Understanding Phase Noise

Introduction

Noise establishes the lower limit of the effectiveness of a system. In today's environment where a receiver has to 'see' everything in the bandwidth it is designed for, noise becomes a critical attribute for the system. A microwave link has three main parameters that establish its performance: dynamic range, sensitivity and selectivity. The first two are dictated by the noise figure and linearity of the implemented devices. The selectivity on the other hand, is dictated by the phase noise contribution, either from a signal generator or signal processor.
Microwave sources were the first to be investigated and their phase noise perfected to a level considered acceptable relative to the degradation of the system. This was mainly due to the device selection criteria, circuit materials, oscillator design techniques and improvements in the semiconductor impurities. As the quality of microwave sources or references has improved, demands for improved noise contribution is placed on signal processing devices. One very important element is an amplifier and it has become a source of phase noise that potentially impacts the system performance.
The topic of phase noise is extensively covered in the literature, with quite ample studies on oscillators, however, the intent of this application note is to describe the origins, challenges, and measurements of the phase noise in amplifiers. It will present practical quantitative results and capabilities of ultra-low phase noise amplifier such as to help the designer in mitigating its impact to the system.

Noise Sources

Main sources of noise are classified as thermal noise, shot noise and 1/f flicker noise. All noise sources are random in nature, some predictable then others.
Among these, the thermal noise brings most familiarity amid engineers. This is generated due to the random thermal agitation of free electrons as an electrical current passes through a conductor. This type of noise is also called white noise, due to its similarity to the white light, composed of all frequencies.
Another form of noise is the shot noise. This is defined as white current noise due to the quantized and random nature of the current flow in a semiconductor. Its power spectrum is flat with frequency.
Flicker noise, well known as 1/f noise, has an amplitude that changes over frequency. The flicker noise is random in nature and is caused by defects in the semiconductor lattice structure, as a result of combination and recombination of carriers within the crystal. Unlike the thermal and shot noise, flicker noise decreases with frequency. This manifests itself at low frequencies near the carrier, usually between .01kHz and 100 kHz, and known as phase noise.

Phase Noise Origins

Several attempts have been made to explain the origin of the phase noise. Most of them are based on some sort of a circuit model derived from practical measured data and/or intuitive observation regarding noise phenomena.

Using a very simplistic model we can assume that a sine wave at a particular fundamental frequency may be perturbed for brief occurrences by noise and generate a new signal of an instantaneous frequency slightly different from the fundamental frequency. The occurrence is called frequency variations or fluctuation. When this takes place, and in real circuits any signal experiences frequency fluctuations, we relate this instead to phase fluctuations, a rather easily measurable quantity. The term most commonly used to describe the randomness quality of the phase fluctuations is phase noise. Converting from frequency fluctuations to phase fluctuations is done on the premises that by definition, frequency is nothing else but the rate of change in phase of a sine wave. This statement will come very handy in the analysis to come.

A familiar representation of these fluctuations in the frequency domain is the power spectral density illustration. However, in real circuits any signal either created or processed will experience fluctuations in both, in amplitude and in phase. Therefore, the spectral density should be separated into its amplitude fluctuations, called AM power spectral density, and into phase fluctuations, which is of main interest when talking about phase noise, otherwise know as the PM spectral density plot.

1. The intuitive way.

By analogy one may think in terms of a phasor diagram representation of a signal or a carrier. This is shown in Figure 1, where the carrier is shown in red. Noise will surround the carrier, and may be represented as noisy sidebands separated from the carrier by small offset frequencies. As mentioned above, the noise near the carrier is split into AM and PM components, shown in blue, also represented as phasors and added at the tip of the carrier phasor. These in turn will produce superimposed phase noise sidebands, impossible to differentiate on a spectrum analyzer.

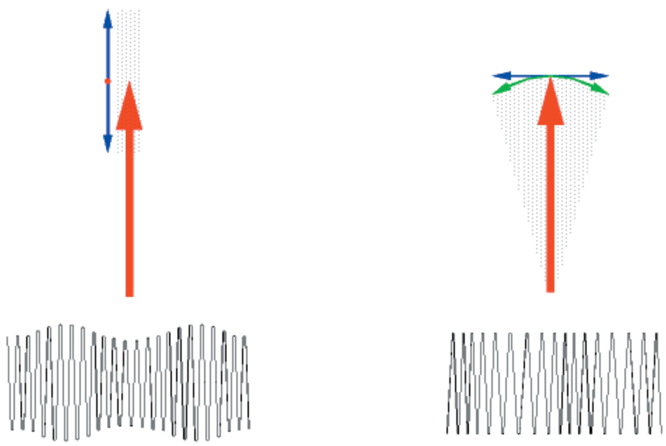


Figure 1 Phasor representation of additive noise contribution of
a) AM components, and b) FM components

The component parallel to the carrier phasor represents the AM noise and moves up and down, giving rise to a wave similar to amplitude modulation but by a tiny noise vector. The component perpendicular to the carrier represents the PM noise, and while moving in the horizontal direction it gives rise to something like phase modulation, though the angle of modulation is very small.

These also can dominate over the other depending on the relevance of the noise in question. For example, an oscillator with certainty will generate excessive PM noise near the carrier, whereas what's important in a low noise amplifier is its AM noise contribution at the output. There is also an additive noise contribution in an amplifier, related to the same PM noise close to the fundamental.

