Lorentzian effect), whereas long (transient) simulation methods take several days to weeks
- Hitting target specifications with free running oscillators may involve several design iterations with silicon fabrication which is unsustainable.

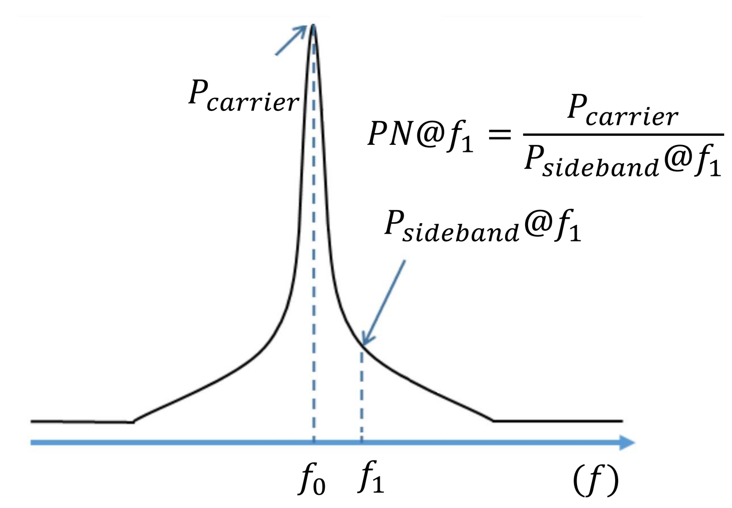
What is Oscillator Phase Noise?

- Device and supply noise cause timing uncertainties
- Resulting in frequency fluctuations
- Called phase noise/jitter



How is Phase Noise Measured?

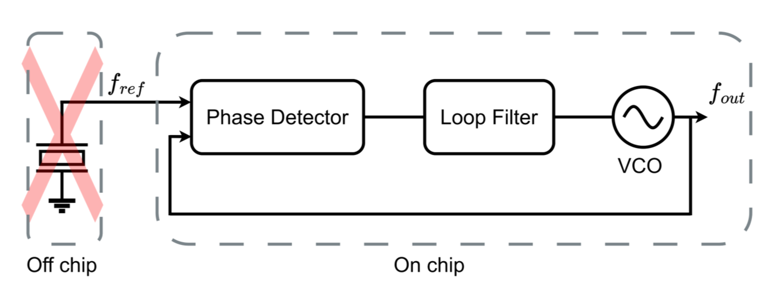
- Power is measured at offsets from the carrier frequency
- Phase noise is ratio of this power to the carrier power
- Expressed in dBc/Hz units (dB w.r.t carrier)
- Often shown only on one side of carrier



Phase Noise Measurement. Adapted from [3]

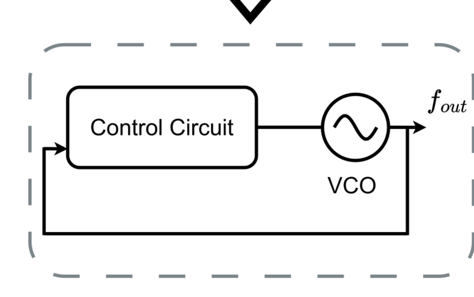
How is Phase Noise Suppressed?

A typical PLL system with an off-chip crystal reference



The high Q crystal provides a stable frequency reference with low phase noise

Crystal requires area and power, both are limited resources in IoT motes



The goal is to eliminate the off-chip crystal.

The solution is free-running oscillators that can meet the stability requirements of modern communication systems

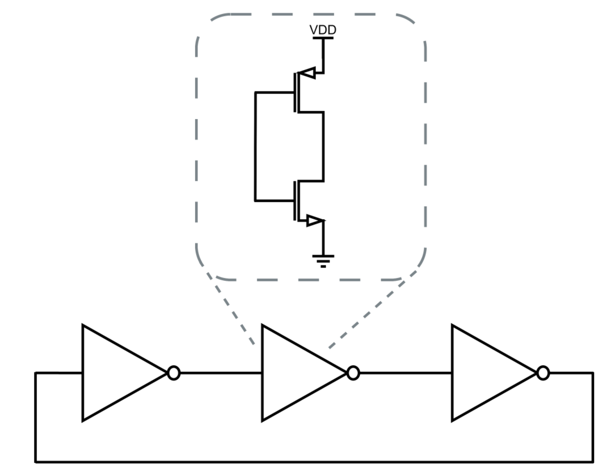
Objectives

- To investigate phase noise simulation methods for free running oscillators, especially at low offset frequencies (close to the carrier)
- To compare simulation results with measurements (without a PLL)
- Determine the validity of Lorentzian tapering in case of free running oscillators

