Analysis and Verification of Jitter in Bang-Bang Clock and Data Recovery Circuit With a Second-Order Loop Filter

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Abstract—This paper provides an in-depth analysis of the third-order bang-bang clock and data recovery (BBCDR) circuit, which accurately predicts its operating characteristics, namely, the jitter transfer function (JTF), the jitter tolerance (JTOL), and the jitter generation (JGEN). By formulating the time-domain waveforms, we introduce a characterizing method and also derive the closed-form equations and their simplified versions under specific conditions, which are related with the second-order loop filter (LF). Our framework is consistent with the conclusions of the prior works. Also, we discuss through the time-domain behavior, the sinking area of the JTOL and other specific phenomenon appearing in the third-order BBCDR loop. We verify all above prediction by system-level simulations with the MATLAB/simulink model.

Index Terms—Bang-bang clock and data recovery (BBCDR), bang-bang phase detector (BBPD), binary, Fourier series, jitter generation (JGEN), jitter tolerance (JTOL), jitter transfer function (JTF), linear phase detector, loop filter (LF), sinking area.

I. INTRODUCTION

CLOCK and data recovery (CDR) circuits [1]–[6] recently incorporating a bang-bang phase detector (BBPD) are widespread in multigigabit data links, e.g., backplane and optical communications. Compared with its linear counterparts [7]–[10], the BBPD has several advantages of design simplicity, proper phase adjustment, all-digital integration [11]–[15], and high-frequency operation [16].

Manuscript received January 21, 2019; revised April 14, 2019; accepted May 3, 2019. Date of publication June 6, 2019; date of current version September 25, 2019. This work was supported in part by the University of Macau under Grant MYRG2017-00167-AMSV and in part by Macau Science and Technology Development Fund (FDCT)—SKL Fund. (Corresponding author: Yong Chen.)

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Fig. 1. Ideal transfer characteristic (solid line) of the BBPD and its Fourier series as well as a smoothing binary characteristic (dashed line).

Fig. 1 depicts the ideal characteristic of a generic BBPD where its binary operation quantizes the positive and negative phase errors between the input pattern and the output clock of the voltage-controlled oscillator (VCO), corresponding to a strongly nonlinear phase-to-voltage conversion. However, the nonlinear behavior of the BBPD-based CDR (BBCDR) loop complicates its analysis and design.

Internal and external jitters incur an undesirable bit error at the output of the BBCDR. The jitter transfer function (JTF), jitter tolerance (JTOL), and jitter generation (JGEN) mainly determine the specification of the BBCDR frequency response and they confront a tradeoff among them. For JTF, a narrow loop bandwidth (BW) is preferable to suppress high-frequency disturbance, but a small loop BW cannot effectively suppress the VCO phase noise, exacerbating the JGEN. Moreover, a large loop BW is desirable to aid the JTOL. To surmount these tradeoffs, an accurate method aiming for jitter analysis is essential for evaluating the jitter performance of the BBCDR.

Past effort has been focused on the hard nonlinearity of the BBCDR [17]–[27]. Almost none of the previous works offers a thorough analysis of a third-order BBCDR loop, i.e., the BBCDR employs just a second-order loop filter (LF). A nonlinear stochastic analysis based on the Markov model

has been applied to evaluate the effect of the timing jitter [17]–[20], but only the first-order BBCDR loop was well studied. The analysis in [21] is extended to the second-order BBCDR loop for the intersymbol interference and the JTOL evaluation, but the analysis of JTF and JGEN is still missing. The phase-domain models of the first- and second-order BBCDRs in [22] are developed separately, while underlining the dynamic characteristic of the BBCDR loop. An event-driven model reported in [23] obtains fast verification. Regrettably, both [22] and [23] do not pay much attention to the jitter specification mentioned above.

There are other prior works [24]–[27] studying the foregoing characteristic of the second-order BBCDR loop. The phase-domain model in [24] is similar to [22] and is only useful for the JTOL analysis without the analysis of JTF and JGEN. Lee et al. [25] calculates the JTOL, JTF, and JGEN based on the dynamic time-domain waveform, but they presume a geometric approximation and a large off-chip LF that may not hold in a fully-integrated circuit. Adrang and Miar-Naimi [26] propose a method using the Fourier series, combined with the time-domain waveform to predict the jitter specification. All aforementioned works have not investigated the jitter features of the third-order BBCDR loop.

In many practical applications, the utilization of a second-order LF restrains the disturbance on the control side of the VCO. Cheng et al. [27] analyzes the stable oscillation mode based on the steady-state waveforms of a third-order phase-locked loop (PLL) with the BBPD, but fail to predict the jitter performance. In this paper, we detail the jitter analysis of a generic third-order BBCDR characterized by the Fourier series and time-domain waveforms. We derive the closed-form equations of both JTF and JTOL, and the simplified equation of the JGEN based on the fundamental (Fig. 1), with the nonideal phenomenon explained in detail. Finally, the behavioral simulation developed in the MATLAB/Simulink program verifies our analysis.

After this introduction, we overview the architecture of the third-order BBCDR and detail our time-domain waveform-based analytical method. Sections III and IV provide the JTF and JTOL analysis, respectively, whereas Section V focuses on the JGEN. Section VI evaluates the accuracy of our analytical methods using the behavioral simulations. Finally, Section VII draws the conclusion.

II. ARCHITECTURE AND ANALYTICAL METHODS OF THIRD-ORDER FULL-RATE BBCDR

Fig. 2 shows the architecture of the typical third-order full-rate BBCDR. The function of the BBPD, namely, Alexander phase detector [28], is to sense the phase error between the centers of the incoming data (D_{in}) and recovered clock (C_{Kout}) from the VCO, and simultaneously deliver the retimed data (D_{out}). The BBPD outputs the “Early” and “Late” signals to the succeeding charge pump (CP), indicating that the sign of the phase error between its inputs, i.e., the recovered clock is leading or lagging the input data [28]. The CP supplies the BBPD outputs to charge or discharge the second-order LF consisting of R_{1}, C_{1}, and C_{2}, for adjusting the VCO control voltage (V_{cont}) so as to reduce the phase error.

