

METHOD AND APPARATUS FOR VARIABLE BIT RATE CLOCK RECOVERY

BACKGROUND OF THE INVENTION

5

Field of the Invention

The present invention relates generally to recovering timing clock of signals in communication networks, and more particularly, to methods and apparatuses for recovering timing clock of variable bit rate signals in communication networks.

Background of the Art

10

High reliability networks, which handle diverse types of traffic from diverse sources, monitor and manage in the time domain the quality of digital transmission. Failure to detect and correct transmission impairments results in unacceptable link error rates and unexpected network failures. Hence, networks must extract from a stream of transmitted data a clock signal to perform the necessary measurements and

15

correct for inevitable transmission degradation.

An extracted clock signal is necessary to perform time domain measurements, such as eye-pattern opening and timing jitter. The extracted clock signal is also essential for distinguishing the individual data bits in the transmitted data stream prior to further processing, such as digital demultiplexing, protocol conversion, packet

20

switching, and measurement of bit error rate (BER).

Clock recovery has traditionally been regarded as a rate specific process, and as a result, conventional point-to-point transmission systems typically use only one or two line rates. Emerging network technologies, for example photonic switching and Wavelength Division Multiplexing (WDM), however, have enabled complex optical

25

network topologies, where links transport diverse types of traffic, such as Internet Protocol (IP), Asynchronous Transfer Mode (ATM), Fiberchannel, Synchronous Optical Network (SONET), and Gigabit Ethernet. Hence, these emerging networks must use clock recovery circuits that are adaptive to the variable rate of the transmitted data.

A phase locked loop is one type of tracking filter often used in a clock recovery circuit for extracting a clock signal from an input data signal. Figure 1 illustrates the primary components of a prior art clock recovery circuit 100, which includes a phase locked loop. The phase locked loop includes a phase comparator 120, a low pass filter 130, a stable voltage controlled oscillator 150 (VCO), and feedback loop 165.

As shown, a transition detector 110, for example a dual edge triggered one-shot, receives a non-return to zero (NRZ) input signal 155, and generates a single pulse of duration τ_{ED} for each transition in input signal 155. The phase locked loop, whose passband frequency f_c is centered on the bit rate frequency f_{bit} of input signal 155, extracts the clock signal from the stream of pulses generated by transition detector 110. Phase comparator 120 compares the phase of the signal at the output of the phase locked loop with the stream of pulses, and generates a phase difference signal. Low pass filter 130 filters and amplifies the phase difference signal to generate a correction signal for adjusting the phase of VCO 150.

For a variable bit rate NRZ input signal, two rate dependent parameters must be properly adjusted in clock recovery circuit 100 for recovering an associated clock signal 160. One rate dependent parameter is the width τ_{ED} of the pulses generated by transition detector 110. While input signal 155 generally does not contain energy at its bit rate frequency f_{bit} , the series of pulses generated by transition detector 110 does contain energy at the bit rate frequency f_{bit} . The amount of energy at the bit rate frequency f_{bit} is maximum when the width of the generated pulses τ_{ED} equals $1/(2f_{bit})$.

The center frequency of VCO 150 is the second rate dependent parameter, which must be properly set to recover clock signal 160 from input signal 155. An active or passive stabilization signal 170 initially sets the center frequency of VCO 150 to a value f_c in the absence of a signal from phase comparator 120. Feedback loop 165 causes the center frequency of VCO 150 to shift from the initial frequency f_c to the bit rate frequency f_{bit} of input signal 155. VCO 150 will lock to the bit rate frequency f_{bit} when its center frequency is close to the bit rate frequency f_{bit} . When the center frequency of VCO 150 exactly equals the bit rate frequency f_{bit} , VCO 150 will phase lock to transitions in input signal 155.

In addition to a phase locked loop, clock recovery circuits may also include a frequency locked loop for tuning the center frequency f_c of VCO 150 to the bit rate frequency f_{bit} . Figure 2 illustrates the basic components of a clock recovery circuit 200, which includes a transition detector 210, phase comparator 220, frequency
5 comparator 260, low pass filter 230, and VCO 250. Frequency comparator 220 compares the stream of pulses generated by transition detector 210 with the output of VCO 250, and generates a locking signal that reflects the difference between the center frequency of VCO 250 and the bit rate frequency f_{bit} . An adder 270 combines the locking signal with the output of phase comparator 220. Feedback loop 265
10 causes the center frequency of VCO 250 to shift from its initial value of f_c to the bit rate frequency f_{bit} , causing the locking signal to transition to zero. At this point, phase comparator 120 continues to control the center frequency and phase of VCO 250.

The stream of pulses generated by transition detector 210 also contains at
15 multiples of the bit rate frequency f_{bit} energy, whose relative amplitude increases as τ_{ED} decreases. As a result, regular patterns in block coded input signals may produce both harmonics and sub-harmonics of the bit rate frequency f_{bit} . Accordingly, existing clock recovery circuits track the harmonics or sub-harmonics of the input data signal when the center frequency of VCO 250 is inappropriately set to a multiple of
20 the bit rate frequency f_{bit} . Consequently, false locking may occur when a clock recovery circuit searches for the bit rate frequency f_{bit} by sweeping the center frequency of VCO 250 across the harmonics. In addition, recurrent patterns in common block coded input data signals also increase the susceptibility of a clock recovery circuit to sub-harmonic locking.

25 Although various techniques are known for sweeping the center frequency of VCO 250 to determine the bit rate frequency f_{bit} , these techniques are too slow and/or lack sufficient accuracy for variable bit rate applications. One example of variable bit rate applications is Wavelength Division Multiplexing (WDM), where an input data signal can have a wide range of bit rates. In addition, the existing techniques cause a
30 clock recovery circuit to readily lock to harmonics and sub-harmonics of the bit rate frequency f_{bit} .

Thus, it is desirable to have methods and apparatuses that do not have the above-mentioned and other disadvantages of the prior art clock recovery circuits for recovering a clock signal from a variable bit rate input data signal.

DESCRIPTION OF THE INVENTION

5 Methods and apparatuses consistent with the present invention recover a clock signal of a variable bit rate data signal by estimating the minimum time interval between transitions in the data signal, and based on the estimated minimum time interval, determining a center frequency of a narrow band filter that extracts the clock signal from the data signal. For example, a clock recovery circuit consistent with the
10 present invention extracts the clock signal from the variable bit rate data signal by estimating a minimum time interval between transitions in the data signal. The clock recovery circuit generates a plurality of pulses that correspond to transitions in the data signal, and adjusts the duration of each of the pulses based on the estimated minimum time interval. The clock recovery circuit inputs into a narrow band filter the
15 adjusted pulses, determines a center frequency of the narrow band filter based on the estimated minimum time interval, and extracts in the narrow-band filter the clock signal from the adjusted pulses.

 Methods and apparatuses consistent with the invention estimate the bit rate of a data signal independently of a primary phase locked loop and frequency locked
20 loop. Such methods and apparatuses directly estimate the minimum time interval between transitions in the data signal, and thus, eliminate the problems of harmonic and sub-harmonic locking that the prior art clock recovery circuits exhibit in variable bit rate applications.

 The description of the invention and the following description for carrying out
25 the best mode of the invention should not restrict the scope of the claimed invention. Both provide examples and explanations to enable others to practice the invention. The accompanying drawings, which form part of the description for carrying out the best mode of the invention, show several embodiments of the invention, and together with the description, explain the principles of the invention.