2. The mathematical way.

Using the notations commonly found throughout the literature, a perfect input wave of amplitude V_c and of frequency f_c can have the expression:

(1) $V_{in}(t) = V_c \sin(2\pi f_c t)$

This is processed by an amplifier from which the output voltage will have the form:

(2) $V_o(t) = [V_{oc} + \varepsilon(t)] * \sin[2\pi f_c t + \phi(t)]$

where V_{oc} is the output amplitude of the carrier, and where the time variations in amplitude and the time variations of the instantaneous frequency (like [$f_c + \Delta f$], where Δf is the fractional frequency deviation from the fundamental) were included into $\varepsilon(t)$ and $\phi(t)$, respectively. The term $\phi(t)$ is called the phase fluctuations of the output signal.
More often than not, the amplitude variations can be reduced by means of creative circuitry, and may be ignored, leaving the frequency deviation as a dominant perturbation. But how big is this perturbation and how does one measure Δf ? Remember that by definition the frequency is nothing else but the rate of change in the phase of a sine wave. Therefore, by measuring the changing rate of the phase fluctuations $\phi(t)$ of $V_o(t)$, one can deduce the change in frequency at time t. How this is accomplished, is described in the next paragraph.

A complex signal as shown in equation (2) is always easily analyzed if broken into its Fourier frequency components of different amplitudes and phases. The power spectrum is often called upon to characterize a physical phenomena, which in this case combines the power of the carrier, and the power of all components as a result of the amplitude and phase fluctuations. We know that the entire RF spectrum can be divided into two spectra, the AM and PM power spectra densities. Retaining just the later part of the fluctuations, and calling it $S_\phi(f)$ one can determine the rms phase deviation measured at the Fourier frequency f from the fundamental f_c. The standard terminology for the spectral density of the phase fluctuations is denoted L with dimensions dBc/Hz:

$$S_\phi(f) = 2\,\mathrm{L}(f)$$

and

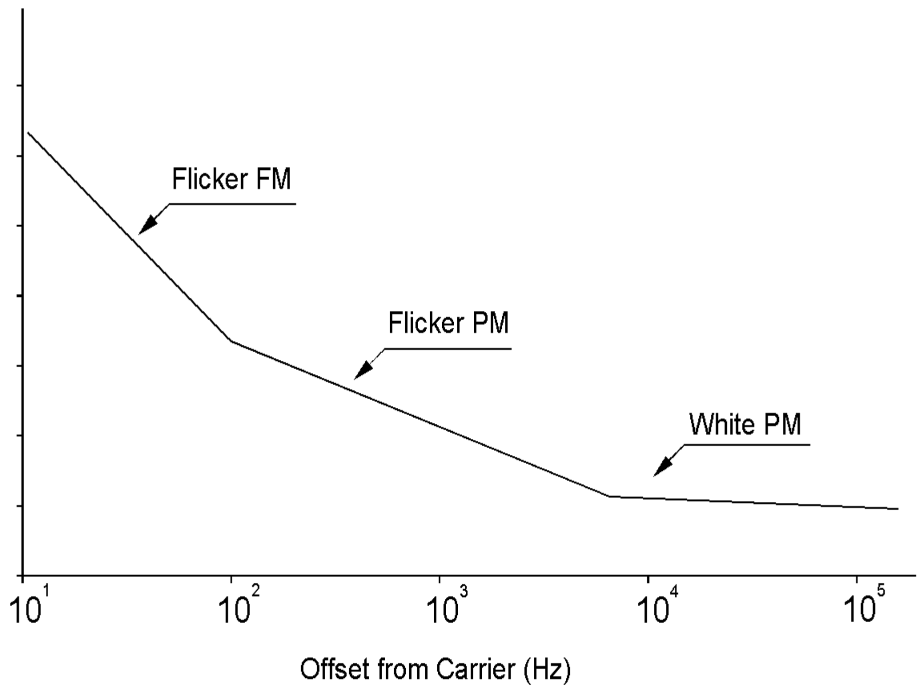
dBc/Hz = 10 log[L(f)]

which is traditionally known as phase noise.

Phase Noise illustration

Traditionally noise processes are illustrated in spectral density plots in the frequency domain. A line with a particular slope, which corresponds to a particular noise type, represents the power-law decay of the spectrum as a function of frequency. This is also called “1/f noise”. For typical microwave processing devices the spectral density of phase will have two or three dominant noise processes. A general view of the spectral density of phase fluctuations is shown in the graph in figure 2. Practical engineering measurements do not refer to the type of noise the units exhibits, but rather express the dBc/Hz at so many Hz from the carrier.

Figure 2. Phase noise versus frequency offset



Conclusion

It was shown that a pure sinusoidal signal going through an amplifier experiences frequency fluctuations which are represented by two orthogonal components, AM and PM fluctuations. Near the fundamental carrier the PM fluctuations are considered to produce the net phase noise. In order to measure the phase noise from the output power spectrum one needs to isolate the AM noise from the PM noise. The most common way of measuring the phase noise is to feed a mixer by the same signal and driven in quadrature. This way, a phase fluctuation between the two input ports will generate a voltage fluctuation at the output port. Using a wave analyzer and performing a spectral analysis on the output signal one can determine the phase noise.