In practical systems, extra C_{2} is usually added in parallel with R_{1} and C_{1} to suppress any sudden artifacts on V_{cont}, which is produced by the charge injection and clock feedthrough of the two switches, thereby improving the transient characteristics. Generally, we have C_{2} \ll C_{1}, but it increases the order of the feedback loop and induces certain nonideal phenomenon. In fact, a quantitative analysis proved to be useful for the choice of C_{2}, instead of selecting a capacitor based on the rule of thumb. Fig. 3 presents the behavior models of a third-order BBCDR. The BBPD is modeled as a phase subtractor followed by a sign function [sgn()]. The second-order LF is defined by its transfer function, while the VCO operates as a phase integrator. K_{VCO} is the VCO gain and I_{PD} is the time-varying current flowing through the LF. Both JTF and JTOL evaluations focus on the output jitter depending on the input jitter, while JGEN concerns about the output jitter induced by the intrinsic noise. Therefore, two separated models are implemented in MATLAB/Simulink to verify the accuracy of our analysis, according to Fig. 3(a) and (b), respectively.
Consider that a sinusoidal jitter is injected as $\phi_{in}$ in Fig. 3(a), when the BBCDR loop experiences the full slewing region, we obtain the steady-state time-domain waveforms as shown in Fig. 4. We denote $f_{jitter}$ as input jitter frequency. It is obvious that $\phi_{out}$ tracks $\phi_{in}$ with the same period $T$ (i.e., $T = 1/f_{jitter}$). We define $\Delta \phi$ as the phase difference between $\phi_{in}$ and $\phi_{out}$. Every time $\phi_{out}$ catches up with $\phi_{in}$, the reversed-sign $\Delta \phi$ changes the polarity of $I_{PP}$, thus producing a periodic square waveform. However, the charged capacitors in LF prevent $V_{cont}$ from changing the polarity immediately. Therefore, an extra phase appears on $\phi_{out}$, which results in the jitter peaking (JP) when $\phi_{out,p} > \phi_{in,p}$.

The impulse response ($h(t)$) of $I_{PP}$ to $\phi_{out}$ in Fig. 3(a) can be deduced from the corresponding transfer function ($H(s)$)

$$H(s) = \frac{R_1C_1s + 1}{R_1C_1C_2s^2 + (C_1 + C_2)s} \frac{K_{VCO}}{s}$$

$$h(t) = K_{VCO} \left[ \frac{t}{C_1 + C_2} + \frac{R_1C_2^2}{C_2} \left( 1 - e^{-\frac{t}{R_1C_2}} \right) \right] u(t)$$

(1)

where $C_{eq} = C_1C_2/(C_1 + C_2)$. Under $0 \leq t \leq T/2$, by the aid of the Fourier series, the periodic function $I_{PD}(t)$ can be expanded as

$$I_{PD}(t) = \frac{4I_p}{\pi} \sum_{n=1}^{+\infty} \left[ \frac{1}{n} \sin(n\omega_p t) \right] n \text{ is odd}$$

(2)

where $\omega_p = 2\pi f_{jitter}$. By convoluting $I_{PD}(t)$ with $h(t)$, $\phi_{out}(t)$ can be expressed by

$$\phi_{out}(t) = \sum_{n=1}^{+\infty} \left[ \frac{1}{n} \int_{-\infty}^{+\infty} \sin(n\omega_p (t - \tau)) d\tau \right] \left[ \tau + \frac{R_1C_2}{k} \left( 1 - e^{-\frac{\tau}{R_1C_2}} \right) \right] u(\tau)$$

(3)

where $k = C_2/C_1$ and

$$\alpha = \frac{4K_{VCO}I_p}{\pi (C_1 + C_2)}$$

(4)

To get the closed-form solution, we rearrange (3) as

$$\phi_{out}(t) = -\sum_{n=1}^{+\infty} \left[ \frac{1}{n} \int_{-\infty}^{+\infty} \sin(n\omega_p (t - \tau)) d\tau \right] \left[ \tau + \frac{R_1C_2}{k} \left( 1 - e^{-\frac{\tau}{R_1C_2}} \right) \right] u(\tau)$$

(5)

Fig. 4 (top) shows $\phi_{out}(0) = \phi_{out}(T)$, and we can obtain $\cos(n\omega_p \tau)|_{\tau=-\infty} = 0$. Similarly, due to $-\phi_{out}(0) = \phi_{out}(T/2)$, we will have $\sin(n\omega_p \tau)|_{\tau=-\infty} = 0$ when $n$ is odd. Thus, (5) can be further simplified as

$$\phi_{out}(t) = -\sum_{n=1}^{+\infty} \left[ \alpha \left( A_n + B_n \sin(n\omega_p t) \right) \right] + n\beta(C_1A_n - C_2B_n \cos(n\omega_p t))$$

(6)

where

$$\beta = \frac{\omega_p R_1C_{eq}}{C_2}$$

(7)

The Fourier coefficients $A_n$ and $B_n$ are determined by

$$A_n = \frac{1}{n^2\omega_p^2}$$

(8)

$$B_n = \frac{R_1C_2^2}{k(1 + n^2\omega_p^2 R_1^2 C_{eq}^2)}$$

(9)

Note that $\phi_{out}(t)$ in (6) is an infinite sum of the orthogonal sines and cosines involving a series of high-order harmonics. Due to the low-pass properties of $H(s)$, the loop characteristic is dominated by the fundamental. Considering that the high-order harmonics contribute slightly to $\phi_{out}$, that is,

$$|\phi_{out}(\omega_p t)| >> |\phi_{out}(n\omega_p t)|, \quad n = 3, 5, \ldots$$

(10)

We simplify (6)–(11) with the fundamental, which will be used in the following analysis:

$$\phi_{out}(t) = -\alpha (A_1 + B_1) \sin(\omega_p t)$$

$$+ \beta (C_1A_1 - C_2B_1) \cos(\omega_p t)$$

(11)

where

$$A_1 = \frac{1}{\omega_p^2}$$

(12)

$$B_1 = \frac{R_1C_2^2}{k(1 + \omega_p^2 R_1^2 C_{eq}^2)}$$

(13)
peaking should be <0.1 dB. Interestingly, \( f_{BW} \) approaches \( f_{peak} \) as JP decreases.

