International Journal of Advances in Engineering and Management (IJAEM)
Volume 3, Issue 8 Aug 2021, pp: 534-540 www.ijaem.net ISSN: 2395-5252

Design Trade-Offs Between Phase Noise and Power Consumption of a Voltage Controlled Oscillator

Nnochiri Ifeoma U.
Department of Computer Engineering, Michael Okpara University of Agriculture Umudike

Submitted: 01-08-2021 Revised: 08-08-2021 Accepted: 11-08-2021

ABSTRACT
This aim of this paper is to serve as a review to basic trade-offs in oscillator performance specifications. Oscillators are basically designed to perform a given task wherein the key parameters like phase-noise and power consumption are set by the hardware design and not by the communication system in an adaptive way. As the medium through communication is virtually subject to changes, this implies that the conditions under which the oscillator operates changes as well. Therefore, the concept of design for adaptively must be given a priority as a cornerstone in the design. And also, the concept of phase noise tuning, as given in this paper, shows how oscillators can trade performance for power consumption in an adaptive way. The quasi-tapped bipolar VCO which is assumed to be used reveals the resulting trade-offs between phase-noise and power consumption imposed by the design.

I. INTRODUCTION

In many electronic systems, oscillators are essential components since they provide frequency reference signals. Basically, a specified external reference frequency is transformed into a programmable high frequency clock or carrier signal with a phase locked loop (PLL). The voltage controlled oscillator (VCO) is the major component for the PLL and determines several performance characteristics of the phase lock loop (PLL).

In this work, effort is also given in reviewing the requirements for VCOs and evaluates the advantages and disadvantages of VCO integration. Voltage controlled oscillators appear in many analog and RF signal processing systems. In this paper we focus VCOs for communication applications. First we focus on the three parts of the title: we investigate what the role of a VCO is in a transceiver and discuss the requirements for a VCO by reviewing a typical VCO data-sheet; next and finally but not the least, we look into the necessity or importance for integrated VCOs. The trade-offs, techniques and/or methods for VCO designs are then reviewed and relations between noise performance and power consumption are highlighted. And finally, we examine the different implementation styles that are achieved in the performance of a voltage control oscillator (VCO) [1][2].

II. CHARACTERIZING PHASE NOISE

Phase noise could be seen as a term that is extensively used for describing short term random frequency variations of a signal. Therefore, frequency stability is a concept for measuring the degree to which an oscillator maintains the same value of frequency over a given period and this process of maintaining a particular frequency over a certain time could be specified in various ways. This may be specified in a number of ways. Three commonly used terms for describing frequency stability are used here. An ideal sine wave oscillator may be described by

$$V(t) = A\mathrm{Sin}2\pi ft \qquad (1)$$

Here, A is the nominal amplitude of the signal, and f is the nominal frequency of oscillation. The instantaneous output of an oscillator may be represented by

$$V(t) = V_o \{1 + A(t)\} \mathrm{Sin} \{2\pi ft + q(t)\} \qquad (2)$$

Where A(t) and q(t) represent the amplitude and phase fluctuations of the signal respectively. The phase term either random or discrete could be seen on the spectrum analyzer and there are two types of fluctuating phase terms. The first, the discrete signals called spurious is seen as distinct components in the spectral density plot. The second term, random in nature, appears as random phase fluctuations and is commonly called phase noise.

There are several methods that are used to characterize phase noise of an oscillator. Despite the method used, the frequency or phase deviation of the source under testis measured in either frequency or time domain. Again, frequency and phase are related to each other, all these terms are also related. Note that it is common to characterize the noise performance of a signal as the ratio of the sideband power that characterizes phase fluctuations to the carrier power level. Mathematically given by:

Sc = Pd/Ts (3)

Where; Sc =Noise performance of a signal and
Pd and Ts = total signal power

But for small phase variation or fluctuations,

$$S_c(F) = \left(\frac{b}{2}\right)^2 \tag{4}$$

Here, b is the modulation index by analogy to modulation theory.

$$S_c(f) = \left(\frac{Df_{peak}}{2F}\right)^2 \tag{5}$$

$$= \frac{(Df_{ems})^2}{2F^2} \tag{6}$$

$S_c(f) = 1/2\ (S_{Dq}(f))$ (7)

The National Bureau of Standards defines Single Side Band Phase Noise as the ratio of power in one phase modulation sideband per Hertz bandwidth, at an offset f Hertz away from the carrier, to the total signal power. Here, f is the offset frequency from the carrier.

