

# Optimizing Clock Synthesis in Small Cells and Heterogeneous Networks

## Introduction

Mobile network operators are increasingly turning to small cell base stations to expand coverage, increase capacity and enable network densification in congested, high-traffic urban environments. Small cells are low-power radio access nodes that can be used by operators to offload mobile data to Internet Protocol (IP) networks and enable more efficient use of radio spectrum in 4G/LTE applications. Small cells are playing a critical role in helping service providers address escalating bandwidth demand. To fully realize the benefits small cells will provide, small cells must first be optimized in terms of size, power, performance and cost. This optimization is critical because small cells must be deployed in compact, space-constrained, non-temperature-controlled outdoor locations. Minimal power consumption is important because small cells are often powered using Power over Ethernet (PoE) solutions. To date, significant effort has been made to optimize baseband system on a chip (SoC) and digital radio front end performance and integration. This whitepaper focuses on a portion of the small cell design that is often overlooked – timing and clock synthesis. New IC architectures are now available that enable lower power, smaller form factor and higher performance small cell clock synthesis.

## Architectures for Low Phase Noise Integer-N PLLs

There are two approaches to building chip architectures for low phase noise integer-N PLLs used in small cell applications. Figure 1 shows the conventional analog architecture used to implement a jitter attenuating phase-locked loop (PLL) for wireless infrastructure applications. This two-stage cascaded PLL architecture uses a discrete, analog narrowband VCXO-based PLL to implement jitter cleaning in the first loop. The VCXO is used as the PLL VCO because of its low phase noise. The second stage PLL relies on an analog wideband PLL to provide clock multiplication. The conventional architecture requires discrete loop filter components in addition to the discrete VCXO.

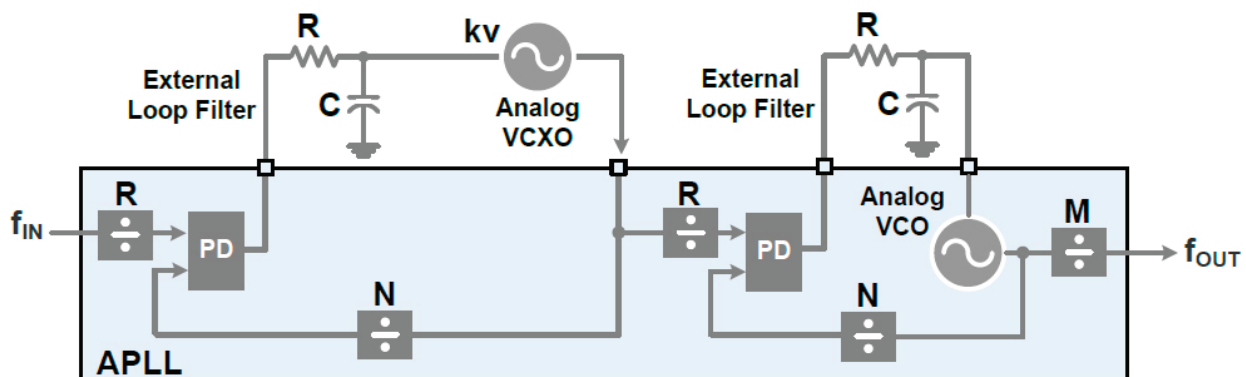


Figure 1. Cascaded PLL Architecture

Figure 2 shows an alternate approach using Skyworks' proprietary fourth-generation DSPLL architecture. DSPLL technology uses a dual-loop PLL architecture with an inner loop and outer loop to realize a low bandwidth jitter attenuating PLL. The inner loop works as a digitally controlled oscillator (DCO) for the outer loop. The inner loop is a wideband PLL based on a low phase noise 15GHz analog LC-oscillator. Rather than controlling the VCO using analog circuitry, the oscillator is digitally steered using a high-resolution frac-N feedback divider. The frac-N feedback divider is modulated in precise steps to enable the entire inner loop to operate as a DCO. The LC-oscillator provides a wide tuning range, enabling the inner loop PLL to operate over a wide frequency range. A low-cost fundamental mode, non-pullable crystal is used as the inner loop reference. The loop filter function is implemented digitally without the need for discrete components.

The DSPLL outer loop performs three functions: synchronization to an externally provided reference clock, jitter attenuation and clock multiplication. Since the inner loop is digitally controlled, the DSPLL outer loop can similarly be implemented using a highly digital architecture. The DSPLL outer loop filter is entirely implemented on-chip using an advanced analog-to-digital converter (ADC) and digital-signal processing (DSP) based architecture, simplifying printed-circuit board (PCB) layout and design and maximizing immunity to board-level noise. An added benefit of this architecture is user-programmability of critical PLL parameters such as the PLL loop bandwidth. The effective frequency tuning resolution of this architecture is 1 part-per-trillion (ppt), enabling very precise PLL control. An added benefit of the DSPLL architecture is no bill of materials (BOM) changes are required to support different input and output frequencies and loop bandwidths.