Fig. 5(b) shows the time-domain waveforms in the transition region, where \( f_{jitter} \) is slightly smaller than \( f_{peak} \). Different from the periodic \( I_{PD} \) (Fig.4, lower), \( I_{PD} \) in this region is no longer a periodic square waveform. It can be divided into two dynamic parts: Region A and Region B. In Region A, the well-tracked condition disables, leading to long-run +\( I_p \) or −\( I_p \).

Inversely, in Region B, \( I_{PD} \) varies rapidly and \( \phi_{out} \) tracks \( \phi_{in} \) in the vicinity of \( \phi_{in,p} \). Although \( \phi_{in} \) is large in Region B and small in Region A, the slope of \( \phi_{in} \) is smaller in Region B than that in Region A. When \( \phi_{out} \) tracks \( \phi_{in} \), they share the same magnitude and slope. Note that the tracking ability of a BBCDR is determined by the maximum slope of \( \phi_{out} \) rather than the absolute magnitude of \( \phi_{out} \). It is worth of mentioning that \( \phi_{out} \approx \phi_{in} \) leads to a 0-dB JTF, indicating that JP happens in the slewing region. As \( f_{jitter} \) decreases, Region B expands, and the BBCDR loop enters the well-tracked region gradually. Inversely, its operation in the Region A will be extended. If Region B fades, \( I_{PD} \) in Fig. 5(b) will return to that in Fig. 4.

A. Derivation of \( f_{BW} \)

Based on (11), \( \phi_{out,p} \) is easy to be deduced as

\[
\phi_{out,p}(f) = \frac{\alpha \beta (A_1 + B_1)^2 + \beta (A_1 C_1 - B_1 C_2)^2}{\alpha^2} \quad (15)
\]

When \( f_{jitter} \) is close to \( f_{BW} \), we can assume \( |\phi_{out,p}/\phi_{in,p}| \approx 1 \), and then we obtain the following equations:

\[
(A_1 + B_1)^2 + \beta^2 (A_1 C_1 - B_1 C_2)^2 = \frac{\phi_{in,p}^2}{\alpha^2} \quad (16a)
\]

\[
\left( \frac{\phi_{in,p}^2}{\alpha^2} + \frac{\sigma^2 R_1^2 C_1^2}{1 + k} \right) \left( 1 + \frac{\sigma^2 R_1^2 C_2^2}{1 + k} \right) = 1 = 0 \quad (16b)
\]

A further approximation with the consideration of \( 2R_1 C_2 f_{BW} \ll 1 \) results in

\[
f_{BW} = \frac{\alpha^2 R_1^2 C_1^2 + (1 + k) \alpha^2 \sigma^2}{8 \pi^2 (1 + k) \sigma^2} \propto \frac{1}{(1 + k)^3} \quad (17)
\]

where

\[
\sigma = \frac{R_1^2 C_1^4}{(1 + k)^2} + \frac{4 \phi_{in,p}^2}{\alpha^2} \quad (18)
\]

Because \( f_{BW} \) is proportional to \( 1/(1 + k)^3 \), i.e., \( C_2 \) appears only in the denominator, we observe that \( f_{BW} \) decreases along with the increment of \( C_2 \).

B. Slope of JTF in the Slewing Region

Based on (15), JTF in the slewing region can be written as

\[
\frac{\phi_{out,p}}{\phi_{in,p}}(f) \approx \rho \sqrt{(A_1 + B_1)^2 + \beta (A_1 C_1 - B_1 C_2)^2} \quad (19)
\]

where \( \rho = \alpha/\phi_{in,p} \). Interestingly, the simulation results depart from the ideal second-order slope (−40 dB/dec). According to (12) and (13), \( \rho A_1 \) and \( \rho B_1 \) are both second-order terms, while the second-order pole of \( \rho B_1 \) may occur after \( f_{BW} \).
Thus, $\rho(A_1 + B_1)$ turns out to fall with a slope of $-40$ dB/dec, and is almost in full frequency range with a flat area, as shown in Fig. 6(a). For the second term, $\rho\beta A_1 C_1$ is first-order while $\rho\beta C_2 B_1$ has a zero at the origin and a complex-conjugate pole pair. Both terms decrease at a slope of $-20$ dB/dec at the frequency of interest, and their difference $(\rho\beta C_1 A_1 - \rho\beta C_2 B_1)$ shows a high-order slope [Fig. 6(b)]. The total slope of $\varphi_{\text{out,}\rho}/\varphi_{\text{in,}\rho}$ is more close to that of $\rho(A_1 + B_1)$ after the point $M$, since $\rho(A_1 + B_1)$ is much larger than $(\rho\beta C_1 A_1 - \rho\beta C_2 B_1)$, as depicted in Fig. 6(c). It means that $\rho(A_1 + B_1) \sin(\omega_p t)$ dominates the $\varphi_{\text{out,}\rho}/\varphi_{\text{in,}\rho}$ and $(\rho\beta C_1 A_1 - \rho\beta C_2 B_1) \cos(\omega_p t)$ can be neglected. It falls at the rate of $-40$ dB/dec in the high-frequency region. Yet, $\varphi_{\text{out,}\rho}/\varphi_{\text{in,}\rho}$ is $-20$ dB/dec rolloff in terms of $f_{\text{jitter}}$, when $(\rho\beta C_1 A_1 - \rho\beta C_2 B_1)$ dominates $\varphi_{\text{out,}\rho}/\varphi_{\text{in,}\rho}$ before the point $M$. Therefore, the slope near the point $M$, which locates behind $f_{\text{BW}}$, may even be $-20$ dB/dec.

C. Jitter Peaking

Referring to the above analysis, JP happens when $\varphi_{\text{out}}$ catches up with $\varphi_{\text{in}}$ at the minimum of input phase, i.e., $-\varphi_0 = \varphi_{\text{in,}\rho}$. It will be observed later in Fig. 11(c) in Section VI-B.