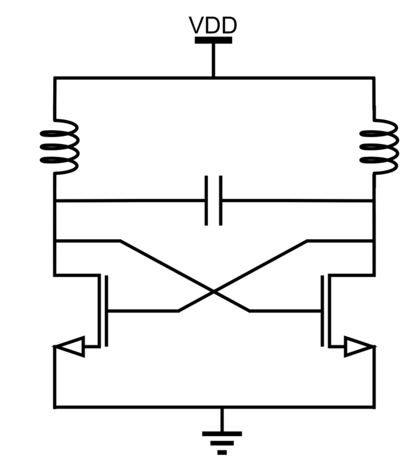
Simulation Methods

- AC Simulation Methods:
  - Fast simulation time, but generally considered less accurate
  - Shows Lorentzian tapering at low frequency offsets to avoid sideband powers greater than carrier.
  - Two main types:
    - Large signal AC simulations: Pnoise (Periodic Noise). Suitable for highly non-linear RC and ring oscillators.
    - Small signal AC simulations: HBNoise (Harmonic Balance Noise). Suitable for high-Q crystal oscillators and LC oscillators
- Transient Noise Simulation Method:
  - Runs long transient simulations
  - Generally considered as most accurate method
  - May take several days or weeks
- However, these simulation methods give different results when computing phase noise
  - This makes it difficult to predict phase noise of free running oscillators through simulations, forcing design iterations with Silicon fabrication.

Circuits Under Test (Free Running Ring/LC Oscillator)