$$S_c(f) = \frac{P_S}{P_{SSB}} \tag{8}$$

Where P_s is the carrier power and P_{ssb} is the sideband power in one Hz bandwidth at an offset frequency f, from the center. The above conditions can be graphically represented with the graph below

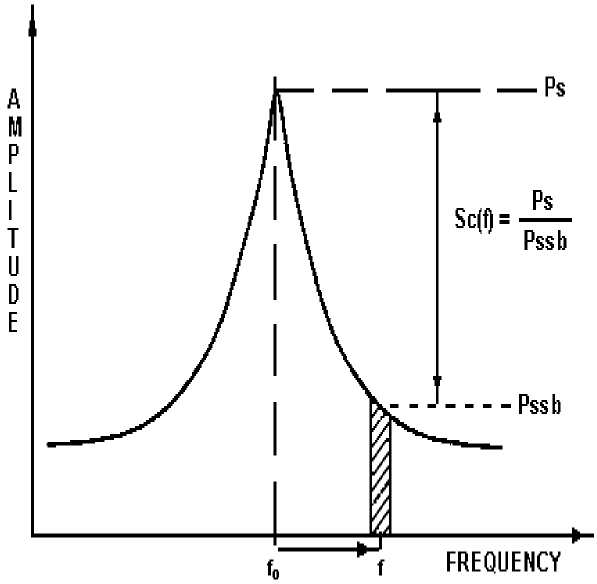

Figure1: Phase Noise

The Single Sideband Phase Noise is usually given logarithmically, that is:

$S_C(f)$ in dB = 10 $_x$ log[$S_C(f)$] (9)

The figure below shows the spectral density plot of the phase modulation sideband and it is expressed in dB relative to the carrier per Hz bandwidth.

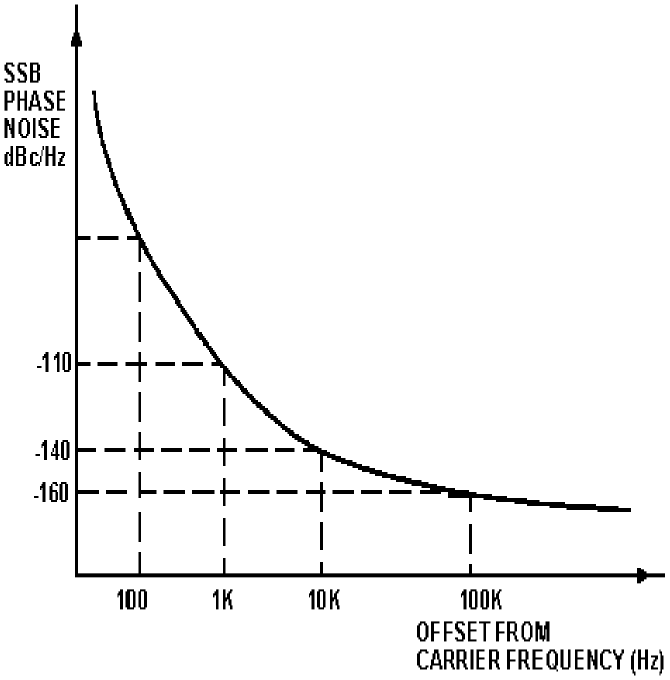

Figure 2: Single sideband phase noise representation [3]

2.1. PHASE NOISE DETERMINATION

As it has been stated that the VCO is an essential instrument in electronics, it is imperative to highlight how the phase noise generated by a VCO can be determined. The following can be used to determine the phase noise generated by a VCO

(i). Q factor of the resonator.
(ii). Q of the varactor diode.
(iii). the active device used for the oscillating transistor.
(iv). power supply noise.
(v). external tuning voltage supply noise.

Note that the noise contribution made by (d) and (e) can be minimized by careful choice of the power supplies. The phase noise of the VCO is therefore determined primarily by the overall Q of the circuit. In order to design a circuit with high Q, the tuning bandwidth must be made small. Therefore a VCO designed for low phase noise performance will have a smaller tuning range. [3] [5]

2.2. HOW PHASE NOISE AFFECTS A SYSTEM.

The noise in a VCO can be caused by the amplifier stages where the subsequent amplifier stages can amplify noise in the transmitter of a local oscillator and this amplified noise is eventually fed to the antenna together with the wanted signal. And as the transmitter local oscillator noise amplified by the subsequent amplifier stages and fed to the antenna, the wanted signal is therefore surrounded by a band of noise originating from the phase noise of the local oscillator and this condition can affect a nearby power station because the noise generated spreads over a wide range of Kilohertz (KHz). The situation is more complicated with receivers and results in reciprocal mixing in the mixer.