We rearrange the above equation in regard to $f_{\text{peak}}$ as follows:

$$\varphi_{\text{in,}\rho} + \varphi_0(f_{\text{peak}}) = 0.$$  \hspace{1cm} (20)

Thus, $f_{\text{peak}}$ can be solved from (14) and (20), and JP can be solved by substituting $f_{\text{peak}}$ into (19)

$$JP \approx \rho \sqrt{(A_1 + B_1)^2 + \left[2\pi R_1 C_{\text{eq}} f_{\text{peak}} \left(\frac{A_1}{k} - B_1\right)\right]^2}.$$ \hspace{1cm} (21)

IV. JITTER TOLERANCE ANALYSIS

The JTOL is a widely used specification to estimate the ability of retiming a jittered input pattern. It specifies the maximum $\varphi_{\text{in},p}$ that can be tolerated by the system without increasing the bit error rate (BER). An approximate condition to avoid increasing the BER is $|\varphi_{\text{in}} - \varphi_{\text{out}}| < 0.5$ UI. Fig. 7 illustrates the typical JTOL curves with first- and second-order LFs. JTOL falls at the slope of $-40$ dB/dec prior to $f_1$, and turns to $-20$ dB/dec afterward, they approach 0.5 UI finally. For the BBCDR with a second-order LF, there is a sinking area, which is different from that of a first-order LF. Detailed time-domain explanation will be discussed in Section VI-C.

It is noteworthy that the BBCDR must experience the full slewing if bit error occurs, otherwise, $\varphi_{\text{out}}$ tracks $\varphi_{\text{in}}$ well, and the data can be sampled correctly. Normally, a sinusoidal jitter is applied to evaluate the JTOL. As illustrated in Fig. 8, $\varphi_{\text{in}}$ can be expressed as follows:

$$\varphi_{\text{in}}(t) = -\varphi_{\text{in,}\rho} \sin(\omega_p t - \theta_0)$$ \hspace{1cm} (22)

where $\theta_0$ is the initial phase of the input jitter. Combining (22) with (14), we can write

$$\varphi_{\text{in,}\rho} \sin \theta_0 = \varphi_0 = \alpha \beta (B_1 C_2 - A_1 C_1).$$ \hspace{1cm} (23)

Due to $\cos \theta_0 = \sin(\pi/2 + \theta_0)$, $\cos \theta_0$ must be negative (Fig. 8). Thus, we obtain

$$\varphi_{\text{in,}\rho} \cos \theta_0 = -\sqrt{\varphi_{\text{in,}\rho}^2 - \varphi_0^2}.$$ \hspace{1cm} (24)

$\Delta \varphi(t)$ is obtained by substituting (22) and (11) into $\varphi_{\text{in}}(t)$ and $\varphi_{\text{out}}(t)$

$$\Delta \varphi(t) = \varphi_{\text{in}}(t) - \varphi_{\text{out}}(t) = [\varphi_0 + \alpha \beta (A_1 C_1 - B_1 C_2)] \cos(\omega_p t)
+ \left[\sqrt{\frac{\varphi_{\text{in,}\rho}^2}{\varphi_0^2} + \alpha (A_1 + B_1)}\right] \sin(\omega_p t).$$  \hspace{1cm} (25)
Substituting (23) and (24) into (25), \( \Delta \varphi \) is rewritten as

\[
\Delta \varphi(t) = \left[ \sqrt{\varphi_{in,p}^2 - \varphi_0^2} + \alpha (A_1 + B_1) \right] \sin(\omega_p t).
\]

Hence, \( \Delta \varphi_{\text{max}} \) is calculated as

\[
\Delta \varphi_{\text{max}} = \sqrt{\varphi_{in,p}^2 - \varphi_0^2} + \alpha (A_1 + B_1).
\]

Equating \( \Delta \varphi_{\text{max}} \) to 0.5 UI yields the JTOL at \( f_{\text{jitter}} \)

\[
\text{JTOL}_1 = \sqrt{\left[ \frac{1}{2} - \alpha (A_1 + B_1) \right]^2 + \varphi_0^2}.
\]

For simplicity, 0.5 UI can be expressed as 1/2 rather than \( \pi \), if the unit of \( K_{\text{VCO}} \) is Hz/V. Also, when \( C_2 \) is ignored compared to \( C_1 \), JTOL2 is obtained as

\[
\text{JTOL}_2 \approx \sqrt{\left[ \frac{1}{2} - \frac{4K_{\text{VCO}} I_p}{\pi C_1} (a_1 + b_1) \right]^2 + \varphi_0^2}.
\]

where

\[
a_1 = \frac{1}{\omega_p^2}, \quad b_1 = \frac{R_1^2 C_1 C_2}{1 + \omega_p^2 R_1^2 C_2}.
\]

The effect of \( C_2 \) on JTOL is nonlinear. In the low-frequency region, JTOL decreases as \( C_2 \) increases. Inversely, JTOL rises depending on \( C_2 \) in the high-frequency region. To verify the above derivation, \( \varphi_0 \) in (25) is replaced by the second-order counterpart [26], i.e., \( \pi K_{\text{VCO}} I_p R_1 / 2 \omega_p \). With the assumption of \( f < (2 \pi R_1 \sqrt{C_1 C_2})^{-1} \), JTOL3 can be deduced from (28)

\[
\text{JTOL}_3 = \left\{ \frac{1}{4} \left( \frac{K_{\text{VCO}} I_p R_1 8 - \pi^2}{2 \pi} \right)^2 + \frac{4K_{\text{VCO}} I_p}{\pi C_1} \right\} \left( \frac{1}{\omega_p} \right)^2 + \left( \frac{\pi K_{\text{VCO}} I_p R_1}{2 \omega_p} \right)^2
\]

which is the same as the result in [26].

V. JITTER GENERATION ANALYSIS

The JGEN describes the jitter arising from various sources such as VCO phase noise, crosstalk, and supply voltage disturbance. It appears as the output jitter when there is no jitter injected from outside. Here, we study the contribution of VCO phase noise to the output of the BBCDR. For JGEN verification, a model can be established by adding an extra sinusoidal jitter to VCO phase noise, without jitter at the input [Fig. 3(b)].