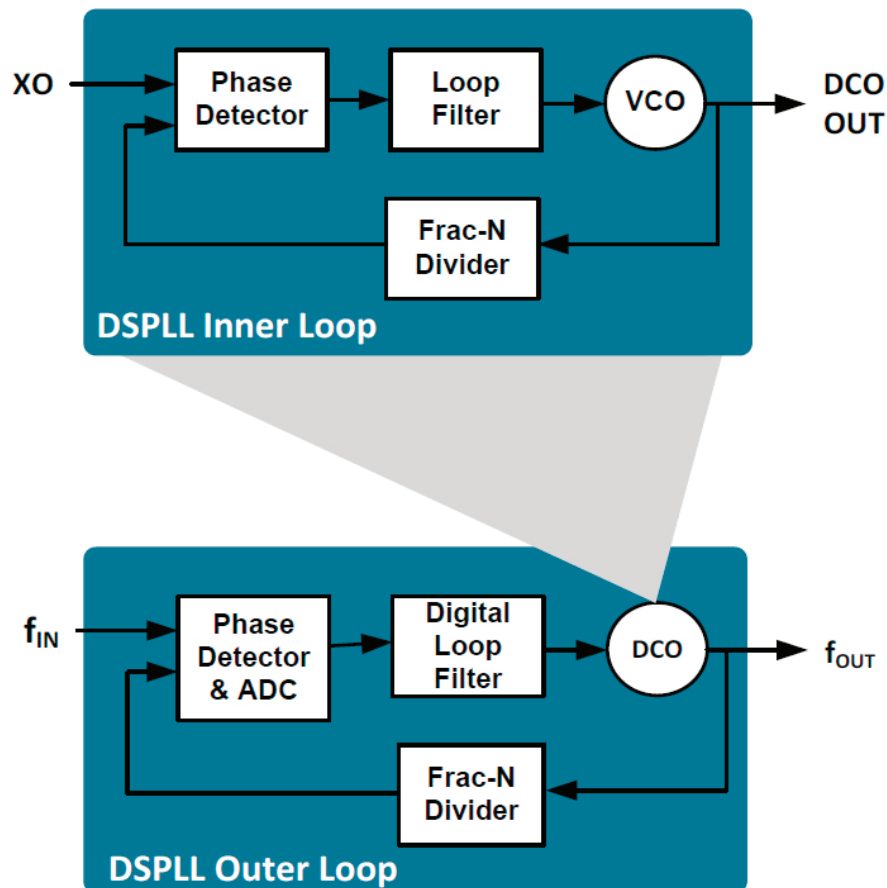


Figure 2. DSPLL Dual-Loop Architecture

## DSPLL Phase Noise Optimization

Skyworks' proprietary DSPLL architecture has been developed and refined over the last 15 years to provide ultra-low phase noise clock generation for high-speed data converters and 10/40/100G transceivers. This innovative architecture combines both analog and digital elements to achieve best-in-class integration and performance. Figure 3 illustrates how Skyworks' fourth-generation DSPLL has been optimized for phase noise. In this example, all frequencies have been normalized to 1 GHz. At close-in offset frequencies, the DSPLL architecture's phase noise closely follows the crystal used as a reference for the inner loop. The DSPLL architecture uses a low-cost, fundamental mode, non-pullable crystal with excellent close-in phase noise. At higher offsets (~1 MHz), DSPLL phase noise follows the voltage-controlled oscillator (VCO). Skyworks' fourth-generation DSPLL architecture uses an ultra-low phase noise LC-oscillator designed in the most advanced CMOS process node used in the timing industry (55 nm CMOS) to achieve very low phase noise at high offset frequencies. The phase noise at the DSPLL output (shown in dark blue) is a combination of these elements, providing optimal performance in a fully integrated solution. The loop bandwidth of the DSPLL can be digitally programmed by the developer to set the point at which the reference clock jitter is filtered (~1 kHz in the diagram below). If the input has relatively low phase noise at close-in offset frequencies, a higher DSPLL loop bandwidth is recommended. If the clock input has higher close-in phase noise, a lower DSPLL loop bandwidth is preferred. The programmability of the DSPLL loop bandwidth enables customers to optimize jitter transfer versus jitter generation to achieve the lowest phase noise possible depending on input conditions.

