4-Cycle-Start-Up Reference-Clock-Less Digital CDR Utilizing TDC-Based Initial Frequency Error Detection with Frequency Tracking Loop

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SUMMARY This paper proposes a reference-clock-less quick-start-up CDR that resumes from a stand-by state only with a 4-bit preamble utilizing a phase generator with an embedded Time-to-Digital Converter (TDC). The phase generator detects 1-UI time interval by using its internal TDC and works as a self-tunable digitally-controlled delay line. Once the phase generator coarsely tunes the recovered clock period, then the residual time difference is finely tuned by a fine Digital-to-Time Converter (DTC). Since the tuning resolution of the fine DTC is matched by design with the time resolution of the TDC that is used as a phase detector, the fine tuning completes instantaneously. After the initial coarse and fine delay tuning, the feedback loop for frequency tracking is activated in order to improve Consecutive Identical Digits (CID) tolerance of the CDR. By applying the frequency tracking architecture, the proposed CDR achieves more than 100 bits of CID tolerance. A prototype implemented in a 65 nm bulk CMOS process operates at a 0.9–2.15 Gbps continuous rate. It consumes 5.1–8.4 mA in its active state and 42 µA leakage current in its stand-by state from a 1.0 V supply.

key words: Clock-and-data recovery (CDR), time-to-digital converter (TDC), serial communication, quick start-up, internet-of-things

1. Introduction

A Clock-and-Data Recovery (CDR) circuit, which recovers the clock signal from the incoming random data sequences to retime the data, is one of the crucial building blocks in data communication devices [1, 2]. Though a Phase-Locked Loop (PLL) based architecture is often used for CDR [3–11], it usually requires long settling time to recover the target clock signal. In the applications that keep communicating for a long period of time, the performance overhead in this start-up is not of critical concern. However, in some applications that work intermittently such as mobile and Internet-of-Things (IoT) sensor node applications [12, 13], the effective usage of a low-power stand-by state is important as well as a dynamic power efficiency in an active state. Thus, in such cases, the data link has to resume its communication immediately after it is activated not to waste power for state transitions.

To realize quick start-up, several different CDR architectures have been proposed [14–20]. Among them a burst-mode CDR (BMCDR) has been used in point-to-multipoint fiber serial communications such as passive optical networks (PON), in which a quick phase locking is crucial [20–26]. As a BMCDR can effectively utilize a low-power stand-by state thanks to its quick start-up feature, it can be considered as a useful choice to realize energy-efficient serial communication systems. Figure 1 conceptually compares start-up features of the CDR techniques. The conventional reference-less PLL-based CDR precisely but slowly locks to the input signal, while the BMCDR can reduce the wait time for phase locking and saves power during the start-up. However, most of the conventional BMCDRs use an external reference clock and need to lock to a predetermined frequency prior to the actual random data input. Thus, these BMCDR techniques still require some dynamic power consumption even in the stand-by state. In order to eliminate the external reference and a priori frequency locking, a reference-clock-less BMCDR scheme utilizing a time-to-digital converter (TDC) based architecture has been proposed [27]. Based on the recent progress in CMOS process scaling, time resolution is becoming more and more superior to a voltage resolution due to the high-speed transistors and the reduced supply voltage [28–32]. By fully utilizing the time-domain information, a power-efficient CDR architecture could be realized. This scheme uses a Cycle-Lock Gated ring Oscillator (CLGO) that quickly locks to the input frequency by detecting 1-UI cycle time of the incoming data stream utilizing Self-Tunable Digitally-Controlled Delay Lines (ST-DCDLs). By employing coarse-fine hierar-
2. Architecture of the Proposed CDR

A block diagram of the proposed CDR is illustrated in Fig. 2, which is similar to the one in [33]. It consists of a gating circuit, a Vernier Phase Detector (PD), a digital controller and a ST-DCDL with a fine DTC. This CDR recovers a half-rate clock, then the incoming data are latched by both the rising and falling edges of the recovered clock. Thus the serial input data will appear at DATAOUT1 and DATAOUT2 alternately. A detailed block diagram of the CDR circuit is shown in Fig. 3(a). Though the actual circuit is implemented with a differential configuration, this figure shows a single-ended version for simplicity. The coarse-fine hierarchical structure is chosen for wide frequency tuning range as well as fine resolution. The gating circuit in Fig. 2 is composed of an edge detector and a polarity adaptor that find the data transition then align its rise/fall polarity to the present transition of the recovered clock [19, 27].

The proposed CDR has two operation phases as in [33], i.e., quick start-up and frequency tracking. Figures 3(b) and (c) respectively highlight the active blocks in these two operation phases. During the initial quick start-up phase, by using “1010” 4-bit preamble, 1 UI cycle time is detected using “1010” 4-bit preamble, 1-UI cycle time is detected during the actual data communication is relatively large because fine resolution TDCs with resistive interpolation is required for the fine ST-DCDL. In this paper, we propose a new architecture of the reference-clock-less CDR based on a ST-DCDL with a fine Digital-to-Time Converter (DTC). With the proposed architecture we can reduce the dynamic power consumption during the active state while inheriting the advantage of the quick start-up and frequency tracking features in [33].