30

BRIEF DESCRIPTION OF THE DRAWINGS

In the Figures:

Figure 1 is a block diagram of a prior art clock recovery circuit, which includes a phase locked loop;

5 Figure 2 is a block diagram of a prior art clock recovery circuit, which includes a frequency locked loop and a phase locked loop;

Figure 3 is a block diagram of a variable bit rate clock recovery circuit, in accordance with an embodiment of the invention;

Figure 4 is a block diagram of a variable bit rate clock memory circuit, 10 which includes a calibration means, in accordance with an embodiment of the invention;

Fig. 5 is a circuit diagram of a forward rate detector, which performs discrete interval pulse-width auto-correlation, in accordance with an embodiment of the invention;

15 Figures 6a, 6b, 6c, 6d, and 6e illustrate timing diagrams of an input signal as it propagates through a set of delay segments, in accordance with an embodiment of the invention;

Figure 7 is a circuit diagram of a delay segment, in accordance with an embodiment of the invention;

20 Figure 8 is a block diagram of a forward rate detector, which performs continuous pulse-width auto-correlation, in accordance with an embodiment of the invention;

Figures 9a, 9b, 9c, and 9d illustrate the timing diagrams of an input signal, output of a time interval generator, and output of an edge transition 25 comparator, in accordance with an embodiment of the invention;

Figure 10 is a circuit diagram of a minimum interval correlator, in accordance with an embodiment of the invention;

Figure 11 illustrates an emitter coupled logic (ECL) implementation of a unipolar minimum interval correlator, in accordance with an embodiment of the 30 invention;

Figures 12a, 12b, 12c, and 12d illustrate an analog implementation of a feedback circuit and associated signals in a forward rate detector, in accordance with an embodiment of the invention;

Figures 13a, 13b, 13c, 13d, and 13e illustrate a digital implementation of a feedback circuit and associated signals in a forward rate detector, in accordance with an embodiment of the invention; and

Figures 14a and 14b are block diagrams of implementations of a rate selector, in accordance with two embodiments of the invention.

BEST MODE FOR CARRYING OUT THE INVENTION

Reference will now be made in detail to the preferred embodiments of the invention, examples of which are illustrated in the accompanying drawings. Wherever possible, the same reference numbers will be used throughout the drawings to refer to the same or like parts.

VARIABLE BIT RATE CLOCK RECOVERY

Figure 3 is a block diagram of a variable bit rate clock recovery circuit 300, in accordance with an embodiment of the invention. Clock recovery circuit 300 comprises forward rate detector 301, rate selector 310, transition detector 320, and narrow band filter 330. Clock recovery circuit 300 includes a programmable clock extraction path and a rate selection path. The clock extraction path includes transition detector 320 and narrow band filter 330. The rate selection path includes forward rate detector 301 and rate selector 310.

Transition detector 320 and forward rate detector 301 receive a variable bit rate input data signal 155. From input signal 155, transition detector 320 generates a pulse in response to each transition in input signal 155. Likewise, forward rate detector 301 estimates the minimum time interval between transitions in input signal 155, and generates a rate estimate signal RE . Rate selector 310 then converts the rate estimate signal RE into control signals RS_1 and RS_2 , which set the width τ_{ED} of the pulses generated by transition detector 320 and the center frequency f_c of narrow band filter 330, respectively. Rate selector 310 may set τ_{ED} and f_c to, for example, $1/(2 f_{bit})$

and f_{bit} , respectively. When rate selector 310 sets the appropriate τ_{ED} and f_c , narrow band filter 330 extracts clock signal 160 from the stream of pulses.

Rate estimate signal RE may be represented as follows:

$$RE = f_{\text{bit}} \cdot K_{\text{frd}}(f_{\text{bit}}), \quad (1)$$

- 5 where f_{bit} is the bit rate frequency of input signal 155 and K_{frd} is either a constant or a slowly varying function of f_{bit} . The pulse width τ_{ED} from the transition detector 320 may be represented as follows:

$$\frac{1}{\tau_{\text{ED}}} = K_{\text{ED}}(RS_1), \quad (2)$$

where K_{ED} is a monotonic function of control signal RS_1 . The center frequency f_c of the narrow band filter 330 may be represented as follows:

$$10 \quad f_c = K_{\text{fc}}(RS_2), \quad (3)$$

where K_{fc} is a monotonic function of control signal RS_2 . In one embodiment, rate selector 310 may perform a one-to-one mapping of rate estimate signal RE to predetermined values of τ_{ED} and f_c as follows:

$$RS_1 = G_1(RE), \quad (4)$$

- 15 where G_1 is a monotonic function of rate estimate signal RE and satisfies the relation:

$$K_{\text{fc}}^{-1} f_{\text{bit}} = G_1(f_{\text{bit}} \cdot K_{\text{frd}}(f_{\text{bit}})), \text{ and} \quad (5)$$

$$RS_2 = G_2(RE), \quad (6)$$

where G_2 is a monotonic function of rate estimate signal RE and satisfies the following relation:

$$K_{ED}^{-1}(2f_{bit}) = G_2(f_{bit} \cdot K_{frd}(f_{bit})) \quad (7)$$

In one embodiment, K_{ED} and K_{frd} may have an approximately linear dependence on rate estimate signal RE , whereas K_{frd} may be nearly constant. In this embodiment, the solutions to equations (5) and (7) may be represented as follows:

$$5 \quad G_1(RE) = g_{11} + g_{12} RE + \varepsilon_1(RE), \quad (8)$$

$$G_2(RE) = g_{21} + g_{22} RE + \varepsilon_2(RE), \quad (9)$$

where g_{11} , g_{12} , g_{21} , and g_{22} are parameters, which may depend on temperature or the interval of rate estimate signal RE . Similarly, the functions $\varepsilon_1(RE)$ and $\varepsilon_2(RE)$ may be slowly varying functions of rate estimate signal RE and temperature. The
 10 parameters g_{11} , g_{12} , g_{21} , g_{22} , ε_1 , and ε_2 may be selected to satisfy, for example, equations (5) and (7). Alternatively, ε_1 and ε_2 may be set to zero.

Figure 4 is a block diagram of variable bit rate clock recovery circuit 400, which includes a calibration means, in accordance with an embodiment of the invention. Clock recovery circuit 400 comprises forward rate detector 301, rate
 15 selector 410, transition detector 320, and narrow band filter 330, selector 420, programmable calibration source 430, and response monitor 450. Calibration source 430 generates, for example, a "1010" signal pattern with predetermined bit rates f_{ref} , for example, $(1/m) \times 2488$ MHz, where m is a programmable integer between 1 and 32, inclusive. Response monitor 450 generates a first control signal at output 454,
 20 which controls the particular value of frequency f_{ref} from calibration source 430.

Selector 420, which is controlled by calibration enable line 421, receives input signal 155 and calibration source 430 at input ports 422 and 424, respectively. Rate selector 410 accepts rate estimate RE from forward rate detector 301 and outputs control signal RS_1 for controlling transition detector 320 and control signal RS_2 for
 25 controlling narrow band filter 330. Calibrate enable line 421 activates the calibrate mode, at which time selector 420 connects calibration source 430 to forward rate detector 301, while outputs 416 and 418 of rate selector 410 are locked at their current values. This inhibits incidental changes in the clock extraction path, which includes

transition detector 320 and narrow band filter 330.

Response monitor 450 receives at input 452 a rate estimate signal RE from output 303 of forward rate detector 301. In auto-calibrate mode, response monitor 450 compares rate estimate signal RE with each predetermined bit rate f_{ref} . Response monitor 450 generates, at output 456, a second control signal RM , which corresponds to the difference between rate estimate signal RE and a predetermined bit rate f_{ref} . Rate selector 410 receives control signal RM at parameter update input 412, and based on control signal RM , adjusts, for example, its rate selection algorithm or entries in a look-up table for setting control signals RS_1 and RS_2 . For example, rate selector 410 may use parameters g_{11} , g_{12} , g_{21} , g_{22} and/or functions ϵ_1 and ϵ_2 to adjust mappings of G_1 and G_2 in equations (8) and (9).

DISCRETE FORWARD RATE DETECTOR

The time interval between transitions in input signal 155 may be represented as $\Delta t = n \tau_{bit}$ where n is an integer greater than or equal to 1 and τ_{bit} is the bit period of input signal 155. In other words, τ_{bit} is equal to the multiplicative inverse of bit rate frequency f_{bit} of input signal 155. Forward rate detector 301 may estimate the bit rate in input signal 155 from a plurality of consecutive transitions in input signal 155, which would represent a set $\{n\}$ of values for run length n . From this set of transitions, forward rate detector 301 may determine the minimum detected interval between transitions τ_{min} , which may be represented as follows:

$$\tau_{min} = \min_{\{n\}} \Delta t.$$

Furthermore, τ_{min} may represent an unbiased estimate of the bit rate τ_{bit} as follows:

$$\lim_{P(n \neq 1) \rightarrow 0} \tau_{min} = \tau_{bit}$$

Digital signals such as input signal 155 may have random bit patterns or may

have prescribed bit patterns constrained by block coding. For a random sequence of bits, the discrete probability density for run length n is $P(n) = 2^{-n}$. The run length distribution for signals, which are encoded using block coding, may also be approximately 2^{-n} for small values of n , for example $n < 5$. This indicates that single
 5 bit intervals with $n = 1$ occur quite often with these types of digital signals, for example about 50% of the time. Based on the high incidence of single bit intervals in input signal 155, forward rate detector 301 may rapidly and reliably estimate f_{bit} from measurements of τ_{min} . In addition, the preamble of a packet represented by input
 10 signal 155 may include a "1010" pattern, allowing nearly instantaneous detection of the rate of input signal 155.