When an RF signal is modulated and mixed with a clean local oscillator source, the outcome will yield a modulated IF signal. Also, a modulated IF signal will be gotten when a clean RF signal is mixed with a modulated local oscillator source. Even to the listener, the modulation still remain the same and the effect of this can be explained by assuming that the noise components are the additional local oscillator’s sources that are offset from the main carrier. And each of these noise components mixes with other signals that are offset from the local oscillator by the recovered IF. For the purpose and content of this work, noise can be defined as the sum of an infinite number of extremely small components spread over a range of frequency and , therefore, the signal it mixes into, the IF signal, are spread into an infinite number of small replicas which have different frequencies. As a result, the frequencies of the weaker signals mix into the noise which amount to scrambling. And scrambling of these weaker signals is the main parameter for applications such as satellite repeaters, sensitive communication receivers, and also mobile phone stations [5].

2.3. WAYS TO MINIMIZE NOISE

Although the noise contribution made by power supply and external voltage supply can be minimized by carefully choosing the power supplies, the following steps are recommended for obtaining the best overall performance from Mini-Circuits VCO's.

In minimizing noise in a VCO, there are some vital steps to be taken. Using a mini-circuit VCO's as an example the following steps are recommended for a better performance:

1. The returns of the power supply (V_{cc}) and tuning voltage must be connected to the printed circuit board ground plane. The VCO ground and the printed circuit board must be the same and as a result, all VCO ground pins must be soldered directly to the board ground plane of the printed circuit board.

2. In minimizing noise in a VCO, suitable and adequate RF grounding is required. By adequate grounding we mean that several chips decoupling components such as capacitors must be provided between the V_{cc} supply and ground.

3. The power supply must be of good working condition and should have low noise too. The best performance is ideally gotten when a DC battery is used for both power supplies, V_{cc} and tuning voltage, V_{tune}.

4. Good load impedance must be used to correctly terminate the output. To achieve this, it is proper to use a resistive pad between the VCO and the external load.

5. Also, in minimizing noise, a low power supply must be used fortuning voltage (V_{tune}) supply and the connection to the tuning port must be short and well screened, shielded and decoupled so as to prevent the VCO from external noise that may modulate the VCO. [3]

2.4. CLASSES OF VCOS

Voltage control oscillators (VCOs) or simply oscillators can be said to be independent circuits capable of producing a stable time varying waveform. As periodic oscillatory circuits, they have at least two states and they oscillate through these states at a constant speed. For typical ICs, there are three different topologies for controlled oscillators namely:

- Ring oscillators: Ring oscillators consist of an odd number of single-ended inverters or an even/odd number of differential inverters with the appropriate connections.
- Relaxation oscillators: Relaxation oscillators alternately charge and discharge a capacitor with a constant current between two threshold levels and
- Tuned oscillators: Tuned oscillators contain a passive resonator- LC tank, transmission line resonator, crystal, SAW - that serves as the frequency setting element.

The first two realizations (ring and relaxation oscillators) are very easy to integrate on a monolithic IC and are very compact. Their frequencies are controlled by either a current or voltage and they also have characteristics of linear tuning. Moreover, frequency tuning can be done over a wide range of magnitude. Tuned oscillators on the other hand are very large in size. And because of their large size and lack of high quality passive inductors in standard IC technologies, tuned oscillators are harder to integrate. However, the spectral purity and frequency stability of a tuned oscillator is higher than relaxation and ring oscillators since it is set by the passive resonator. But, relaxation and ring oscillators are typically very sensitive to noise in the switching thresholds and charging currents compared to tune oscillator. [1][2]

2.5. SPECTRAL PURITY

For the purpose and scope of this work, discussion on spectral purity will be limited to an extent although it is the ideal performance measure of a VCO together with its power consumption. Noise sources (such as thermal,1/f, supply or substrate interference) cause changes in the amplitude and frequency of oscillation which makes output spectrum of the oscillator to be an impure tone but has noise sidebands. In the time domain, this impure tone and noise sideband indicates that there is an amplitude variation. It also means that the zero crossing of the output waveforms are not perfectly and/or equally spaced in time thereby giving rise to a condition known as jitter which means that they exhibit random variation around a nominal value.