Three stage Ring Oscillator

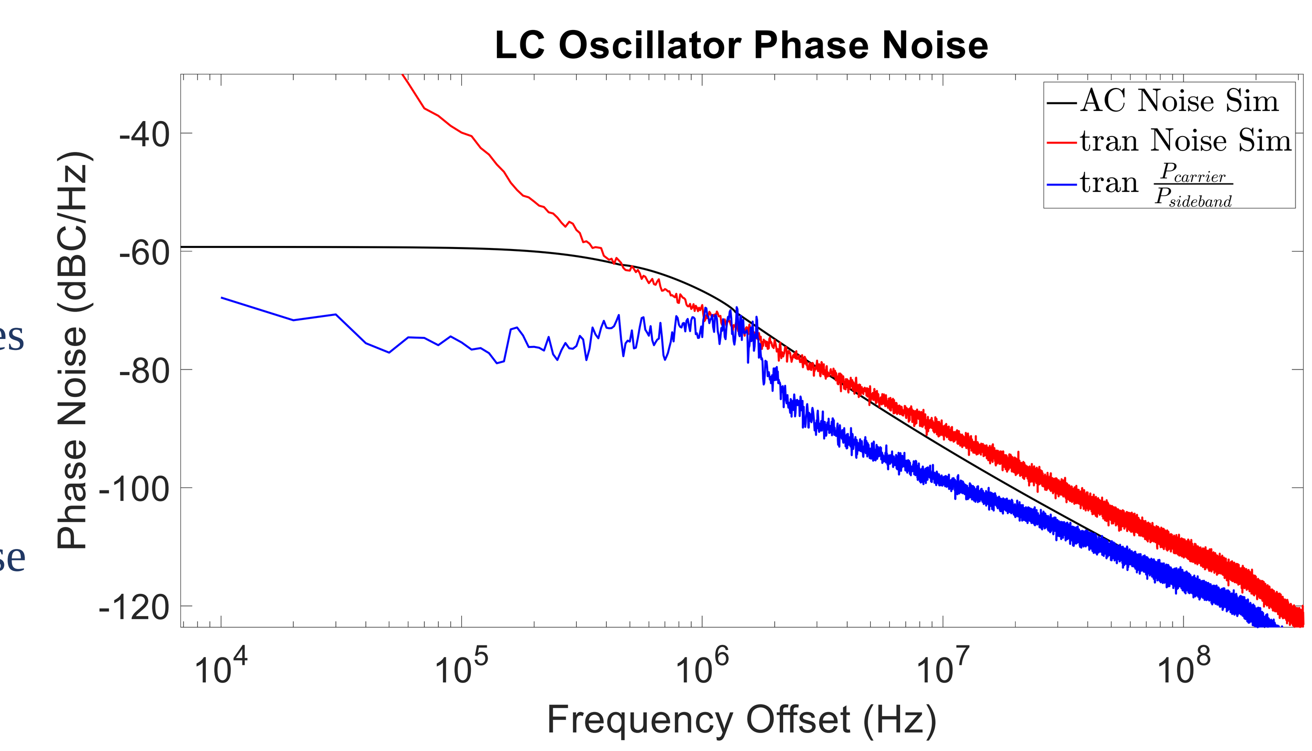


Cross coupled LC Oscillator

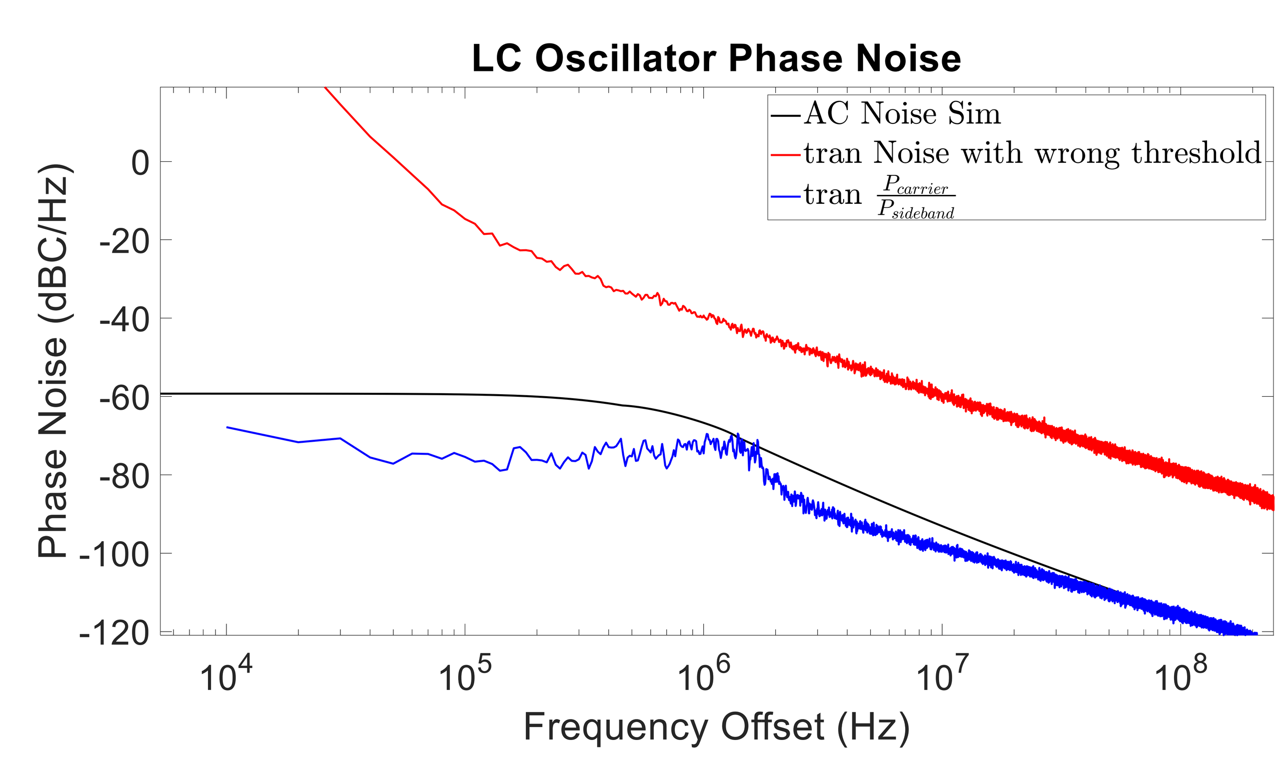
- Very low power and on-chip area
- But suffers form poor phase noise

- Moderate power, but large on-chip area
- Better phase noise than Ring, but worse than crystal

Phase Noise Simulation Results



- Different Phase Noise computation methods give varying results
- The AC Noise simulation method (aka PNoise) shows Lorentzian tapering at low offset frequencies
- Transient noise simulation methods also vary



- Furthermore, when using transient noise methods, using wrong voltage threshold for computation gives huge offset in calculated phase noise

Current and Future Work

- Currently investigating these simulation differences
- Future work would include making real oscillators in Silicon and testing phase noise to compare with simulation results

References

[1] AI Image Generator - PIXLR, https://pixlr.com/image-generator/ (accessed Apr. 7, 2024).

[2] B. Razavi, RF Microelectronics. Pearson Education, 2011.

[3] K. Siddiq, M. K. Hobden, S. R. Pennock and R. J. Watson, "Phase Noise in FMCW Radar Systems," in IEEE Transactions on Aerospace and Electronic Systems, vol. 55, no. 1, pp. 70-81, Feb. 2019, doi: 10.1109/TAES.2018.2847999.

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