Figure 5 shows a circuit diagram of forward rate detector 301, which performs discrete interval pulse-width auto-correlation, in accordance with an embodiment of the invention. As shown, forward rate detector 301 comprises N gated delay segments S_1 through S_N , rising-edge-triggered D-type flip-flops 530₁ through 530 _{N} , R-S latches
 15 550₁ through 550 _{N} , buffers 560 and 570, counter 540, and an N -line priority encoder 590, where N is an integer greater than one.

Delay segments S_1 - S_N connect to each other in serial fashion, where each delay segment S_1 - S_N successively delays by time τ_i the falling edge initiated by input signal 155, where $1 \leq i \leq N$. Depending upon the embodiment, the particular values of τ_i may
 20 differ between delay segments S_1 - S_N . As shown in Figure 5, delay segments S_1 - S_3 include resettable falling edge triggered delay elements 510₁-510₃ and OR/NOR gates 520₁-520₃, respectively. Outputs of each edge triggered delay elements 510₁-510₃ connect to a respective first input 524₁-524₃ of OR/NOR gates 520₁-520₃. The last delay segment S_N , however, includes delay element 514 _{N} and an inverter 580 instead
 25 of an OR/NOR gate.

Buffer 560, which receives input signal 155, drives delay segment S_1 . Delay segment S_1 includes delay element 510₁, whose output 514₁ is sensed by a first input to OR/NOR gate 520₁, which includes complementary output 526₁ and output 528₁. Output 528₁ of OR/NOR gate 520₁ drives the next delay segment S_2 . Accordingly, the
 30 falling edge transition of input signal 155 passes consecutively through each of delay segments S_1 - S_N . For example, delay element 510₁ delays output 528₁ of delay

segment S_1 by time τ_1 , and delay elements 510₁ and 510₂ delay output 528₂ of delay segment S_2 by time $\tau_1 + \tau_2$. Hence, the total delay through k delay segments may be represented as $\sum_{i=1}^k \tau_i$.

As the input transition propagates through delay segments S_1 - S_N , consecutive
 5 outputs 528₁-528₃ may transition from a high state to a low state, while the corresponding complementary outputs 526₁-526₃ and 584 may transition from a low state to a high state. Each falling edge transition in input signal 155 initiates a series of pulses, which are then compared to the arrival of a subsequent rising transition in input signal 155. D-type flip-flops 530₁-530_N perform the comparison by latching the
 10 state of delayed outputs 526₁-526_N and 584 upon the subsequent rising transition in input signal 155.

R-S latches 550₁-550_N receive and store the state of D-type flip-flop outputs 536₁-536_N via "SET" inputs 552₁-552_N, respectively. Outputs 556₁-556_N of R-S latches 550₁-550_N connect to inputs 595₁-595_N of N-line priority encoder 590, which
 15 generates at output 598 the binary equivalent of the number of active outputs 536₁-536_N.

Clock input 542 of counter 540 connects to input signal 155. Counter 540 generates at output 544 a pulse, which resets R-S latches 550₁-550_N after a preset number of transitions, for example 32, in input signal 155.

20 High speed operation is achieved by partitioning the net time delays into small intervals τ_1 - τ_N , and simultaneously resetting each delay element 510₂-510_N via common control line 574 of buffer 570. Buffer 570 delays the simultaneous reset signal, such that the minimum hold-time requirement of D-type flip-flops 530₁-530_N is satisfied.

25 Operation of forward rate detector 301 may be initiated on the rising edge transitions in input signal 155 as well as the falling edge transitions in input signal 155. Forward rate detector 301 may, for example, include a duplicate circuit, which is driven by an inverted replica of input signal 155, for sensing the length of each pulse in input signal 155 following a rising transition in input signal 155.

30 Figures 6a-e illustrate timing diagrams of input signal 155 as it propagates through delay segments S_1 - S_N , in accordance with an embodiment of the invention.

Figures 6a-c show a falling edge transition in input signal 155 as it propagates through delay segments S_1 - S_N . At the end of a pulse in input signal 155, the delayed edge may pass through a portion or all of delay segments S_1 - S_N . Because a pulse with the shortest duration in input signal 155 would pass through the fewest number of delay segments S_1 - S_N , output 528_k of the k^{th} delay segment S_k is at a high state when the sum of delay times τ_i satisfies the constraint $n\tau_{\text{bit}} < \sum_{i=1}^k \tau_i$, where τ_{bit} equals the multiplicative inverse of the bit rate frequency f_{bit} of input signal 155.

As shown in Figures 6b-e, outputs 528₁ and 528₂ of delay segments S_1 and S_2 , respectively, are activated within the $n\tau_{\text{bit}}$ period of input signal 155, whereas outputs 528₃ and 584 of delay segments S_3 and S_N are not activated within that time period. The waveforms indicated by the dashed lines in Figures 6d-e show the state of outputs 528₃ and 584, respectively, for an input pulse of longer duration. After a small number of transitions input signal 155, depending on the run length distribution $P(n)$, a pulse with $n = 1$ appears in the input signal 155, after which time the state of outputs 556₁-556_N represents an upper and lower bound on τ_{bit} . The state of outputs 556₁-556_N tracks increasing and decreasing values of τ_{bit} when the pulses from counter 540, for example, occasionally reset R-S latches 550₁-550_N. Priority encoder 590 derives at output 598 a binary representation of τ_{bit} from the state of outputs 556₁-556_N. This binary representation of τ_{bit} is rate estimate signal RE, which is uniquely determined by τ_{bit} and the particular values of τ_1 - τ_N . The resolution of the estimate of τ_{bit} may be improved by performing multiple scans with different combinations of values for τ_1 - τ_N .

Table 1 lists several common line rates in input signal 155 and the segmental delays τ_i , which may be used to distinguish between the line rates. The first two columns list some common line rates f_{bit} and the corresponding bit interval τ_{bit} for input signal 155, respectively. The third column lists the net delays for distinguishing between consecutive rates, which is the average of τ_{bit} for two consecutive rates. Since the net delay through k delay segments may be represented as $\sum_{i=1}^k \tau_i$, the segmental delays τ_i represent the differences between the net delays listed in the third column. The segmental delays, which are listed in the fourth column and may be readily achieved, demonstrate the feasibility of discrete rate detector 301 for operating

over a wide range of line rates.

TABLE 1

	Line Rate f_{bit} (MHz)	Period τ_{bit} (nsec)	Net Delay	Segmental Delay τ_i (nsec)
5	2488.32	0.402	---	---
	1250	0.800	0.601	---
	1065	0.939	0.870	0.269
	800	1.250	1.095	0.225
	622.08	1.608	1.429	0.334
10	531	1.833	1.746	0.317
	265	3.744	2.829	1.083
	194	5.144	4.459	1.630
	155.52	6.430	5.787	1.328
	132.5	7.547	6.989	1.202
15	125	8.000	7.774	0.785
	51.84	19.29	13.645	5.871

DELAY SEGMENT

Figure 7 is a circuit diagram of delay segment S_2 (shown in Figure 5), in accordance with an embodiment of the invention. Although Figure 7 shows a circuit diagram of delay segment S_2 , generalization to delay segments S_1 and S_3-S_N is readily apparent. High speed performance may be optimized by merging the threshold function found in a traditional implementation of delay circuit 510₂ with OR/NOR gate 520₂ using a gated differential amplifier. Input 512₂ of delay segment S_2 drives the base of transistor Q_{702} , which serves as a voltage follower. The emitter of Q_{702} and a programmable current source I_{708} connect to capacitor C_{704} at output 514₂ through resistor R_{706} . Current from the emitter of Q_{702} rapidly charges C_{704} to a preset value while the current from I_{708} discharges C_{704} at a controlled rate. The voltage at output 514₂ is sensed by a gated differential amplifier, which includes Q_{720} and Q_{722} . The

bases of Q_{720} and Q_{722} connect to output 514₂ and to a reference voltage V_{740} , respectively. The emitters of transistors Q_{720} and Q_{722} connect via node 730 to a fixed current source I_{730} .