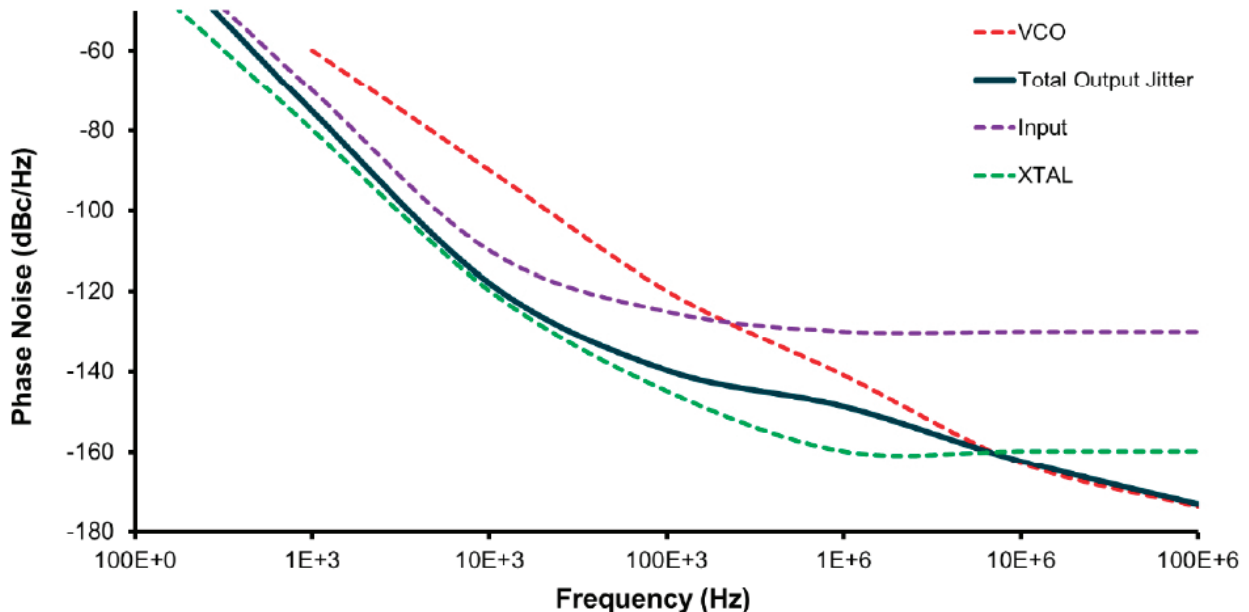


Figure 3. DSPLL Phase Noise Optimization

## Advantages of the DSPLL Architecture

The single-oscillator DSPLL architecture provides unparalleled integration and flexibility compared to conventional, two-oscillator analog cascaded PLL architectures. While these two architectures provide similar functions, including jitter attenuation and clock multiplication, there are significant differences in terms of PCB footprint, power consumption and performance.

## PCB Footprint

Table 1 compares the PCB footprint of the two architectures. Note that this comparison is a sum of component area only without regard to PCB spacing or design rules. The DSPLL PCB footprint is three times smaller than the cascaded PLL due to a combination of factors. The DSPLL does not require a large, bulky VCXO, simplifying the PCB layout and design while minimizing the total solution cost. The DSPLL loop filters are integrated on chip, further simplifying the PCB layout. The DSPLL uses multiple on-chip voltage regulators to filter board-level supply noise and minimize the need for discrete filtering components. In contrast, cascaded PLLs require more dedicated power supplies, each with its own unique filtering requirements. DSPLL-based products do not require a low drop-out (LDO) regulator, while the cascaded PLL's VCO is sensitive to noise injection and requires an external LDO for power supply filtering. The DSPLL architecture's small footprint makes it a better choice for space-constrained small cell, pico cell and mobile backhaul applications.

Cascaded PLL	Area (mm <sup>2</sup> )	Si5380 DSPLL	Area (mm <sup>2</sup> )
DUT	81.0	DUT	81.0
VCXO	151.2	Crystal	8
Loop filters	9.3	Loop filters	0
Supply filtering	22.8	Supply filtering	3.7
Other	17.7	Other	1.5
<b>Total</b>	<b>282.0</b>	<b>Total</b>	<b>94.3</b>

Table 1. DSPLL Architecture Delivers 66% PCB Area Savings vs. Cascaded PLL

## Power Consumption

There is a significant difference in power consumption between cascaded PLL and DSPLL-based clock devices. Table 2 shows the typical power consumption of the two options. The unique, all-digital DSPLL architecture is more power-efficient, consuming more than 30 percent less power than analog PLL-based cascaded PLL devices. Skyworks' fourth-generation DSPLL-based products combine the most advanced process technology used in the timing industry (55 nm CMOS) with an efficient, digital-intensive architecture to deliver significant power savings versus conventional solutions. A power-efficient architecture is especially important for PoE-powered small cells and pico cells given their limited power budget.

