Abstract

Recent advancements in communication systems design place strict demand on system timing accuracy. As frequencies approach 1GHz, and beyond designers are required to pay special attention to timing variations. Jitter has become a familiar parameter to designers as system speeds accelerate. Jitter is usually characterized in the time domain via metrics such as deterministic jitter, random jitter, cycle-cycle jitter, etc. An alternative and more thorough approach to quantifying timing accuracies is through frequency domain analysis techniques. Phase noise, a common metric for RF engineers now find applicability to common designs as the frequencies of operation extend into the gigahertz range.

This article discusses the definition and relationship of jitter and phase noise in an oscillator application. Although jitter is the more prevalent metric used today there is a strong interest in being able to provide additional metrics such as phase noise for those applications where ‘noise’ is paramount. Data will be taken with Aeroflex’s PN9000 at 311MHz frequency in support of SONET/SDH OC-192 applications.

Jitter and Phase Noise:

Jitter and phase noise are just different ways of quantifying the same phenomenon. As an example of this phenomenon, one of the reference clocks of a SERDES to SONET framer is 311MHz. This clock signal at 311MHz will have a period of 3.21 nanoseconds for one complete cycle. Successive cycles of a ‘noise-free’ waveform will measure exactly 3.21 nanoseconds.

Unfortunately, ‘noise-free’ waveforms do not exist. As shown in figure 1, there are variations in the ideal timing event of the period which causes uncertainty about when the next edge of the signal will occur. This uncertainty is referred to as jitter or phase noise.

![Figure 1. Waveform Timing Variations](image)

Jitter in Time Domain:

Jitter is in the time domain and is defined by the ‘deviation of a timing event of a signal from its ideal position.’ Jitter is the convolution of all independent jitter components defined within a Probability Density Function (PDF). A PDF in simplest terms describes the feasibility of a given measurement relative to all other possible measurements to fall within the known region and is typically represented by a normalized histogram. Jitter includes contributions from both deterministic and random elements.

Deterministic Jitter:

Is a non-Gaussian PDF and is characterized by a bounded peak-peak value that cannot be statistically analyzed.
There are various sources of deterministic jitter. The following are the most prominent:

- **Crosstalk:** This occurs when incremental inductance from one conductor (signal line) converts induced magnetic field from an adjacent signal line into induced current. This induced current results in either an increase or decrease in voltage resulting in jitter.
- **Electromagnetic Interference (EMI) radiation:** EMI sources include power supplies, AC power lines, and RF-signal sources. Like crosstalk, a noise current is induced on the timing signal path thereby modulating the voltage level of the time signal.
- **Inter-Symbol Interference (ISI) has two contributors:**
  - **Simultaneous switching:** This can induce current spikes on power and ground planes, creating an opportunity for shifting of the threshold voltage levels.
  - **Reflections in transmission lines:** Causes ISI by changing where the edges occur. A reflection will cause energy to flow back through a conductor that sum with the original signal. This can cause an amplitude change that is different for each conductor in differential pairs creating a time variation in the crossing points, therefore introducing a certain amount of jitter.

**Random Jitter:**

Is characterized by a Gaussian distribution and assumed to be unbounded. As a result it generally affects long-term device stability.

This long-term device stability is a result of thermal vibrations of semiconductor crystal structure causing mobility to vary depending upon the instantaneous temperature of the material. Additionally, imperfections to semiconductor process variation such as non-uniform doping density all are contributors to random jitter.

Because random jitter is Gaussian in nature, the distribution is quantified by the standard deviation or $1\sigma$ and mean ($\mu$) as shown in figure 2.

This normal distribution yields two common jitter specifications:

- **Root Mean Squared (RMS) jitter:** or the value of one standard deviation of the normal distribution. Since this changes very little as the number of samples increases, it is a more meaningful measurement. However, it is only valid in pure Gaussian distributions. If any deterministic jitter exists in the distribution, the use of 1-sigma based on the entire jitter histogram for the estimation of probability of occurrence is invalid.
- **Peak-to-peak jitter:** or the distance from the smallest to the largest measurement on the normal curve. In most circuits, this value increases with the number of samples taken and can theoretically reach to infinity.

![Figure 2. Gaussian distribution with a mean ($\mu$) and a standard deviation ($\sigma$). This figure represents a PDF for a Gaussian distribution.](image-url)
Jitter in Frequency Domain:

Phase noise is another measure of timing error of the zero crossing points with the results provided in the frequency domain. The following equations and figure apply:

\[ V(t) = A \sin(\omega t + \phi(t)) \]
\[ V(t) = A \sin(\omega_0(t + \Delta T(t))) \quad \text{where} \Delta T(t) = \frac{\phi(t)}{\omega_0} \]

![Figure 3: A Noisy Clock/Oscillator](image)

Figure 3 shows a plot of a clock/oscillator signal exhibiting phase noise.

![Figure 4: Oscillator Spectral Density](image)

Figure 4 shows a plot of a clock/oscillator signal exhibiting phase noise.
If phase noise wasn’t present the entire power of the oscillator would be concentrated at the frequency \( f = f_0 \). However, that is not the case. Phase noise distributes some of its oscillator’s power to adjacent frequencies resulting in a term called sidebands. Again referring to figure 4 the sidebands are shown falling off at \( 1/f_m \) rate for frequencies some distance away from the carrier \( f_0 \). The \( f_m \) frequency is the offset from the center frequency.