The base of a gating transistor Q_{724} connects to common control line 574 via
 5 second input 522₂. The collector and emitter of Q_{724} connect to output 526₂ and node 730, respectively. The amplifier has inverting and non-inverting outputs at outputs 526₂ and 528₂, respectively. Output 528₂, which connects to the collector of Q_{722} , is obtained from the voltage drop across R_{728} . Output 526₂, which connects to the collectors of Q_{720} and Q_{724} , is obtained from the voltage drop across R_{726} . The value of
 10 reference V_{740} may be altered by positive feedback via control node 742, which connects to output 526₂ to provide threshold level hysteresis. A voltage greater than that set by reference V_{740} at either output 514₂ or common control line 574 forces output 526₂ to a low state and output 528₂ to a high state. In the last delay segment S_N , the gating transistor corresponding to Q_{724} may be omitted.

15 In the initial quiescent state, input 512₂ and common control line 574 may be at a high state, and output 526₂ may be at a low state. In this state, the high signal on input 512₂ controls Q_{702} to preset the voltage across capacitor C_{704} . A high signal at common control line 574 activates Q_{724} and forces output 528₂ to drive the next delay segment S_j to a high state even before the voltage on C_{704} reaches the preset value.
 20 When input signal 155 transitions from a high state to a low state, common control line 574 goes low and turns Q_{724} off. The initial state is held by the preset voltage across C_{704} , which controls Q_{720} . Depending on the time constant of the preceding delay segment S_i and the duration of the low state, the voltage at input 512₂ may transition to a low state at some time after input signal 155 transitions from a high
 25 state to a low state. This turns Q_{702} off and allows C_{704} to be discharged by current from I_{708} . If the duration of the low state is still sufficient, the voltage at output 514₂ drops below the reference voltage set by V_{740} and causes output 526₂ to transition to a high state and the output 528₂ to transition to a low state. The low state at output 528₂ activates the delay element 510₃ in subsequent delay segment S_j .

30 The response time following detection of a threshold may be improved by a positive feedback from output 526₂ to slightly vary V_{740} . The time delay τ_2 associated

with delay segment S_2 is governed by the charge conservation at output 514₂. The value of time delay τ_2 may be determined by the difference between the preset voltage across C_{704} , V_{PRESET} , the value V_{740}^{th} of reference voltage V_{740} when control 742 is at a low state, differential amplifier offset voltage V_{OS}^{th} at the switching threshold, the value of capacitor C_{704} , stray capacitance C_S associated with output 514₂, current I_{708} , base current I_b of Q_{720} , and the charge $Q_2(I_{708})$ stored in the emitter of Q_{702} . This relationship may be represented as follows:

$$(I_{708} + I_b) \tau_2 = (V_{\text{PRESET}} - V_{740}^{th} - V_{OS}^{th}) (C_{704} + C_S) - Q_e(I_{708}) \quad (10)$$

The resolution of the discrete rate detector depends on the selection of time delays τ_1 - τ_N , which may be programmed, for example, through the value of current I_{708} for each corresponding delay segment S_1 - S_N .

CONTINUOUS FORWARD RATE DETECTOR

Figure 8 is a block diagram of forward rate detector 301, which performs continuous pulse-width auto-correlation, in accordance with an embodiment of the invention. As shown, forward rate detector 301 comprises minimum interval correlator 840, feedback circuit 830, and output 303. Output 303, whose value is rate estimate signal RE , receives output 836 of feedback circuit 830.

Minimum interval correlator 840 includes a tunable (or programmable) edge-triggered time interval generator 810 and an edge transition comparator 820.

Time interval generator 810 receives at inputs 812 and 816 input signal 155 and output 836 of feedback circuit 830, respectively. In response to a transition in input signal 155, time interval generator 810 generates at output 814 a corresponding transition delayed by time τ , which is controlled by rate estimate signal RE .

Alternatively, in response to a transition in input signal 155, time interval generator 810 may generate at output 814 a corresponding set of transitions delayed by a set of times τ , which may have different values and are controlled by rate estimate signal RE .

The value of τ is related to rate estimate signal RE through a known relationship $\tau = \tau(RE)$. Time interval generator 810 may, for example, be implemented such that the product of rate estimate signal RE and $\tau(RE)$ is nearly constant to a first order.

- 5 Edge transition comparator 820 receives at inputs 822 and 824 input signal 155 and output 814 of interval generator 810, respectively. Output 826 of edge transition comparator 820 generates a signal, which is monotonically related to the difference between τ and τ_{bit} . Edge transition comparator 820 generates at output 826 a positive pulse when a subsequent transition in input signal 155 occurs before τ time
- 10 has elapsed. Output 826 is received by input 832 of feedback circuit 830, which outputs rate estimate signal RE at output 836 to adjust τ , such that a prescribed rate of pulses are generated at output 826. The time constants within the feedback circuit 830 may be controlled via input 834 by the rate of transitions in input signal 155. The prescribed rate of pulses from output 826 may have a constant duty cycle.
- 15 Alternatively, the prescribed rate may depend on the rate of transitions in input signal 155.

- In one embodiment, the relationship between the rate estimate signal RE and $1/\tau$ may, for example, be linear. Output 836 of feedback circuit 830 controls τ via negative feedback to input 816 of interval generator 810. The negative feedback sets
- 20 rate estimate signal RE such that $\tau(RE)$ equals τ_{bit} . Hence, bit rate frequency f_{bit} of input signal 155 may be determined based on rate estimate signal RE since bit rate frequency f_{bit} is nearly proportional to rate estimate signal RE . In addition, to reduce noise in rate estimate signal RE , forward rate detector 301 may also include, for example, an analog or digital means in feedback circuit 830 or rate selector 310 for
- 25 filtering noise in rate estimate signal RE .

- In accordance with another embodiment of the invention, forward rate detector 301 may estimate τ_{bit} using a pulse width auto-correlation method. Figures 9a-d illustrate the timing diagrams of input signal 155, output 814 of time interval generator 810, output 826 of edge transition comparator 820, in accordance with this
- 30 embodiment. Figure 9e illustrates the distribution of values at output 826 for different values of τ and an arbitrary fixed value of τ_{bit} .

Figure 9a shows input signal 155 with a transition occurring at time $\Delta t = 0$ and a subsequent transition at $\Delta t = \tau_{bit}$. The transition at $\Delta t = 0$ triggers time interval generator 810, whose output pulse is delayed by τ . Three values of τ are indicated by fast F, slow S, and aligned A.

5 Figures 9b and 9c illustrate state of output 814 of time interval generator 810 for two different embodiments. Figure 9d illustrates state of output 826 of edge transition comparator 820 for the two embodiments.

10 In the first embodiment, time interval generator 810 includes one or more resettable edge triggered delay elements, for example delay elements 510_1 - 510_N shown in Figure 5. As shown in Figure 9b, in this embodiment, time interval generator 810 generates at output 814 a pulse, which starts after τ time has elapsed and is reset by the next transition in input signal 155.

15 In the second embodiment, time interval generator includes an edge triggered one-shot, which is described below in detail. As shown in Figure 9c, in this embodiment, time interval generator 810 generates at output 814 a single pulse starting at time $\Delta t = 0$, which has duration τ .

20 In both embodiments, if time τ is set shorter than τ_{bit} , as indicated by F, the next transition in input signal 155 occurs at $\Delta t = \tau_{bit}$ after τ time has elapsed, and output 826 is set to a low state. If time τ is set to a longer duration than τ_{bit} , as indicated by S, a subsequent transition in input signal 155 at $\Delta t = \tau_{bit}$ occurs before τ time has elapsed, and output 826 is set to a high state.

25 There is perfect alignment between the pulse generated at output 814 of time interval generator 810 and input signal 155 when $\tau = \tau_{bit}$, as indicated by A, and a transition in input signal 155 that occurs at τ_{bit} overlaps with τ . Output 826 may be in a high or a low state when there is perfect alignment. Transitions in input signal 155 that occur long after time τ may be ignored since they may represent a run of bits with $\Delta t = n\tau_{bit}$ and $n \geq 2$.