Description	Cascaded PLL	Si5380 DSPLL
Supply Voltage	3.3 V	3.3 V analog + 1.8 V core
Supply Current	600 mA	300 mA
<b>Power</b>	<b>1.9 W</b>	<b>1.3 W</b>

Table 2. DSPLL Delivers >30% Power Savings vs. Cascaded PLL

## Phase Noise Performance

Cascaded PLLs rely on discrete voltage-controlled crystal oscillators (VCXOs) to deliver excellent phase noise and jitter performance (see Figure 4). On the other hand, these solutions are more susceptible to board-level noise since each of the discrete nodes in the architecture, including the charge pump output, loop filter and VCXO, is a potential point for noise entry.

The DSPLL architecture delivers even better phase noise performance as cascaded PLL + VCXO arrangements without the need for discrete VCXOs, loop filters or LDOs (see Figure 5). As an added benefit, DSPLL-based products are more immune to board-level noise since the architecture is fully integrated.

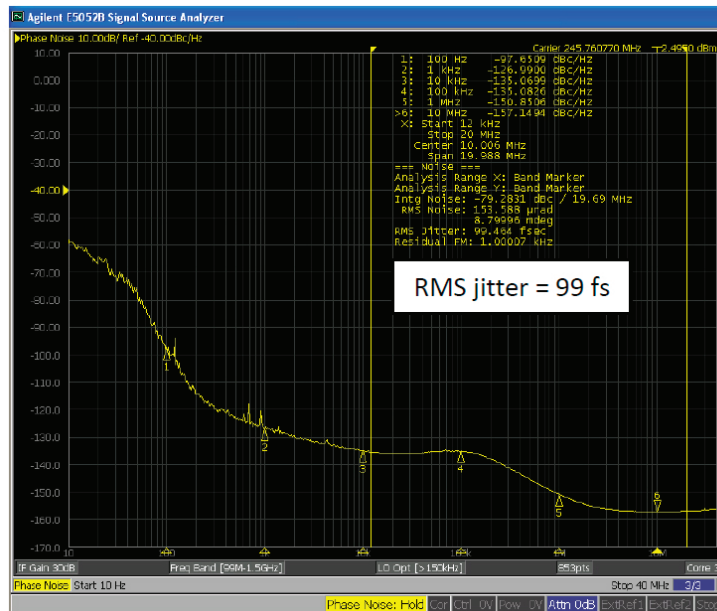


Figure 4. Cascaded PLL Phase Noise Performance (245.76 MHz carrier)

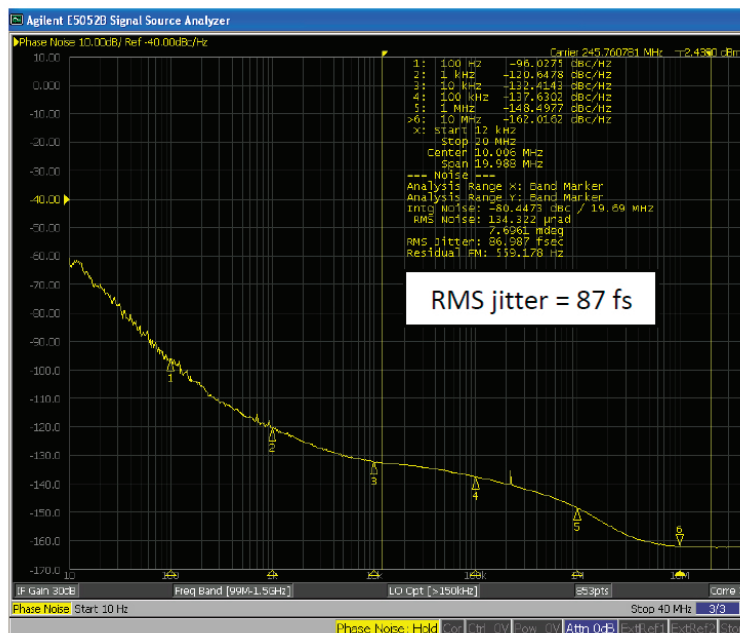


Figure 5. DSPLL Phase Noise Performance (245.76 MHz carrier)

An added benefit of the DSPLL architecture is highly consistent performance over temperature. Figure 6 shows the DSPLL architecture's phase noise at -40, 0 and 85 degrees Celsius. Consistent phase noise performance is critical in small cell and repeater applications since this equipment is typically deployed in a non-temperature-controlled environment. The measurement below assumes a highly jittered reference clock is provided as an input to the DSPLL.