Phase noise is specified in dBc/Hz at a given offset where dBc is the level in dB with respect to the carrier ‘c.’ The phase noise of an oscillator at a given offset is derived from the ratio of the power in a 1 Hz bandwidth at the offset frequency to the total power of the carrier.

Referencing figure 4 phase noise is represented by the ratio of the area of the rectangle with 1 Hz bandwidth at offset \( f_m \) to the total area under the power spectrum curve, which is approximately the difference in the height of the spectrum at the center and at \( f_m \). The spectrum is the power spectrum of an oscillator with a noisy phase-angle.

The spectrum of these phase-angle fluctuations themselves can also be shown in figure 5.

![Figure 5: Phase Fluctuation Spectral Density](image)

The spectrum in figure 4 is the power spectrum of the oscillator whereas the spectrum in figure 5 is the noisy phase angle term called the spectral density of phase fluctuations.

For offsets sufficiently far from the carrier, the phase noise in dBc/Hz measured from the power spectrum in figure 4 is equal to the value of the spectral density of phase fluctuations in figure 5.

The spectrum in figure 5 is shown on a log-log scale with phase noise sidebands that fall at \( 1/f_m^2 \) or 20 dB/decade. Within the sidebands there are regions where the phase can fall \( 1/f^3 \), \( 1/f^2 \) and even \( 1/f^0 \) which is a direct result of the noise involved.

The \( 1/f^2 \) region is referred to as the ‘white frequency’ variation region since it is due to white or uncorrelated fluctuations in the period of the oscillator. The behavior in this region is dominated by the thermal noise in the devices of the oscillator circuit. For low enough offset frequencies the flicker noise of devices generally comes into play and the spectrum in this region falls at \( 1/f^3 \).
Translating Between Frequency Domain and Time Domain

As described earlier, jitter and phase noise characterize the same phenomenon. It can be useful to derive a jitter value from a phase noise measurement. This can be done as follows:

An oscillator has a phase noise plot which is shown in figure 6. This plot identifies the band from 12KHz to 20MHz. The $\Phi(f)$ plot gives the sideband noise distribution in the form of a power spectral density function in units of dBc. The power level of the carrier is not important since the jitter reflects only the relative levels of phase noise (modulation) when compared to the ideal carrier. Therefore, the total noise power of the sidebands can be determined by integrating the $\Phi(f)$ function over the band of interest which in this case is 12kHz to 20MHz.

![Figure 6: Phase Noise Plot Showing 12kHz to 20MHz](image)

These equations below yield the power level of the phase modulating (jitter producing) noise in this band. From this, we can determine the RMS jitter.

The definite integral used is as follows:

$$N = NoisePower = \int_{12kHz}^{20MHz} \Phi(f)df$$

As an example, the RMS jitter value for a 311MHz clock/oscillator can be calculated using the noise power values plotted in figure 6. Integrating the phase noise curve over the 12kHz to 20MHz yields a number of -63dBc

$$IntegrationOfCurve = \int_{12kHz}^{20MHz} \Phi(f)df = -63dBc$$
The equation below can be used to determine the RMS jitter caused by this noise power:

\[ \text{RMSPhaseJitter} (\text{radians}) = \sqrt{10^{N/10}} \times 2 \]

The RMS phase jitter value in radians is therefore:

\[ \text{RMSPhaseJitter} = \sqrt{10^{-63/10}} \times 2 = 1416e^{-6} \text{ Radians} \]

This can be expressed in other units, such as Unit Interval (UI) or time. To convert to time, divide the above equation by the frequency of the carrier in radians, as follows:

\[ \text{RMSJitter (sec)} = \frac{\text{Jitter (radians)}}{2 \pi f} \]

This jitter value in radians can be converted to RMS jitter into seconds or time domain.

\[ \text{RMSJitter} = \frac{1416e^{-6}}{2 \pi \times 311e^6} = 0.72 \text{ pi cos econds (RMS)} \]

The same 311MHz oscillator will have a typical total jitter value in the range of 2ps to 4ps. Therefore, the RMS jitter calculation of 0.72ps is a small portion of the maximum overall jitter.

**Test Setup:**

**Phase Noise:**

The phase noise test characterizes the output spectral purity of an oscillator by determining the ratio of desired energy being delivered by the oscillator at the specific output frequency to the amount of undesired energy being delivered at neighboring frequencies. This ratio is usually expressed as a series of power measurements performed at various offset frequencies from the carrier. The power measurements are normalized to a 1 Hz bandwidth basis and expressed with respect to the carrier power level.

The following block diagram show a typical test setup for the phase noise measurements.
The phase noise measurement was taken by the Areoflex PN9000 phase noise measurement system using the added phase noise measurement technique. A low noise floor frequency source was used in the VCXO. The PN9000 equipment noise floor allows for measurements as low as -160 dBC and is capable of measuring -60 dBC below the VCXO providing adequate measuring capability in measuring the noise contributed by the DUT.

**Measured Data:**

![Graph showing phase noise measurements](image)

**Summary:**

Demands for increased clock speeds are here to stay. Unfortunately, all devices have a certain amount of instability so quantifiable measurements such as phase noise/jitter are necessary when undergoing its full characterization. Therefore, having a very good understanding of phase noise and how it is computed and verified in the lab are essential to providing the high-speed silicon for today and into the future.