30 Figure 9e illustrates the distribution of values assumed by output 826 for different values of τ and a given value of τ_{bit} . This distribution represents the transfer function of minimum interval correlator 840, which includes time interval generator 810

and edge transition detector 820. Based on statistical interpretation of relative frequency, the graph in Figure 9e also illustrates the mean value at output 826 that would be observed after many instances of transitions of input signal 155. The graph in Figure 9e has a steep slope at $\tau = \tau_{bit}$, which distinguishes between conditions F and S. The shape of the transition between F and S may be determined by, for example, the distribution $P(n)$ of run lengths n .

Edge transition comparator 820 compares the interval between the trailing edge of input signal 155 and output 814 of time interval generator 810, and via feedback circuit 830, adjusts τ to the value $\tau_{bit} = 1/f_{bit}$. After the settling time of feedback circuit 830, the adjusted τ represents an estimate of τ_{bit} . Hence, in this embodiment, harmonic locking does not occur because the estimated τ_{bit} is uniquely related to f_{bit} .

MINIMUM INTERVAL CORRELATOR

Figure 10 shows a circuit diagram of minimum interval correlator 840 (shown in Figure 8), in accordance with an embodiment of the invention. In this embodiment, the response to falling edge transitions and rising edge transitions in input signal 155 are effectuated through two separate paths. Minimum interval correlator 840 is partitioned into a falling edge triggered minimum interval correlator 1090 and a rising edge triggered minimum interval correlator 1092. Minimum interval correlators 1090 and 1092 each perform the functions of time interval generator 810 and transition comparator 820 shown in Figure 8.

Minimum interval correlators 1090 and 1092 include outputs 826₁ and 826₂, which collectively form output 826 of minimum interval correlator 840. Although minimum interval correlators 1090 and 1092 include separate outputs 826₁ and 826₂, their respective inputs 302₁ and 302₂ connect to input signal 155.

Minimum interval correlator 1090 includes non-inverting buffer 1010, capacitor C_{1018} , programmable current source I_{1016} , comparator 1030, voltage reference V_{1038} , non-inverting buffer 1050, and positive edge triggered D-type flip-flop 1070. Minimum interval correlator 1092 includes inverting buffer 1020, capacitor C_{1028} , programmable current source I_{1026} , comparator 1040, voltage reference V_{1048} , inverting

buffer 1060, and positive-edge triggered D-type flip-flop 1080.

Input 302, which includes nodes 302₁ and 302₂, receives input signal 155.

Node 302₁ connects to non-inverting inputs 1012 and 1052 of buffers 1010 and 1050, respectively, in minimum interval correlator 1090. Output 1014 of buffer 1010

5 connects via node 1003 to capacitor C_{1018} , programmable current source I_{1016} , and input 1032 of comparator 1030. Reference input 1034 of comparator 1030 connects to voltage reference V_{1038} . Output 1036 of comparator 1030 connects to D input 1072 of D-type flip-flop 1070, whose clock input 1074 is driven by output 1054 of buffer 1050.

10 Node 302₂ connects to inverting inputs 1022 and 1062 of buffers 1020 and 1060, respectively, in minimum interval correlator 1092. Output 1024 of buffer 1020 connects via node 1004 to capacitor C_{1028} , programmable current source I_{1026} , and input 1042 of comparator 1040. Reference input 1044 of comparator 1040 connects to voltage reference V_{1048} . Output 1046 of comparator 1040 connects to D input 1082
15 of D-type flip-flop 1080, whose clock input 1084 is driven by output 1064 of buffer 1060. Outputs 1076 and 1086 of D-type flip-flops 1070 and 1080 form output 826₁ and 826₂, respectively. Programming inputs 1017 and 1027 control via input 816 current sources I_{1016} and I_{1026} , respectively.

The operations of minimum interval correlators 1090 and 1092 are similar
20 except that all processing is active on opposite transitions in input signal 155. The operation of minimum interval correlator 1090 is as follows: Output port 1014 assumes a low impedance state with a preset output level of V_{PRESET} when input 1012 is at a high state, and assumes a high impedance state when input 1012 is at a low state. For example, V_{PRESET} may be more positive than reference voltage V_{1038} . A high
25 state in input signal 155 causes buffer 1010 to charge capacitor C_{1018} to V_{PRESET} .

When the input signal 155 undergoes a transition from a high to a low state, current flow from output 1014 of buffer 1010 is inhibited, and capacitor C_{1018} is freely discharged by programmable current from I_{1016} . If the duration of the low state in input signal 155 is sufficiently long, the voltage at node 1003 drops below the level
30 set by V_{1038} , and output 1036 of comparator 1030 transitions to a low state. D-type flip-flop 1070 captures via the rising edge transition at the output 1054 of buffer 1050

the state of output 1036 at time $\Delta t = n\tau_{bit}$, when input signal 155 undergoes a subsequent low to high transition.

The time required for capacitor C_{1018} to discharge from V_{PRESET} to V_{1048} is $\tau(I_{1016})$. Output 826₁ may be at a low state if $\Delta t > \tau(I_{1016})$, and may be at a high state if $\Delta t < \tau(I_{1016})$. Output 826₁ may always be low when $\tau < \tau_{bit}$. If $\tau > \tau_{bit}$, there may be small values of run-length n for which output 826₁ may be at a high state. Output 826₁ may, however, be at a low state for large n .

Figure 9e shows the distribution of values of output 826₁ averaged over typical values of run-length n . The time constant $\tau(I_{1016})$ may be represented as follows:

$$(I_{1016} + I_b) \tau = (V_{PRESET} - V_{1038} - V_{OS}^{th})(C_{1018} + C_s) - Q_{O_{1014}}(I_{1016}), \quad (11)$$

where V_{OS}^{th} is the offset voltage at a threshold of comparator 1030, C_s is the stray capacitance associated with node 1003, I_b is the input bias current of comparator 1030, and $Q_{O_{1014}}(I_{1016})$ is the charge removed by output 1014 when buffer 1010 is turned off.

Similar operation occurs in minimum interval correlator 1092 for rising edge transitions in input signal 155. Outputs 826₁ and 826₂ indicate whether τ is greater or less than τ_{bit} . In accordance with one embodiment, outputs 826₁ and 826₂ may be used to control τ through I_{1016} and I_{1026} using negative feedback. Rate estimate signal RE may be determined from the value of control signal 816 necessary to achieve $\tau = \tau_{bit}$.

Minimum interval correlator 1090 of Figure 10 constitutes one embodiment of a unipolar minimum interval correlator, which is active on the falling edge of input signal 155. Unipolar minimum interval correlator 1090 may include a programmable gated delay, which includes buffer 1010, capacitor C_{1018} , current source I_{1017} , comparator 1013, and D-type flip-flop 1070. D-type flip-flop 1070 may include two latches (not shown), which are controlled by node 302₁ via clock input 1074. In one embodiment, one of the latches in 1070 may be shared with the programmable gated delay to create a falling edge triggered non-retriggerable one-shot. By performing several latching and comparison operations in parallel, higher operating speeds may be achieved in this embodiment.

Figure 11 illustrates an emitter coupled logic (ECL) implementation of unipolar minimum interval correlator 1090, in accordance with an embodiment of the invention. Unipolar minimum interval correlator 1090 comprises edge transition comparator 1104 and falling-edge triggered non-retriggerable one-shot 1102. Edge transition comparator 1104 includes invertors 1110 and 1156, non-inverting buffer 1114, NOR gates 1130 and 1150, and node 1138. Node 1138 performs a wired-OR operation.

Falling edge triggered non-retriggerable one-shot 1102 includes comparator 1160, timing capacitor C_{1164} , programmable current sources I_{1016} and I_{1179} , diodes D_{1175} and D_{1176} , reference voltages V_{REF} and V_{CLAMP} , operational amplifier 1170, NOR gates 1120 and 1140, inverter 1146, buffer 1124, and nodes 1128 and 1166. Nodes 1128 and 1166 each perform a wired-OR operation.