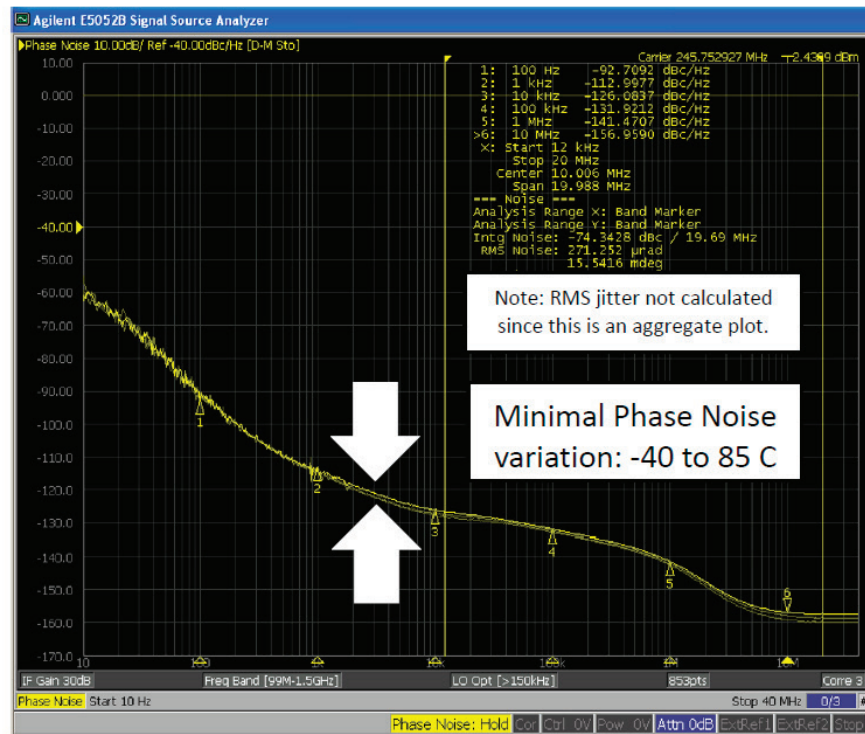


Figure 6. DSPLL Phase Noise Performance over Temperature (245.76 MHz Carrier)

## Loop Filter Integration and Adjustable Jitter Attenuation

Cascaded PLLs require external loop filters for PLL1 and PLL2. Given that these components are off chip, they are sensitive to board-level noise getting into the PLL and impacting device jitter and phase noise. In contrast, the DSPLL architecture's loop filters are on-chip, providing higher immunity to board-level noise. The PLL bandwidths of a cascaded PLL design are fixed. With their discrete architecture, the only way to change the PLL bandwidth is to change the loop filter component values. This makes it difficult to finetune the PLL bandwidth to optimize jitter attenuation at the application level. In contrast, the outer loop bandwidth of the DSPLL can be simply programmed via device registers without the need for external BOM changes. Figure 7 shows how lowering the DSPLL loop bandwidth results in greater attenuation of the reference clock jitter. The device loop bandwidth can be simply programmed via registers without the need to calculate loop filter component values or the PLL's phase margin, simplifying design.