The rest of this paper is organized as follows. Section 2 explains the architecture of the proposed CDR and the operating principles of the quick start-up. Then in section 3 the chip fabrication and measurement results are summarized. Finally section 4 concludes this paper.

Fig. 3: (a) A detailed block diagram of the CDR circuit, (b) and (c) are disabled during quick start-up and frequency tracking phases, respectively.

Fig. 4: A block diagram of the trigger generator.

Fig. 2: The proposed CDR architecture based on cycle-lock gated-oscillator (CLGO) with frequency tracking loop.
A schematic diagram of the trigger generator is illustrated in Fig. 4. During the quick start-up phase, the trigger generator sends trigger signals to the coarse ST-DCDL and the Vernier TDC by detecting the 1st and 2nd falling transitions in “1010” 4-bit preamble signal, respectively. Simulated waveforms during the quick start-up phase are shown in Fig. 5. The coarse trigger signal rises at the first falling edge of the positive input (red line of the top waveform). The time difference between the fine DTC output and the coarse trigger is measured by the ST-DCDL, so that the total delay through the MUX, the fine DTC and the coarse ST-DCDL in Fig. 3 is coarsely tuned to be 1-UI time interval. After that, at the second falling edge of the positive input, the fine trigger signal rises to measure the residual time difference between the output of the coarse ST-DCDL and the fine trigger by using the Vernier TDC. Then the fine DTC tunes the delay according to the code from the Vernier TDC to generate a finely-tuned half-rate recovered clock waveform.

To make this circuit recover the half-rate clock, the signal path delays must be designed properly so that the internal TDCs can detect the correct delays. But the process, voltage and temperature (PVT) variations would cause the delay mismatch between different signal paths that may lead to erroneous TDC outputs. Thus the circuits need to be delay-matched are designed with large-enough transistor sizes using the same circuit structures as much as possible in order to mitigate the impact of the PVT variations within the range that can be taken care by the frequency tracking feedback loop, which will be activated after the quick start-up phase.

Fig. 6(a) shows a block diagram of the ST-DCDL, which is simply composed of a delay-line-based TDC. Its input-to-output delay is tunable by selecting one of the outputs of the delay line through the internal MUX. As it shares the single delay line to measure and generate the delay, the ST-DCDL tunes the delay by itself utilizing the output code from the internal TDC. As shown in Fig. 6(b) the buffer circuit for the coarse delay line is implemented with a pseudo differential buffer with switches to disable the output. Once the coarse 1-UI time interval detection is finished and the ST-DCDL selects the proper output, the buffers for more delay will be disabled by turning off these switches to save power.

Fig. 7 illustrates the schematic diagrams of the fine DTC, which is composed of a series connection of pseudo differential buffers with 1-bit delay tunability. By turning on and off one of the two current source/sink, each buffer stage can finely change its delay between fast and slow settings. With $N$ stages of this buffer tuned with a thermometer coded delay tuning word as shown in Fig. 7, we can achieve a digitally tunable delay with fine resolution while its monotonicity is guaranteed.

A schematic diagram of the Vernier TDC used to detect the residual time difference after coarse tuning is illustrated in Fig. 8. In a Vernier TDC, two delay lines with delay difference of $\Delta t$ is used to achieve a fine time resolution of $\Delta t$ [29]. Here in this implementation, the same buffer circuit used in the fine DTC in Fig. 7 is employed to realize two different delays. The slower delay line (the upper one in Fig. 8) uses the slow setting by turning off the internal cur-
Then at the 2nd falling edge, the fine trigger is asserted to operate by measuring the 1-UI pulse width using its internal TDC. In Fig. 10, at the 1st falling edge in the preamble the coarse trigger is asserted and the ST-DCDL coarsely tunes itself realize the same time resolution with the shared buffer circuit, the proposed CDR tunes the fine delay instantaneously without any processing delay in the quick start-up phase. Thus we can maintain the benefit of 4-cycle start-up as in \[27,33\] also with the proposed CDR architecture. Of course, due to PVT variations, the actual delay resolution of the Vernier TDC and the fine DTC may be slightly different that leads to tiny delay error in the recovered clock. This remaining error will be taken care by the frequency tracking loop activated after the initial lock, which will be explained later in this section.