Input 1111 of inverter 1110 and node 1144 of one-shot 1102 receive input signal 155. The falling edge of input signal 155 triggers one-shot 1102 to generate an output pulse of duration $\tau(I_{1016})$ at output 1127 of buffer 1124. Duration τ is directly controlled by controlled current source I_{1016} or indirectly by input 816 via control input 1017 to I_{1016} . Output 1127 of buffer 1124 is at a high state in the reset state, and transitions to a low state during time τ . One-shot 1102 cannot be retriggered by a subsequent change in the state of input signal 155 until after both time τ has elapsed and input signal 155 returns to a high state.

Input node 1144 connects to input 1142 of NOR gate 1143 and input 1121 of NOR gate 1120. The open emitter output 1143 of NOR gate 1140 connects via node 1128 to input 1122 of NOR gate 1120, input 1147 of inverter 1146, and non-inverting open emitter output 1126 of buffer 1124. Output 1148 of inverter 1146 connects to input 1141 of NOR gate 1140 to create an R-S latch.

A high state at node 1144 sets node 1128 to a low state when output 1126 is low, while a high state at output 1126 overrides input 1144 to set node 1128 to a high state. Output 1126 of buffer 1124 may be at a high state during time τ , and may inhibit NOR gate 1120 from responding to changes in input signal 155. Open emitter output 1123 of NOR gate 1120 connects via node 1166 to the open emitter output of comparator 1160, capacitor C_{1164} , and input 1125 of buffer 1124.

Capacitor C_{1164} connects to non-inverting input 1161 of comparator 1160, the cathode of diode D_{1175} , and programmable current source I_{1016} . Output 1173 of opamp 1170 drives the anode of diode D_{1175} . Opamp 1170 may be configured, for example, as a voltage follower with diode D_{1176} in the feedback loop between output 1173 and
 5 inverting input 1172.

Diode D_{1176} may be biased at the same current density as D_{1175} by programmable current source I_{1178} . Node 1179 controls current I_{1178} and node 1017 controls current I_{1017} . Both control node 1017 and control node 1179 connect to input 816. Inverting input 1162 of comparator 1160 connects to voltage source V_{REF} . Non-
 10 inverting input 1174 of opamp 1170 connects to voltage source V_{CLAMP} . Inverting output 1127 of buffer 1124, which is controlled by node 1166, forms the output of one-shot 1102, and connects to input 1134 of gate 1130 in edge transition comparator 1104.

In the quiescent state, the input signal 155 and input node 1144 may be in the
 15 high state, nodes 1128 and 1166 may be in the low state, and the voltage at node 1165 may be held at V_{CLAMP} . When the input node 1144 transitions to a low state due to a negative transition in input signal 155, output 1123 of NOR gate 1120 transitions to a high state. The coupling through capacitor C_{1164} forces node 1165 to a high state. A positive feedback through comparator 1160 and C_{1165} holds node 1166 at a high state
 20 until the voltage at node 1165 decreases to V_{REF} .

When node 1166 transitions to a high state after input signal 155 transitions to a low state, buffer 1124 drives node 1128 to a high state, activating a first latch, which includes inverter 1146 and NOR gate 1140. Output 1123 of NOR gate 1120 may be subsequently inhibited when node 1128 transitions to a high state. The first latch
 25 continues to hold node 1128 at a high state, and inhibits output 1123, which may only be reset after node 1166 transitions to a low state at time τ . The first latch is reset to a low state through NOR gate 1140 when both node 1166 returns to a low state and input signal 155 transitions to a high state, restoring one-shot 1102 to the quiescent state. The voltage on capacitor C_{1112} has sufficient time to reach steady state since
 30 one-shot 1102 triggers only on the falling edge transitions.

The pulse duration τ may be related to the capacitor discharge current I_c by conservation of charge at node 1185. This relationship may be represented as follows:

$$(I_{1016} + I_b) \tau = [\Delta V_{1166}(I_{1016}, \tau) + V_{CLAMP} - V_{REF} - V_{OS}^{th}] C_{1164} + (V_{CLAMP} - V_{REF} - V_{OS}^{th}) C_s + \Delta Q_B^{th} - Q_d(I_{1016}), \quad (12)$$

where C_s is the stray capacitance associated with node 1165 and Q_d is the charge stored in diode D_{1175} . ΔV_{1166} represents the rising voltage waveform at 1166 after the falling transition in input signal 155 triggers one-shot 1102.

In accordance with an embodiment of the invention, the parameters associated with comparator 1160 are as follows: I_b is the input bias current, V_{OS}^{th} is the input offset at threshold and ΔQ_B^{th} is the input charge required to switch comparator 1160. This expression shows that I_{1016} may be nearly proportional to f_{bit} when $\tau = \tau_{bit}$.

Non-inverting buffer 1114 receives output 1112 of the inverter 1110, which matches the turn-on delay of one-shot 1102. NOR gate 1130 compares outputs 1116 and 1127 of buffer 1114 and one-shot 1102, respectively. Open emitter output 1136 of NOR gate 1130 may be a current pulse, which may, for example, be a function of the time interval between the subsequent rising edge in input signal 155 and the rising edge of output 1127 of one-shot 1102 after delay time τ .

Node 1138 transitions to a high state when input signal 155 transitions to a high state while output 1127 of one-shot 1102 is at a low state. NOR gate 1150 and inverter 1156 connect to each other to form a second latch, which is activated by a high state at node 1138. If node 1138 is raised sufficiently high, then feedback loop around gate 1150 and inverter 1156 holds node 1138 at a high state until input signal 155 transitions to a low state and output 1116 of gate 1114, which connects to NOR gate 1150, transitions to a high state.

The relationship between the current pulse from output 1136 of gate 1130 and $\tau - \tau_{bit}$ may be represented as follows: Charge Q_{O-1136} in the current pulse from gate 1130 is proportional to $\tau - \tau_{bit} - \xi \tau_{gate}$, where $\xi \tau_{gate}$ is a fixed fraction of the nominal gate response-time. The probability that node 1138 may be set to a high state depends on Q_{O-1136} through a function $F_{gate}(Q_{O-1136})$, whose characteristics are shown in Figure

9e. The average time that node 1138 remains at a high state, once activated, may approximately be $\bar{n}_1 \tau_{\min} + \tau_{\min} - \xi \tau_{\text{gate}}$. The signal at node 1138 may be used to control τ through I_{1016} by using a negative feedback.

ANALOG FEEDBACK CIRCUIT

5 Figure 12a illustrates an analog implementation of feedback circuit 830, in accordance with an embodiment of the invention. In this embodiment, feedback circuit 830 comprises a summation circuit 1210, a low pass filter 1220, a differential amplifier 1230, and a reference voltage V_{1250} . Low pass filter 1220 includes an output 1224, and differential amplifier 1230 includes an output 1236. Figures 12b-d
10 illustrate a change in bit rate of input signal 155, change in low-pass filter output 1224, and change in amplifier output 1236.

Feedback circuit 830 receives at nodes 832₁ and 832₂, which collectively form input 832, outputs 826₁ and 826₂, respectively, of minimum interval correlator 840. Node 832₁ connects to input 1212 of summation circuit 1210, and Node 832₂ connect
15 to summation circuit input 1214. Low pass filter 1220 filters output 1216 of summation circuit 1210, which is applied to non-inverting input 1232 of differential amplifier 1230. Reference voltage V_{1250} connects to inverting input 1234 of differential amplifier 1230. Output 1236 of amplifier 1230 forms feedback circuit output 836.

20 Inputs 1212 and 1214 of summation 1210 receive nodes 832₁ and 832₂ pulses from outputs 826₁ and 826₂ of unipolar minimum interval correlators 1090 and 1092, respectively, when $\tau_{\text{bit}} < \tau$. Low pass filter 1220 removes high frequency variations from the combined signal at output 1216 of summation 1210. Differential amplifier 1230 amplifies the difference between the filtered signal at output 1224 of filter 1220
25 and reference voltage V_{1250} . The amplified difference between V_{1224} and V_{1250} appears at output 1236, and may be used to control the period τ of time interval generator 810. Differential amplifier 1230 may incorporate phase margin compensation, which may be necessary to maintain overall feedback loop dynamic stability.