The power in the noise sidebands is important for wireless receiver and transmitter applications. The close-in sidebands result in spurious responses of the receiver to nearby interfering channels or blockers; they also contribute to the degradation of the modulation accuracy of the transmitter. The far-out sidebands must be low enough to reduce the spurious emissions by the transmitter to relax its output filter requirements. The jitter in the zero-crossings of the output waveform of a phase-locked loop is partly due to the noise or spurious sidebands of the VCO but a large contribution comes from the noise of the other components in the loop. Jitter is a limiting factor in data communications applications since it closes the eye in the eye diagram and so it makes data detection more error prone. In digital circuitry timing jitter reduces the timing margin. For mixed mode applications jitter must be small enough not to affect the accuracy of A/D or D/A conversion. [2][7]

III. VCO DESIGN TRADE-OFFS

Having evaluated the characteristics of phase noise, ways to minimize phase noise and how phase noise affects a system, we shall investigate the relation between spectral purity and power consumption in this section and how the design is being affected by the large tuning range. As mentioned earlier in the section of “classes of VCO” that oscillators are independent circuits, it is important to know that they are also non-linear circuits and this their non-linearity is essential for their operations and noise performance evaluation which in other hands makes the analysis and prediction of phase noise in oscillator somewhat a difficult task. The infinite noise power at the center frequency f_o, of an oscillator can be ascribed as one of the fundamental problems and inconsistencies that are associated to the linear noise analysis of an oscillator but, an in-depth analysis and understanding of this phenomenon that is analytically treatable gives a good insight in the tread-off between parameters. Although the fundamental problems and inconsistencies of an oscillator can be analytically treatable, the analysis should take into account the switching behavior of an oscillator. And also, thorough analytical derivation of the phase noise of an oscillator can be performed by using rigorous and approximated harmonic balance equations. The outcome of this rigorous standard analysis allows the evaluation of the contribution of the different noise sources and noise folding in oscillator. It can also be said that the different noise sources and noise folding in oscillator can be evaluated from this thorough analytical deviation of the phase noise of an oscillator [6].

IV. REASONS/NEEDS FOR CONTRORRABLE OSCILLATOR

A controllable oscillator is an oscillator whose frequency can be controlled and as mentioned earlier, that an oscillator is an integral part of many electronic system, most of these electronic signal processing systems required frequency or time reference signal so as to utilize the full capacity of communication channels, e.g. wireless, wired and optical channels ,transmitters modulate the baseband message signal into different parts of the spectrum to exploit better propagation characteristics or to frequency multiplex several messages, and the receivers down converter them for demodulation. These operations require accurate frequency reference signals. Digital circuits and mixed mode circuits (e.g. A/D and D/A converters) to pace and synchronize their operations using a clock signal as a time reference signal. To build accurate fixed frequency or any time reference signal, the stable properties of quartz crystals can be used as a resonator for the lower end of the spectrum. It is important to know that due to the physical limitations and material properties the quality of the crystal resonator is described for higher frequency range, probably for frequency in megahertz, MHz. In the case of programmable carrier frequencies which are often required in many communication applications, the cost and board space of a multitude of crystals is usually not acceptable instead, in this case, an RF oscillator whose frequency can be controlled is that has less accuracy is incorporated in the feedback loop and its output frequency is locked to a more accurate low frequency reference.

A controllable oscillator is a useful component in electronic signal processing system. Take for instance; in data communication where the data rate is very accurately standardized, still a local clock signal is derived from the incoming data signal with a clock recovery circuits which tracks small variations in the sender’s clock rate also requires a controllable oscillator, that is an oscillator whose frequency is controllable, to align the phase of the local clock for optimal recovery of data. A controllable oscillator can also be used to modulate and demodulate frequency and also an angle modulated carriers.

The figure3 below is used to describe an oscillator that is incorporated in a phase locked loop (PLL).

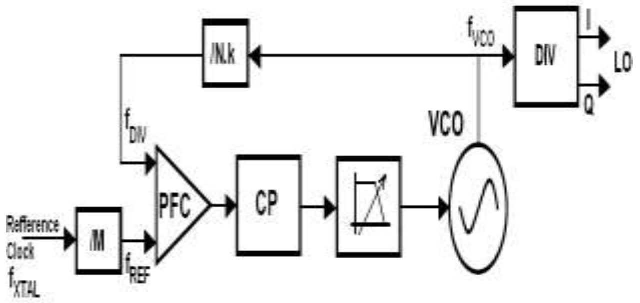

Figure3: An oscillator that is incorporated in a phase locked loop (PLL).