The loop gain (LG) of the third-order BBCDR is demonstrated as

\[
\text{LG}(s) = \frac{K_{\text{PD}} I_p K_{\text{VCO}} (R_1 C_1 s + 1)}{(R_1 C_1 C_2 s + C_1 + C_2)s^2}
\]

where \( K_{\text{PD}} \) is the gain of the BBPD. It has three poles and one zero, with two poles at the origin and the zero below the last pole. JGEN in (34) and JTF in (35) are deduced. In addition, we can obtain JTOL in (36) by equating \( \Delta \varphi \) to 0.5 UI

\[
\text{JGEN}(s) = \frac{1}{1 + \text{LG}(s)}
\]

\[
\text{JTF}(s) = \frac{\text{LG}(s)}{1 + \text{LG}(s)}
\]

\[
\text{JTOL}(s) = \frac{1}{2} \left[ 1 + \text{LG}(s) \right].
\]

It is obvious that the denominator in (34) is negative, when \( s < -1/R_1 C_2 \). If \( s > -1/R_1 C_1 \), this denominator is positive. Real poles of JGEN only appear within \((-1/R_1 C_2, -1/R_1 C_1)\). In general, complex poles are also located in above interval. Yet, there are two zeros at the origin and the last zero appears when \( s = -1/R_1 C_2 \). It implies that JGEN has a high-pass profile. Because of the denominator of JTF and the numerator of JTOL are the same as the denominator of JGEN, they have the same corner frequency.

Similar to the JTOL analysis, \( \varphi_{\text{VCO}} \) and \( \varphi_{\text{out}} \) can be viewed as \( \varphi_{\text{in}} \) and \( \Delta \varphi \) in Fig. 3(a), respectively. Thus, the following equation can be written directly according to (27):

\[
\varphi_{\text{out,p}} = \sqrt{\varphi_{\text{VCO,p}}^2 - \varphi_0^2} + \alpha (A_1 + B_1).
\]

Thus, JGEN can be expressed as

\[
\text{JGEN} = \sqrt{\varphi_{\text{VCO,p}}^2 - \varphi_0^2 + \alpha (A_1 + B_1)}.
\]

This result holds when the BBCDR enters the full slewing region as shown in Fig. 5. Consider \( 2 \pi R_1 C_2 f \gg 1 \) and \( C_2 < \ll C_1 \), we can simplify (38) as

\[
\text{JGEN} = 1 + \frac{4K_{\text{VCO}} I_p}{\pi \varphi_{\text{VCO,p}} C_2 \omega_p^2}.
\]

JGEN decreases as \( C_2 \) increases. We can observe that: 1) when \( \omega_p \) rises, JGEN approaches 0 dB and 2) since the second term in (39) is positive, JGEN is larger than 0 dB, indicating that the peaking always exists in the third-order BBCDR loop.
VI. Behavioral Simulations and Discussions

A. MATLAB/Simulink Model

To validate the results derived in the previous section, we develop the top-level behavior model in MATLAB/Simulink for JTF and JTOL verification, as shown in Fig. 9(a). It mainly consists of three parts: 1) the BBCDR loop corresponding to the phase-domain model [Fig. 3(a)]; 2) the JTOL Detector block; and 3) the JTF Calculation block. In the BBCDR loop, the subsystem Input Jitter Generator provides a sinusoidal jitter, which is expressed by \( \phi_{in} = 2\pi \phi_{in,p} \sin(2\pi \times 10^6 f_{jitter} t) \). The subsystem Triggered Binary Decision operates with the beat of a pulse signal periodically, whose frequency is equal to \( f_{VCO} \), i.e., the frequency of the VCO. Fig. 9(b) shows the algorithm of Maximum Extractor. In the IDLE state, \( \phi_{max} \) is assigned to zero, and the simulation time of the system will be compared to a threshold time in terms of \( f_{jitter} \). If the simulation time is larger than \( N \cdot T \), which indicates the third-order BBCDR loop operating steadily, and then MaxExtract state returns \( \text{Max} \{ \phi_{max}, \phi_{out} \} \). Otherwise, it jumps back to the IDLE state. Here, Max[] is the function to return the maximum element of inputs. We begin the simulation with an ideal binary decision and consider the nonideal effect later.

By properly setting the simulation parameters, i.e., Stop time of the simulation and Max step size of the solver, we can obtain a good tradeoff between the simulation accuracy and efficiency. The Stop time of simulation is set according to
Fig. 11. Time-domain waveforms around $f_{\text{peak}}$ and their tendency. The loop parameters of LP-I in Table I are preset for simulation with $\phi_{\text{in},p} = 0.5$ UI. (a) $f_{\text{jitter}} = 2.3$ MHz. (b) $f_{\text{jitter}} = 2.31$ MHz. (c) $f_{\text{jitter}} = 2.313$ MHz. (d) $f_{\text{jitter}} = 2.32$ MHz. (e) $f_{\text{jitter}} = 2.34$ MHz. (f) Normalized time difference between the peaking of $\phi_{\text{in}}$ and the intersection point, corresponding to case (a)–(e), respectively.

$f_{\text{jitter}}$, for example, $\text{StopTime} = 10/f_{\text{jitter}}$ when $f_{\text{jitter}} < 1$ MHz and $\text{StopTime} = 100/f_{\text{jitter}}$ when $f_{\text{jitter}} > 30$ MHz, and $\text{Max step size}$ is preset to $0.05/f_{\text{VCO}}$.

Fig. 12. Simulation and calculation results JTF with the loop parameters of LP-I in Table I. The input jitter amplitude, $\phi_{\text{in},p}$, varies from 0.05 to 1 UI. (a) JTF under different $\phi_{\text{in},p}$ from (19). (b) $f_{\text{peak}}$ of JTF from (20). (c) JP from (21). (d) Slope in slewing region versus $\phi_{\text{in},p}$.

Fig. 13. Simulation and calculation results in (19) of JTF with the loop parameters of LP-II in Table I. The ratio of $C_2/C_1$, defined as a coefficient $k$, ranges from 0.1 to 0.4. (a) JTF under different $k$. (b) $f_{\text{peak}}$ of JTF from (20). (c) JP from (21). (d) Slope in slewing region versus $k$.

Fig. 14. Flowchart of automatic algorithm for JTOL verification.

Two sets of the loop parameters (LP) in Table I with considerable difference are used for verifying our above analysis, proving that our proposed method is not a special case only applicable to a certain loop parameter.