Figure 12b illustrates an increase in bit rate f_{bit} of input signal 155 from f_{bit1} to
30 $f_{\text{bit2}} > f_{\text{bit1}}$ occurring at time $t = 0$. The change in the bit rate is detected by minimum

interval correlator 840, which generates a change in the rate of pulses that appear at inputs 1212 and 1214 of summation 1210 and consequently at output 1216. The level at output 1224 for $t < 0$ may be maintained by a constant rate of pulses from minimum interval correlator 840. The horizontal dashed line in figure 12c illustrates that prior to the change at $t = 0$, a negative feedback holds output 1224 at nearly V_{1250} . A change in the rate of pulses at $t > 0$ at output 1216 generates a transient change in output 1224. The amplified signal appearing at output 1236 changes until period τ of time interval generator 810 settles to a new value of $1/f_{bit}$.

Minimum interval correlator 840 may generate an output pulse when isolated "ones" and "zeroes" occur in input signal 155. Input 1212, which is connected to falling edge transition comparator output 826₁ via node 832₁, may be active following high-to-low transitions in input signal 155. The probability that output 826₁ transitions to a high state following an isolated "zero" may be represented by $F(\tau - \tau_{bit})$, as shown in Figure 9e.

Let $P_0(n)$ and $P_1(n)$ denote the distribution of run lengths n for consecutive "zeroes" and "ones," respectively, in input signal 155. The probability that an isolated "zero" occurs following a high-to-low transition is therefore $P_0(n = 1)$. The occurrence rate of isolated "zeroes" may be represented as follows:

$$\text{rate of isolated 0} = \frac{P_0(1)}{(\bar{n}_0 + \bar{n}_1) \tau_{bit}},$$

where $\bar{n}_0$ and $\bar{n}_1$ represent the average length for a run of "zeroes" and "ones," respectively. The average time interval that output 826₁ remains at a high state prior to a subsequent high-to-low transition can be represented as follows:

$$\text{persistence time} \approx (\bar{n}_1 + \zeta \bar{n}_0) \tau_{bit},$$

The holding property of the edge transition detector 820 may be represented by parameter ζ . In an embodiment where minimum interval correlator 1090 includes D-

type flip-flop 1070, ζ may equal 1. Alternatively, in an embodiment where minimum interval correlator 1090 includes falling edge triggered non-retriggerable one-shot 1102, ζ may equal 0. If the durations of consecutive runs are independent, the average value of input 1212 may be represented as follows:

$$\bar{V}_{1212} \propto (\text{rate of isolated 0}) \times F(\tau - \tau_{bit}) \times (\text{persistence time}) \quad (13)$$

An analogous expression to equation 13 applies to input 1214 of rising edge transition comparator output 826₂. The filtered output 1224 may be represented as follows:

$$\bar{V}_{1224} \propto \frac{(\bar{n}_0 + \zeta \bar{n}_1) P_1(1) + (\bar{n}_1 + \zeta \bar{n}_0) P_0(1)}{\bar{n}_0 + \bar{n}_1} F(\tau - \tau_{bit}). \quad (14)$$

- 10 In accordance with an embodiment, the average value $\bar{V}_{1224}$ of low-pass filter output 1224 may be used to control τ using a negative feedback. The small-signal gain has the desirable feature that it is independent of τ_{bit} .

DIGITAL FEEDBACK CIRCUIT

- Figure 13a illustrates a digital implementation of feedback circuit 830, in accordance with an embodiment of the invention. In this embodiment, feedback circuit 830 comprises R-S latches 1310 and 1320, positive D-type flip-flops 1330 and 1340, AND gates 1350 and 1360, N-stage up/down counter 1370, M-stage binary counter 1390, and digital to analog converter (DAC) 1380. Up/down counter 1370 includes up-count clock (Clk_U) input 1372 and down-count clock (Clk_D) input 1374.
- 20 Figures 13b-e illustrate changes in bit rate f_{bit} of input signal 155, signal applied to Clk_U input 1372, signal applied to Clk_D input 1374, and analog output 1384 of DAC 1380.

- Feedback circuit 830 receives at inputs 832₁ and 832₂ outputs 826₁ and 826₂, respectively, of minimum interval correlator 840. Input 834 of feedback circuit 830 receives input signal 155. Node 832₁ connects to "set" input 1312 of latch 1310, and node 832₂ connects to "set" input 1322 of latch 1320. Latch outputs 1316 and 1326

connect to inputs 1332 and 1342 of D-type flip-flops 1330 and 1340, respectively.

Clock input 1392 of counter 1390 receives input signal 155 via input 834.

Terminal count (TC) output 1396 connects to "reset" inputs 1314 and 1324 of latches 1310 and 1320, respectively. Clock inputs 1334 and 1344 of D-type flip-flops 1330 and 1340 connect to the second stage (Q_1) output 1394 of counter 1390.

AND gate 1350 receives inputs from non-inverting outputs 1336 and 1346 of D-type flip-flops 1330 and 1340, respectively, and TC output 1396 of counter 1390. AND gate 1360 receives inputs from inverting outputs 1338 and 1348 of D-type flip-flops 1330 and 1340, respectively, and TC output 1396 of counter 1390. Output 1358 of AND gate 1350 connects to Clk_U input 1372, and output 1368 of AND gate 1360 connects to Clk_D input 1374.

In one embodiment, up/down counter 1370 generates a parallel binary word, which is monotonically related to the difference between the number of pulses applied to Clk_U input 1372 and Clk_D input 1374. In another embodiment, up/down counter 1370 generates a parallel binary signal representing a successive approximation for rate estimate signal RE using a succession of step sizes, which may, for example, vary with the pattern of pulses applied to Clk_U input 1372 and Clk_D input 1374.

"Set" inputs 1312 and 1324 of latches 1310 and 1320 receive pulses from outputs 826₁ and 826₂, respectively, of unipolar minimum interval correlators 1090 and 1092 when $\tau > \tau_{bit}$ is detected by edge transition comparator 820 via nodes 832₁ and 832₂.

A pulse generated by unipolar minimum interval correlator 1090, which is active on falling edge transitions in input signal 155, sets output 1316 to a high state. Similarly, a pulse generated by unipolar minimum interval correlator 1092, which is active on rising edge transitions in input signal 155, sets output 1326 to a high state.

Counter 1390 counts the number of transitions in input signal 155 modulo 2^M , where M equals, for example, 4. Second stage (Q_1) output 1394 clocks D-type flip-flops 1330 and 1340 on every fourth low-to-high transition in input signal 155, storing the prevailing state of latches 1310 and 1320, respectively.

TC output 1396 transitions to a high state following each 2^M low-to-high transitions in input signal 155, and transitions to a low state after the next low-to-high

transition in input signal 155. The rising edge of TC output 1396 may be near the center of pulses from Q_1 output 1394. A high state on TC output 1396 enables AND gate outputs 1358 and 1368, and resets latches 1310 and 1320 to a low state.

Output 1358 transitions to a high state when TC output 1396 is at a high state if both D-type flip-flop non-inverting outputs 1336 and 1346 are at a high state, advancing the state of up/down counter 1370 forward by one count. Output 1368 transitions to a high state when TC output 1396 is at a high state if both D-type flip-flop inverting outputs 1338 and 1348 are at a high state, decreasing the state of up/down counter 1370 by one count. The state of up/down counter 1370 increases when both unipolar minimum interval correlators 1090 and 1092 detect $\tau > \tau_{bit}$, and decreases when neither unipolar minimum interval correlator 1090 and 1092 detect $\tau > \tau_{bit}$. The state of up/down counter 1370 holds when only one of unipolar minimum interval correlators 1090 and 1092 detects $\tau > \tau_{bit}$. The binary signal at up/down counter output 1376 may be used to control τ using negative feedback.

Feedback circuit 830 may generate a digital signal at output 836 using, for example, output 1376 of up/down counter 1370. Alternatively, feedback circuit 830 may generate an analog signal at output 836 using, for example, output 1384 of DAC 1380, whose input 1382 connects to counter output 1376.

Figure 13b illustrates an increase in bit rate f_{bit} of input signal 155 from f_{bit1} to $f_{bit2} > f_{bit1}$ at time $t = 0$. Prior to $t = 0$, negative feedback may hold period τ of interval generator 810 close to $1/f_{bit1}$. Minimum interval correlator 840 may detect the change in the bit rate, which results in a change in the rate of pulses that appear at both latch inputs 1312 and 1324. The presence of pulses at both latch inputs 1312 and 1324 causes both D-type flip-flop non-inverting outputs 1336 and 1346 to transition to a high state, toggling Clk_U input 1372 as shown in Figures 13c.