Fig. 9 shows the simulation results of the delay resolutions of the coarse and fine delay tuning. The ST-DCDL achieves \(\sim 33 \text{ ps/step delay resolution while the fine DTC realizes } \sim 10 \text{ ps/step.}\)

To tune these coarse and fine delays, the proposed CDR requires a 4-bit “1010” preamble at the start-up. As shown in Fig. 10, at the 1st falling edge in the preamble the coarse trigger is asserted and the ST-DCDL coarsely tunes itself by measuring the 1-UI pulse width using its internal TDC. Then at the 2nd falling edge, the fine trigger is asserted to measure the residual delay difference with the Vernier TDC. In the quick start-up phase, the output code from the Vernier TDC is directly fed to the fine DTC to tune the delay instantaneously thanks to the shared buffer structure with the same time resolution. Now we can have a finely tuned recovered clock. However, this initially-tuned delays might contain certain amount of error due to PVT variations and jitter, as well as the input frequency drift. This frequency error accumulates as phase error and results in poor CID tolerance. Thus, as in \[33\], a feedback loop for frequency tracking shown in Figs. 2 and 3 is activated after the initial clock recovery process. After activating the feedback loop, the Vernier PD, which uses the same Vernier TDCs, detects the phase error between the incoming data and the recovered clock as illustrated in Fig. 10(b). The PD output is processed by the digital controller whose block diagram is shown in Fig. 11. The digital controller realizes a lowpass characteristic with output dithering by the \(\Delta\) modulator to effectively improve the frequency resolution. The output of the digital controller is fed to the fine DTC to achieve frequency tracking.

3. Chip Implementation and Measurement Results

The prototype of the proposed CDR is fabricated in a 65 nm bulk CMOS process, whose chip micrograph and layout image are shown in Fig. 12. The proposed CDR occupies \(98 \times 157 \mu m^2\) area. The CDR operation is verified from 0.90 to 2.15 Gb/s continuous rate while it consumes 5.1–8.4 mA current from 1.0 V supply. The measured leakage current
during the stand-by state is 42 µA.

Firstly, the 4-cycle start-up behavior of the proposed CDR is verified as shown in Fig. 13. After “1010” 4-bit preamble input, it successfully recovers the clock and data. As shown in Fig. 2, the incoming data are latched by both the rising and falling edges of the half-rate recovered clock. Thus the serial input data will appear at DATAOUT1 and DATAOUT2 alternately. We can also observe that the transition edge in the incoming data is injected to realign the phase of the recovered clock. Fig. 14 shows the measured eye diagrams of the input data and the half-rate recovered clock signals in the cases of without and with the dithering in the digital controller. The clock jitter is ~19.3 ps\text{rms} and ~17.4 ps\text{rms} for the cases without and with the dithering, respectively. Fig. 15 compares the CID tolerance measurement results between the cases without and with the dithering. Before and after the intentional consecutive 0 and 1 input at the middle of the waveforms, PRBS data sequence is injected to the circuit. The CID tolerance improves from 44 bits to 102 bits by enabling the dithering in the digital controller. These results demonstrate that the dithering effectively improves the frequency tuning resolution, which leads to better frequency tracking capability. Fig. 16 shows the jitter tolerance measurement result. Especially for high-frequency jitter, the proposed CDR has relatively poor jitter tolerance. This is mainly because the frequency characteris-

Finally, Table 1 compares the proposed work with similar prior works. The proposed CDR does not require an external reference clock and the frequency lock prior to the data input, which leads to the immediate start-up with no dynamic power consumption during the stand-by state. Especially compared with [33], the proposed CDR reduces the dynamic power consumption during the active state about 3× while maintaining the same benefits of the 4-cycle quick start-up as well as the wide-range continuous-rate frequency tracking features. Although the maximum CID tolerance is reduced to 102 bits, this number is large enough because we may be able to choose proper coding schemes such as 64b/66b to have enough transitions by accepting some over-

Fig. 12: Chip micrograph and layout of the proposed CDR.

Fig. 13: Measured waveforms of the 4-cycle start-up behavior at 2.15 Gb/s input.

Fig. 14: Measured waveforms of the input data and recovered clocks for 2.15Gb/s inputs (a) without and (b) with dithering in the digital controller.

Fig. 15: CID tolerance measurement results at 2.0 Gb/s input (a) without and (b) with dithering.

Table 1: Comparison with prior works.
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References


### Table 1: Performance comparison with prior works.

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<th>CDR Scheme</th>
<th>Ref.</th>
<th>[17]</th>
<th>[18]</th>
<th>[27]</th>
<th>[33]</th>
<th>This Work</th>
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<td>Tech. [nm]</td>
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<td>90</td>
<td>65</td>
<td>65</td>
<td>65</td>
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<td>1.4</td>
<td>1.2</td>
<td>1.0</td>
<td>1.4</td>
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<tr>
<td>Rate [Gb/s]</td>
<td>2.5</td>
<td>2.2</td>
<td>1.40–2.06</td>
<td>1.2–2.3</td>
<td>0.90–2.15</td>
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<tr>
<td>Power [mW]</td>
<td>13.68</td>
<td>6.1</td>
<td>9.5</td>
<td>13.2–24.6</td>
<td>5.1–8.4</td>
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<tr>
<td>Area [mm²]</td>
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<td>0.0064</td>
<td>0.019</td>
<td>0.015</td>
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<td>CID Tol.</td>
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<td>128bits</td>
<td>13bits</td>
<td>292bits</td>
<td>102bits</td>
<td></td>
</tr>
<tr>
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<td>Prior to data</td>
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<td>4bit</td>
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<tr>
<td>Phase Lock</td>
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<td>No</td>
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