B. JTF Simulation

Fig. 10 shows simulated time-domain waveforms in regard to the well-tracked region in Fig. 5. The loop parameters of LP-I in Table I are preset, with $\phi_{\text{in},p} = 0.5$ UI and $f_{\text{jitter}} = 2$ MHz. Note that the corresponding $f_{\text{peak}}$ is $\sim 2.313$ MHz. As shown in Fig. 10(a), $\phi_{\text{out}}$ tracks $\phi_{\text{in}}$ well and they lead each other alternatively. Thereafter, $\phi_{\text{out}}$ reverses its polarity rapidly and produces a sawtoothlike $V_{\text{cont}}$. Obviously, $\phi_{\text{out}} \approx \phi_{\text{in}}$ and a 0-dB JTF are obtained. To illustrate the details, a zoomed-in
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Fig. 15. Simulation and calculation results for JTOL, where JTOL1, JTOL2, and JTOL3 are the calculation results from (28), (29), and (32), respectively. JTOL curves (a) are obtained using the loop parameters of LP-I in Table I, while JTOL curves (b) are obtained using the loop parameters of LP-II in Table I with \( k = 0.1 \).

TABLE I
PARAMETERS FOR JITTER VERIFICATION

<table>
<thead>
<tr>
<th>Loop Parameter Designation</th>
<th>LP-I</th>
<th>LP-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \varphi_{\text{in}} ) (UI)</td>
<td>variable</td>
<td>0.5</td>
</tr>
<tr>
<td>( I_p ) (( \mu )A)</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>( R_I ) (( \Omega ))</td>
<td>1500</td>
<td>400</td>
</tr>
<tr>
<td>( C_1 ) (pF)</td>
<td>500</td>
<td>70</td>
</tr>
<tr>
<td>( C_2 ) (pF)</td>
<td>25</td>
<td>( k \cdot C_1 )</td>
</tr>
<tr>
<td>Coefficient ( k )</td>
<td>0.05</td>
<td>variable</td>
</tr>
<tr>
<td>( K_{\text{VCO}} ) (GHz/V)</td>
<td>0.1</td>
<td>0.8</td>
</tr>
<tr>
<td>Data Rate (Gbps)</td>
<td>9.95328</td>
<td>40</td>
</tr>
</tbody>
</table>

view of the Time Interval \( A \) is shown in Fig. 10(b), where \( t_1, t_2, \) and \( t_3 \) are the time instants corresponding to the intersections of \( \varphi_{\text{in}} \) and \( \varphi_{\text{out}} \). Between \( t_1 \) and \( t_2, \varphi_{\text{out}} \) exceeds \( \varphi_{\text{in}} \), so that the CP generates a \(-50-\mu A \) \( I_{PD} \), and \( V_{\text{cont}} \) keeps decreasing. Inversely, \( \varphi_{\text{in}} \) leads \( \varphi_{\text{out}} \), thus the \( 50-\mu A \) \( I_{PD} \) pulls \( V_{\text{cont}} \) up within \([t_2, t_3]\). Fig. 11 depicts the time-domain waveforms around \( f_{\text{peak}} \), the loop parameters preset for the simulation are also listed in Table I, namely, LP-I with \( \varphi_{\text{in},p} = 0.5 \) UI.

Fig. 11(a)–(e) shows the waveforms of \( \varphi_{\text{in}} \) and \( \varphi_{\text{out}} \) with the same initial condition. \( \Delta t_1 \) is defined as \( T_{\text{ipn}} - T_n \), where \( T_{\text{ipn}} \) is the time instant of the intersection point of \( \varphi_{\text{in}} \) and \( \varphi_{\text{out}} \) in the same cycle and \( T_n \) is the \( n \)th time instant corresponding to the \( \varphi_{\text{in}} = \varphi_{\text{in},p} \). When \( f_{\text{jitter}} < f_{\text{peak}} \), \( \Delta t_1 \) keeps decreasing with the simulation time and tends to a negative constant at steady state [Fig. 11(a) and (b)]. However, when \( f_{\text{jitter}} > f_{\text{peak}} \), \( \Delta t_1 \) shows a reverse tendency and tends to a positive steady constant [Fig. 11(d) and (e)]. When \( f_{\text{jitter}} \approx f_{\text{peak}} \), \( \Delta t_1 \) stays almost constant during the simulation time. Fig. 11(f) shows the normalized \( \Delta t_1 \) versus the number of cycles; it is clear that the tendency of \( \Delta t_1 \) represents the location of \( f_{\text{jitter}} \) in relation with \( f_{\text{peak}} \).

In order to validate our JTF analysis in Section III, two groups of the loop parameters of the BBCDR are simulated in the MATLAB/Simulink model, as depicted in Fig. 9. The corresponding loop parameters are used for the equations derived in Section III. In reality, \( \varphi_{\text{in}} \) consists of various frequency components with different \( \varphi_{\text{in},p} \). However, \( f_{\text{BW}} \) is sensitive to \( \varphi_{\text{in},p} \), so that the relationship between \( \varphi_{\text{in},p} \) and \( f_{\text{BW}} \) must be studied. As another important parameter, \( C_2 \) suppresses the jitter due to the ripple on \( V_{\text{cont}} \) and plays a key role in the loop stability. Hence, \( k \) is also swept to provide an intuitive insight. Fig. 12 shows the simulation and calculation results of JTF with the loop parameters of LP-I in Table I. In Section III, the JTF feature depends on \( \varphi_{\text{in},p} \) heavily. Fig. 12(a) depicts a cluster of JTF curves corresponding to \( \varphi_{\text{in},p} \) ranging from 0.05 to 1 UI. We can observe that \( f_{\text{peak}} \) [Fig. 12(b)] decreases from 8.22 to 1.38 MHz as \( \varphi_{\text{in},p} \) increases. Fig. 12(c) illustrates the monotonically decreasing function of \( J_P \), which is
reasonable considering JTF \( = 20 \log (\phi_{\text{out}},p/\phi_{\text{in}},p) \). It means that a larger \( \phi_{\text{in}},p \) indicates smaller peaking. The slope in the slewing region is between \(-20\) and \(-40\) dB/dec and is rather flat, as shown in Fig. 12(d). Compared to the third-order calculation results from (19)–(21), the second-order calculation results are based on \( C_2 = 0 \), and it shows a considerable deviation from the simulation results, especially when \( \phi_{\text{in}},p \) is small. Also, the slopes from second-order calculation results are always \(-20\) dB/dec.