## DSPLL Jitter Transfer - Varying Loop BW at 25°C:

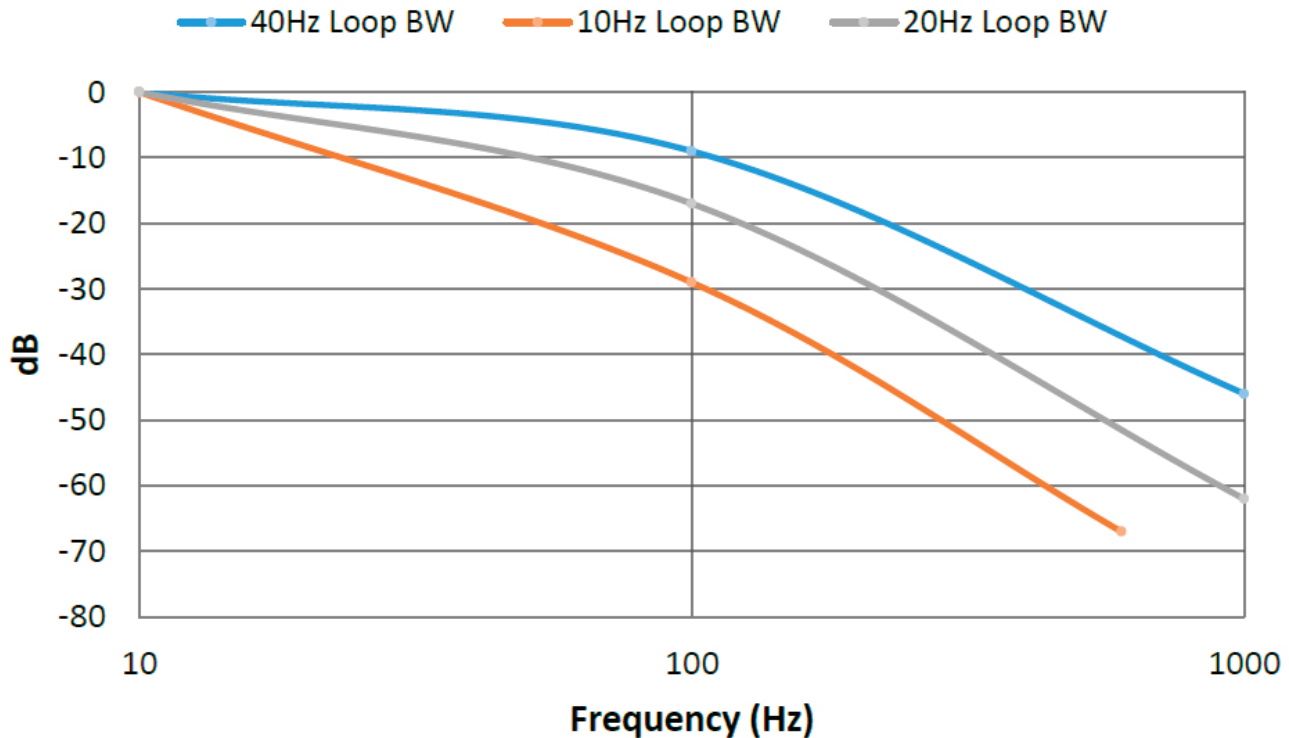


Figure 7. DSPLL Provides Adjustable Jitter Attenuation

### Jitter Transfer

A narrowband PLL must be able to tolerate a significant amount of jitter on its input without losing PLL lock, filter the noise on its reference clock and minimize the amount of jitter transferred to its output. This is especially critical in applications where the narrowband PLL is synchronized to a line-recovered clock from a clock and data recovery (CDR) IC such as a common public radio interface (CPRI) or CPRI over optical transport network (OTN) device. A PLL's jitter transfer function is a ratio of its output jitter spectrum to the applied input jitter spectrum. A well-designed, high-performance PLL will demonstrate low jitter peaking at the PLL bandwidth and consistent operation over temperature. As shown in Figure 8, DSPLL delivers comparable jitter transfer performance in comparison to conventional cascaded PLLs when synchronized to a high jitter input clock. However, DSPLL provides superior loop bandwidth flexibility since it's digitally programmable by the user, enabling the user to optimize jitter performance even after the PCB is fabricated. In addition, the DSPLL architecture delivers highly consistent performance over temperature (see Figure 6), ensuring repeatable performance across operating conditions. Excellent jitter transfer performance helps to simplify HetNet network deployments since it enables small cells and pico cells to be installed farther away from supporting infrastructure.