A phase locked loop consists of

- a voltage controlled oscillator (VCO),
- frequency Divider,
- phase detector (PD),
- charge pump (CP) and
- lead-lag loop filter;
- the VCO's output

Frequency is set to a multiple of the reference oscillator's frequency depending on the divider ratio [4][7].

4.1. VCO SPEC-SHEET

A VCO also has the following specifications despite being used as a control frequency. In a VCO specification sheet, VCO SPE-SHEET, the following are commonly specified:

Center Frequency: This is the output frequency of the VCO with its control voltage at its center value and is expressed in [Hz]. In this paper we use or its angular frequency equivalent in [rad/sec] interchangeably.

Tuning Range: This is the range of output frequencies that the VCO oscillates at over the full range of the control voltage

Tuning Sensitivity: is the change in output frequency per unit change in the control voltage, typically expressed in [Hz/V]. VCOs intended for frequency synthesis applications can have a nonlinear relationship between control voltage and oscillation frequency so that several values are quoted or min/max boundaries are given. VCOs for (de)modulation will quote the linearity of the tuning input and the bandwidth of the tuning input.

Spectral Purity: can be specified depending on the application, in the time domain in terms of jitter or in the frequency domain in terms of phase noise or carrier/noise ratio.

Load Pulling: quantifies the sensitivity of the output frequency to changes in its output load In some applications the output load of the VCO is switched while the VCO must remain at the same frequency to avoid frequency errors.

Supply Pulling: quantifies the sensitivity of the output frequency to changes in the power supply voltage and is expressed in [Hz/V]. The power up or down of other circuits can create significant transients in the power supply voltage and it is again desirable that the VCO frequency remains undisturbed.

Power Consumption: specifies the DC power drain by the oscillator and its output buffer circuits.

Output Power: is the power the oscillator can deliver to a specified load. The variation of the output power over the tuning range is also specified.

Harmonic suppression: specifies how much smaller the harmonics of the output signal are compared to the fundamental component and is typically expressed in [dBc][1][2][7].

V. CONCLUSIONS

In conclusion, in demand for integrated oscillator is growing with proliferation of wireless terminals and unprecedented advent of higher communication data rates and digital clock rates. Whereas for digital and data applications fully integrated ring oscillators are being widely used, the use of fully integrated tuned oscillators is only emerging in wireless products. Performance concerns as well as large area still inhibit the widespread acceptance of integrated tuned oscillators. The reduction of the number of RF interfaces in the package, the ease of use of fully integrated parts, compact board size and the implementation of automatic trimming techniques will however outweigh the high cost for large volume wireless terminals. The good performance of oscillators and the introduction of better interconnect technologies in deep submicron technologies holds interesting prospects for highly integrated transceivers combining RF and analog front-ends with digital signal processing back-ends. The constant move to higher bit-rates will require a shift from non-tuned ring oscillators to fully integrated tuned oscillators for data and digital applications.

REFERENCES

[1]. Peter Kinget, BabakSoltanian, SongtaoXu, Shih-an Yu, and Frank Zhang, ‘‘Advanced Design(2019). Techniques for Integrated Voltage Controlled LC Oscillators’’Columbia University
[2]. Peter Kinget, (2016). Bell Labs - Lucent Technologies Murray Hill, NJ (USA ‘‘Integrated ghz voltage controlled oscillators’’
[3]. Mini-circuit, (2013). VCO Phase noise
[4]. U.P.S Bull, series C. vol 72 iss, 4.(2010), Silvian SPIRIDON1, FlorentinaSPIRIDON2, Claudius DAN3, Mircea BODEA4 ‘‘Phase- noise and area – power consumptiontrade-off in the frequency synthesizer forsoftware defined radio transceivers’’
[5]. Rf,rfic and microwave theory, (2020). design www.rfic.co.uk
[6]. Chen Nan, DiaoShengx, Huang Lu, BaiXuefei, and Lin Fujiang, (2018)‘‘Design optimizations of phase noise, power consumption and frequency tuning for VCO’’, University of Science and Technology of China, Hefei 230027, China
[7]. Peter Kinget (2017). Bell Labs - Lucent Technologies Murray Hill, NJ (USA) INTEGRATED GHz VOLTAGE CONTROLLED OSCILLATORS