Fig. 13 plots the simulation and calculation results of JTF with the loop parameters of LP-II in Table I. Note that \( f_{\text{peak}} \) decreases from 7.27 to 5.27 MHz, when \( k \) varies from 0.1 to 0.4 [Fig. 13(b)]. Although the ripple on \( V_{\text{cont}} \) is suppressed by \( C_2 \) in LF, a larger \( C_2 \) enlarges JP. When \( k \) reaches 0.4, JTF shows an undesired JP of larger than 1.5 dB [Fig. 13(c)]. Fig. 13(d) shows that the slope in the slewing region decreases slightly as \( k \) increases. The consistency between simulation and calculation results in Figs. 12 and 13 verifies our JTF analysis. To achieve a JP of \(<0.1\) dB, \( k \) should be further smaller, and larger \( \phi_{\text{in}},p \) should be chosen comparing with those in Table I.

**C. JTOL Simulation**

In JTOL simulation, it is hard to determine the exact \( \phi_{\text{in}},p \) at a given \( f_{\text{jitter}} \) when the bit error occurs. Thus, we design an automatic algorithm for the JTOL verification, as shown in Fig. 14. \( f_{\text{min}} \) and \( f_{\text{max}} \) denote the lower and upper limits for the frequency of interest, respectively. The simulation starts with \( f_{\text{jitter}} = f_{\text{max}} \). \( f_{\text{jitter}} \) is compared with \( f_{\text{min}} \) at first to decide whether the simulation stops or not. If \( f_{\text{jitter}} > f_{\text{min}} \), the model activates for seeking an appropriate \( \phi_{\text{in}},p \). Under the initial state, \( \phi_{\text{in}},p \) is set to \( \phi_{\text{in}},p_0 \), and a settling time of \( N \cdot T \) is entailed for steady operating of the BBDCDR, as discussed in the JTF simulation.

The key variable \( \text{Flag} \) will be set to 1 when a bit error is detected (\( \Delta \phi_{\text{max}} > \pi \)). If \( \text{Flag} \) is equal to 0, \( \phi_{\text{in}},p \) increases by multiplying the factor \( \text{Amp}_\text{step} \), and the bit-error-detection repeats until \( \text{Flag} = 1 \). It is worth mentioning that the iteration counter (\( j \)) is limited up to 20 for monitoring and avoiding the abnormal operation in the simulation. When the appropriate \( \phi_{\text{in}},p \) is found, \( \phi_{\text{in}},p \) \( \text{Sweep Loop} \) breaks in Fig. 14, and \( f_{\text{jitter}} \) is outputted with its corresponding \( \phi_{\text{in}},p \) as the JTOL value at a specific jitter frequency. Afterward, \( f_{\text{jitter}} \) changes to a lower frequency based on the \( f_{\text{jitter}} \) \( \text{Switch Algorithm} \), which returns to the decision (\( f_{\text{jitter}} > f_{\text{min}} \)). Then, we repeat the above procedure to obtain the overall JTOL curve. For example, we apply \( \phi_{\text{in}} = \phi_{\text{in}},p \cdot \sin(2\pi \cdot 10^6 \cdot f_{\text{jitter}} \cdot t) \) and \( f_{\text{jitter}} \) is set to 80 MHz. \( \phi_{\text{in}},p \) is 0.4 UI and multiplied by \( \text{Amp}_\text{step} \) of 1.005 each time. The detection keeps operation until \( \Delta \phi_{\text{max}} = \pi \). It can be found that when \( \phi_{\text{in}},p \) reaches 0.5 UI, \( \text{Flag} = 1 \) is obtained. Next, \( f_{\text{jitter}} \) is reduced to

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**Fig. 17.** (a) MATLAB/Simulink model for JGEN verification due to the VCO’s phase noise, according to the phase-domain model in Fig. 3(b). (b) Algorithm for Nonideal Binary Decision.

**Fig. 18.** Simulation and calculation results. (a) JGEN and (b) JTF using the loop parameters of LP-I in Table I with 0.1-UI \( \phi_{\text{in}},p \) (\( \phi_{\text{VCO}},p \)), while (c) JGENs and (d) JTFs in are achieved using the loop parameters of LP-II in Table I with \( k = 0.1 \).
70 MHz. This procedure is repeated until $f_{\text{jitter}}$ is less than $f_{\text{min}}$ of 0.4 MHz. A group of $\phi_{\text{in,p}}$ is achieved with their corresponding jitter frequencies. Finally, the overall JTOL curve is plotted by connecting $\phi_{\text{in,p}}$ at 80, 70, 60 MHz and so on.

The simulation JTOL curves are obtained by performing the above algorithm, the AMP_step in the last run is set to 1.005, which guarantees the accuracy of the simulation. Fig. 15 shows the comparison of the simulation and calculation results according to (28), (29), and (32). Compared to the JTOL3 based on the second-order LF (i.e., $C_2$ equals 0) from (32), JTOL1 and JTOL2 give better predictions, especially for the sinking area. Note that there is little difference between JTOL1 and JTOL2. Therefore, JTOL2 is recommended for its simplicity. As depicted in Fig. 15, the calculated results predict the JTOL well at high frequency because the BBCDR experiences the full slewing all the time, which is consistent with the presupposition in Section IV. Inversely, at low $f_{\text{jitter}}$, the calculated JTOL1 and JTOL2 depart from the simulation results slightly, because the BBCDR operating at the specific frequency does not experience the full slewing any longer, as shown in Fig. 5(b). However, the theoretical curves from JTOL1 and JTOL2 are in high agreement with the simulation results.
Interestingly, the simulated JTOL curve of a third-order BBCDR exhibits a sinking area before approaching to 0.5 UI. It can be explained by the time-domain waveforms (Fig. 16). As $f_{\text{jitter}}$ increases, $\phi_{\text{out}}$ presents a larger phase shift regarding $\phi_{\text{in}}$, leading to a smaller $\Delta \phi_{\text{in}}$. Here, $\Delta \phi_{\text{in}}$ is the time difference between the minimum of $\phi_{\text{in}}$ and maximum of $\phi_{\text{out}}$. Thus, $\Delta \phi_{\text{max}}$ increases even if the same $\phi_{\text{in},p}$ is applied and the JTOL worsens. In the extreme case, when $\Delta \phi_{\text{in}} = 0$, $\Delta \phi_{\text{max}} = \phi_{\text{in},p} + \phi_{\text{out},p}$, JTOL must be less than 0.5 UI, indicating a sinking point on the overall JTOL.