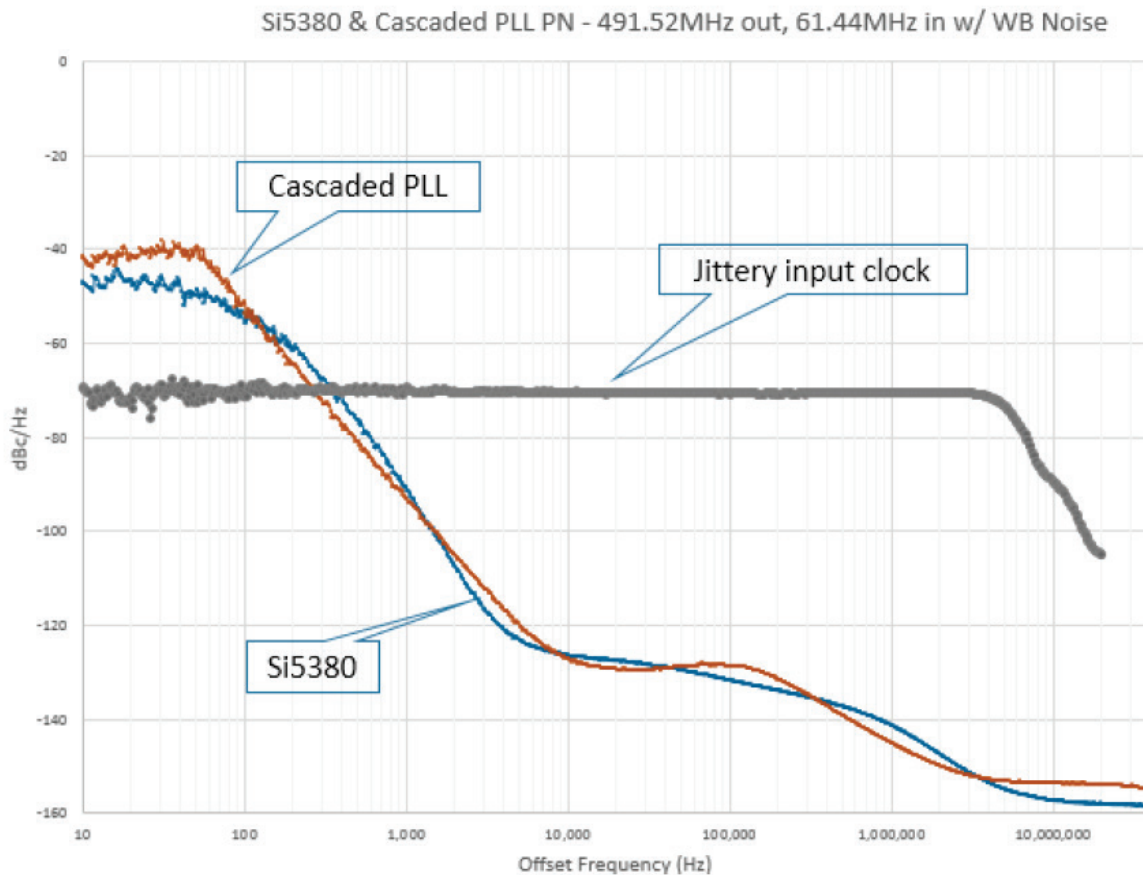


Figure 8. DSPLL Provides Comparable Jitter Transfer Performance but Adds Loop Bandwidth Configuration Flexibility

### Short-Term Holdover

High-performance PLLs need to provide a stable, accurate output clock even if there is a problem with the upstream PLL driving the timing synchronization chain. If the upstream PLL's clock goes away, the downstream PLL needs to enter holdover and provide an accurate output clock until the upstream PLL's clock reappears. During this holdover period, the accuracy of a cascaded PLL's output clock is largely a function of how tightly the VCXO can be held. Cascaded PLLs typically use an on-chip digital-to-analog converter (DAC) to drive the VCXO with its last known control voltage setting. It can be difficult to hold a VCXO using this approach since this implementation is analog in nature, suffers from higher initial frequency offset error, and is susceptible to leakage and frequency drift over time.

In contrast, the DSPLL architecture uses an averaged input clock frequency as its holdover frequency to minimize the disturbance of the output clock frequency when an input clock suddenly fails. The final averaged holdover frequency value is calculated from a programmable window within the stored historical frequency data. Both the window size and the delay are programmable. This feature enables the holdover circuit to ignore frequency data that may be corrupt just before the input clock failure. As an additional benefit, when the DSPLL exits holdover and re-acquires lock to a new input clock, the pullin process is glitch-less and controlled by the DSPLL's outer loop bandwidth, ensuring that an abrupt frequency shift doesn't occur. Figure 9 shows the holdover performance of the DSPLL in comparison to cascaded PLLs. The DSPLL has excellent initial frequency offset performance and, when combined with holdover averaging, provides highly stable performance in holdover applications.