D. JGEN Simulation

For JGEN verification, a MATLAB/Simulink model [Fig. 17(a)] is developed according to the phase-domain behavior model in Fig. 3(b). $\phi_{\text{in}}$ is set to zero and an additive jitter is injected to the VCO by the subsystem $\phi_{\text{VCO},p}$ Generator, which is the same as Input Jitter Generator Fig. 9(a). The finite gain of the BBPD [26] is taken into account by the subsystem Nonideal Binary Decision, and its algorithm flowchart is shown in Fig. 17(b). When $-\phi_{\text{m}} < \Delta \phi < \phi_{\text{m}}$, BinaryOut outputs $\Delta \phi$ or $\phi_{\text{m}}$, indicating a finite gain. When $|\Delta \phi| > \phi_{\text{m}}$, it shows a binary characteristic, corresponding to the nonideal bang-bang curve (see Fig. 1).

Fig. 18(a) and (b) shows the simulated JGEN with a larger overshoot of 5 dB and JTF with a larger peak of 3 dB, respectively, under the loop parameters of LP-I with 0.1-UI $\phi_{\text{VCO},p}$($\phi_{\text{in},p}$). Fig. 18(c) and (d) shows the simulated JGEN with a 2-dB overshoot and JTF with a 0.05-dB peak, respectively, using the loop parameters of LP-II with $k = 0.1$. For both loop parameters, we obtain the calculation results (dotted line) from (19) and (38), which is consistent with the simulation results (solid line) significantly. In addition, Fig. 18(a) and (c) shows the effect caused by the finite gain of the BBPD. For the ideal BBPD, JGEN exhibits an ideal high-pass characteristic, however, when $\phi_{\text{m}}$ increases, it shows a finite slope.

E. Overall Discussion Including the Effect of $\phi_{\text{m}}$

Consider the above analysis, we must make the tradeoff between the insights from the calculation results and the calculation accuracy. Observing the deterioration of the BBPD curve by random jitter, we detail the effect of $\phi_{\text{m}}$, ranging from 0 to $0.5 \pi$, in JGEN, JTF, and JTOL. Fig. 19(a)–(c) is obtained using the loop parameters of LP-I in Table I with 0.1-UI $\phi_{\text{in},p}$($\phi_{\text{VCO},p}$) and Fig. 19(d)–(f) is achieved using the loop parameters of LP-II with $k = 0.1$. JGEN presents a typical high-pass profile, meaning that the BBCDR only suppresses low-frequency jitter of the VCO. For the ideal BBPD, a sharp rising appears at the corner frequency. Differing from the phenomenon when $f_{\text{jitter}}$ is higher than the corner frequency, $f_{\text{VCO}}$, leading to $\phi_{\text{out}} \approx 0$ at $f_{\text{jitter}}$ lower than the corner frequency [Fig. 3(b)]. However, the discrete phase detection makes $\phi_{\text{out}}$ nonzero and random with $\phi_{\text{out},p}$ in proportion to $f_{\text{VCO}}$. Thus, the curve in the well-tracked region is unsmooth and approximated as a constant. Meanwhile, the fast switching between well-tracked and slewing regions produces the sharp rising between them. As $\phi_{\text{m}}$ increases, the BBCDR loop attenuates less VCO jitter below the corner frequency. Finally, the behavior of a third-order linear CDR will occur when $\phi_{\text{m}}$ exceeds $\phi_{\text{VCO},p}$.

For JTF in Fig. 19(b), if $\phi_{\text{m}}$ is larger than $\phi_{\text{in},p}$ (e.g., 0.1 UI) and the BBPD completely operates in the linear phase-detection mode, JP decreases as $\phi_{\text{m}}$ increases (dashed line). JTF curves will be smooth without a sharp rising. Inversely, if $\phi_{\text{m}}$ is smaller than $\phi_{\text{in},p}$ (e.g., 0.1 UI) and the BBPD fully enters the bang-bang phase-detection mode, JP increases as $\phi_{\text{m}}$ increases (solid line). This bang-bang phase-detection mode will hold in Fig. 19(e), when $\phi_{\text{in},p}$ of 0.5 UI is relatively large compared to $\phi_{\text{m}}$. JP is monotonically increasing with respect to $\phi_{\text{m}}$, and thus the maximum JP occurs at $\phi_{\text{m}} = 0.5$ UI [Fig. 19(e)]. The sinking region of JTOL is corresponding to the peaking area of JGEN and JTF. Moreover, the corner frequency moves to lower frequency slightly with lower magnitude of JTOL.

VII. CONCLUSION

The JTF, JTOL, and JGEN characteristics of the third-order BBCDR have been studied in terms of LG, indicating that they share the same corner frequencies. The time-domain waveforms happening in the well-tracked region and slewing region in the vicinity of the corner frequency have been analyzed. The leveraged insights explain the sinking area of JTOL and the sharp rising of JGEN. The resultant formulas confirm the $C_2$ contribution to the BBCDR loop design when compared with the conventional analysis of a second-order BBCDR loop. The MATLAB/Simulink models are developed to verify the accuracy of our analytical methods. Meanwhile, in order to match a practical condition, the nonideal effect of BBPD has been discussed in the simulation results. This paper focuses on the analysis of the full-rate third-order BBCDR loop, indicating its effectiveness and practicability for analyzing the features of the half-rate and quarter-rate BBPD with different frequencies of the VCO. When the divider in the feedback path can be taken into consideration in the phase-domain behavior model, the analytical method and conclusion can be modified to reveal the characteristics of the bang-bang PLL.

REFERENCES


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