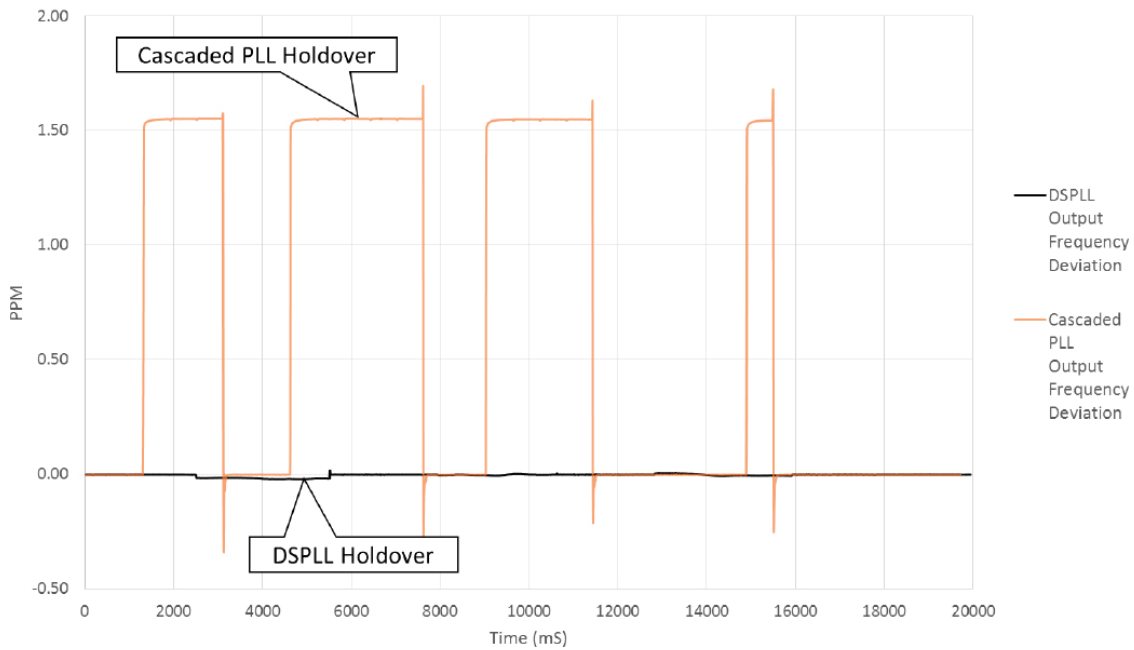


Figure 9. DSPLL Provides Highly Accurate Short-Term Holdover

## Vibration Effects

Because they use discrete VCXOs, cascaded PLLs are more susceptible to vibration effects. Lightly tapping the evaluation board of a cascaded PLL shows a large increase in low frequency spurs and an elevated noise floor, as shown in Figure 10. A similar test on a timing device with DSPLL technology does not produce any spurious signals or an elevated noise floor.

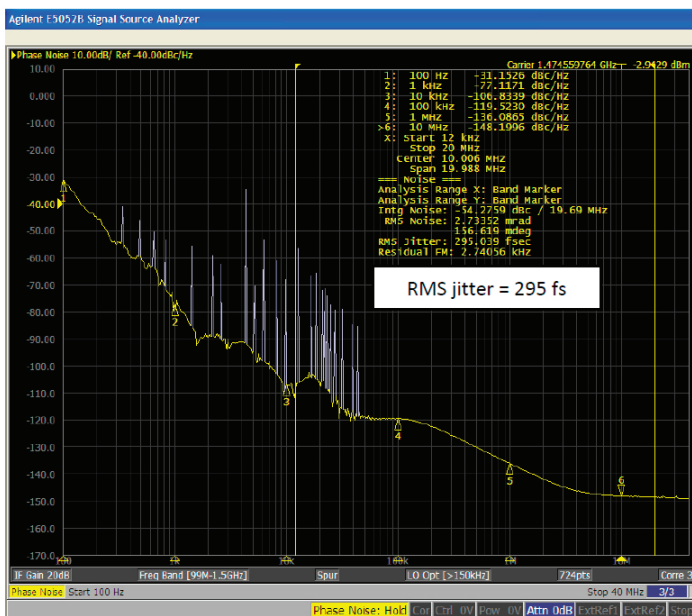


Figure 10. Cascaded PLLs Susceptible to Vibration

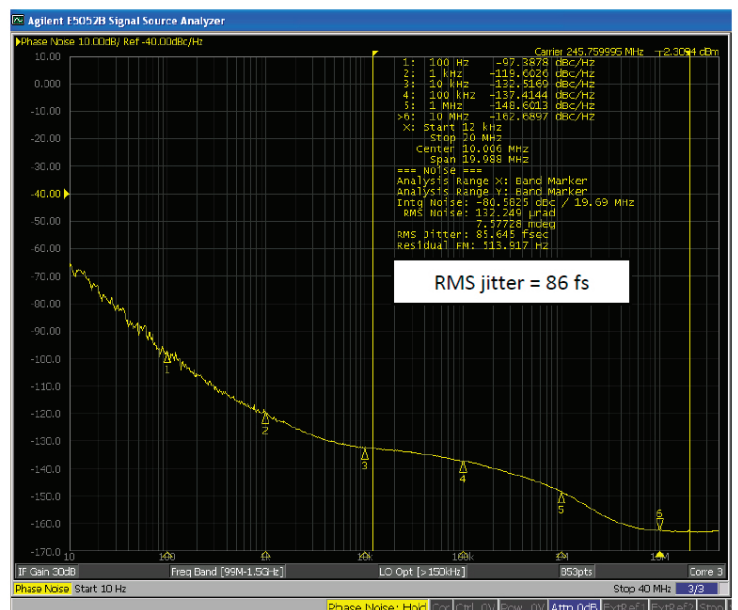


Figure 11. DSPLL Not Susceptible to Vibration Effects

## Summary

Skyworks' proprietary fourth-generation DSPLL architecture combines the best of both analog and digital technologies. This revolutionary architecture combines an analog low phase noise LC-VCO, a digital PLL architecture and cutting-edge 55 nm CMOS technology to provide a solution that offers higher integration, smaller form factor, lower power and more robust performance compared to conventional cascaded PLL devices. These benefits greatly simplify the design of small cells, pico cells, micro cells, point-to-point radios and mobile backhaul equipment.

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