In Figure 13d, Clk_D input 1374 is not toggled immediately after $t = 0$ since $\tau > 1/f_{bit2}$. Figure 13e illustrates analog output 1384 of DAC 1380, which is driven by digital words generated by up/down counter 1370 with, for example, monotonic count states. In up/down counter 1370, upward counting proceeds while $\tau > 1/f_{bit2}$, and stops when $\tau = 1/f_{bit2}$.

RATE SELECTOR

Rate selector 310 tracks changes in the bit rate frequency of input signal 155 while rejecting transient errors in the rate estimate signal *RE*, which may be caused by jitter and pattern dependent variation in input signal 155. Figures 14a-b are block diagrams of implementations of rate selector 310, in accordance with two embodiments of the invention.

In the first embodiment, which is shown in Figure 14a, rate selector 310 comprises a rate translation 1402, which includes a function block 1410 and a function block 1420. Rate translation 1402 may receive as input rate estimate signal *RE*, which is generated by discrete rate detector 301 of Figure 5. The rate estimate signal *RE* may also be filtered prior to translation by 1402.

In the second embodiment, which is shown in Figure 14b, rate selector 310 comprises rate translation 1402 and a rate estimate filter. The rate estimate filter includes a rate correction block 1430, adaptive filter 1440, filter control 1450, rate change detector 1460, expected rate comparator 1470, and summation 1480. Correction block 1430 receives at input 1432 rate estimate signal *RE*, which may be generated by, for example, continuous rate detector 301 of Figure 8. Adaptive filter 1440 receives at input 1442 output 1434 of rate correction block 1430. The output of filter 1440 may be applied as an alternative input to rate translation 1402.

Rate translation block 1402 performs a direct one-to-one mapping of an estimated line rate into control signals RS_1 and RS_2 , which appear at output nodes 316 and 318, respectively. Input 1412 of function block 1410 and input 1422 of function block 1420 receive an estimate of the line rate, for example, rate estimate signal *RE* from discrete rate detector 301 or output from adaptive filter 1430. Function block 1410 generates control signal RS_1 at node 316. Function block 1410 may implement, for example, the function implicitly represented by equation (5) or the relationship represented by equation (8).

Function block 1420 generates control signal RS_2 at node 318. Function block 1420 may implement, for example, the function implicitly represented by equation (5) or the relationship represented by equation (8).

Several conventional techniques may be used to perform the one-to-one

mapping. For example, an analog computer may be used to convert the rate estimate signal RE into control signals RS_1 and RS_2 . Alternately, rate detector 301 or rate selector 310 may be implemented using an A/D converter whose binary outputs select an appropriate entry from a look-up table for control signals RS_1 and RS_2 . The look-up table may include rate specific parameters for τ_{ED} and f_c .

In yet another implementation, rate selector 310 may include a finite-state machine for converting a digitized rate estimate signal RE into control signals RS_1 and RS_2 using, for example, an appropriate mapping algorithm.

When used in conjunction with, for example, continuous rate detector 301 of Figure 8, rate correction 1430 and adaptive filter 1440 may improve the accuracy of the line rate estimate, which is received by rate translation 1402. Rate estimate signal RE is applied to input 1432 of rate correction block 1430. Output 1434 from correction block 1430 goes to input 1442 of adaptive filter 1440, input 1462 of rate change detector 1460, and input 1472 of expected rate comparator 1470.

Input 1444 controls the response of filter 1440. Input signal 155 is also applied via node 314 to inputs 1464 and 1474 of rate change detector 1460 and expected rate comparator 1470, respectively. The rate at which operations are performed within rate change detector 1460 and expected rate comparator 1470 may, for example, be controlled by input signal 155 via input 314.

Rate change detector 1460 includes output 1466, and expected rate comparator 1470 includes output 1476. Outputs 1466 and 1476 are combined in summation 1480, and applied to input 1452 of filter control 1450. Filter control 1450 includes output 1454, which is applied to input 1444 of adaptive filter 1440. Adaptive filter output 1446 connects to inputs 1412 and 1422 of function blocks 1410 and 1420, respectively.

Rate estimate signal RE appearing at input 312 of rate detector 301 may include predictable or measured error. Correction block 1430 may implement an algorithm, which compensates for predicted or measured discrepancy between the rate estimate signal RE and the bit rate of input signal 155.

Adaptive filter 1440 outputs a modified rate estimate RE_F , which depends on

the current value of rate estimate signal RE and the current value's relationship to the past behavior of rate estimate signal RE . Considering the behavior of rate estimate signal RE and modified rate estimate signal RE_F at a set of discrete times, the current and past values of rate estimate signal RE may be represented by the set of values
 5 $\{RE_i\}$ while the corresponding values of modified rate estimate signal RE_F may be represented by the set of values $\{RE_{Fj}\}$. Adaptive filter 1440 may, for example, construct modified rate estimate signal RE_F from rate estimate signal RE using the following relationship:

$$RE_{Fk} = \sum_{i=-\infty}^k a_{k-i} RE_i + \sum_{j=-\infty}^{k-1} b_{k-j} RE_{Fj}, \quad (15)$$

where a_i and b_j are coefficients which may be programmed through input 1444
 10 subject.

Filter 1440, which includes an implementation of equation 15, reacts rapidly to changing rate estimate signal RE when coefficient a_1 is large, and conversely, reacts slowly when coefficients a_i are large for $i \gg 1$. Coefficients b_j may be selected to affect persistent memory of a particular estimate. The constraint $\sum_i a_i = 1$ may
 15 prevent bias in modified rate estimate signal RE_F , while the constraint $\sum_j b_j < 1$ may avert instability. Coefficients a_i and b_j may be selected based on patterns in the variation of rate estimate signal RE following a correction by rate correction 1430.

Rate change detector 1460 may distinguish small or insignificant fluctuations in rate estimate signal RE , which is applied to input 1462, from rapid or significant
 20 changes in the corrected rate estimate. Rate change detector 1460 may construct a histogram of rate change values, and compute the likelihood that a current rate change is significantly different from rate changes in the recent past. The magnitude of output 1466 may reflect the magnitude or duration of a change in the current rate estimate relative to previous changes. The response time for performing rate change
 25 discrimination may be set by the rate of transitions at input 1464.

Expected rate comparator 1470 may compare the current rate estimate signal RE with known common line rates or previous values of $\{RE_i\}$, which have persisted

for a significant time interval. The magnitude of output 1476 may reflect the proximity of rate estimate signal *RE* to known rates or previous persistent rates. The response time for comparing rate estimate signal *RE* against expected rates may be set based on the rate of transitions at input 1464.

- 5 While it has been illustrated and described what are at present considered to be preferred embodiments and methods of the present invention, it will be understood by those skilled in the art that various changes and modifications may be made, and equivalents may be substituted for elements thereof without departing from the true scope of the invention.

In addition, many modifications may be made to adapt a particular element, technique or implementation to the teachings of the present invention without departing from the central scope of the invention. Therefore, it is intended that this invention not be limited to the particular embodiments and methods disclosed herein, but that the invention include all embodiments falling within the scope of the appended claims.

CLAIMS

1. A method for recovering a clock signal from an input signal having a variable bit rate, said method comprising the steps of:
 - estimating a minimum time interval between transitions in the input signal;
 - determining a center frequency of a narrow-band filter based on the estimated minimum time interval; and
 - extracting, at the determined center frequency, the clock signal from the input signal.
2. The method of claim 1 further comprises the steps of:
 - before the extracting step, generating a first plurality of pulses corresponding respectively to transitions in the input signal;
 - adjusting the duration of each of the first plurality of pulses based on the estimated variable bit rate; and
 - inputting into the narrow-band filter the adjusted first plurality of pulses.
3. The method of claim 1, wherein the estimating step further comprises the step of:
 - determining the variable bit rate of the input signal based on the estimated minimum time interval.
4. The method of claim 1, wherein the estimating step comprises the steps of:
 - generating a second plurality of pulses that correlate to the transitions in the input signal; and
 - adjusting the duration of each of the second plurality of pulses, such that minimum time intervals between the transitions in the input signal match the durations of the corresponding second plurality of pulses.
5. The method of claim 2, wherein the extracting step comprises the



steps of:

generating a phase correction signal proportional to a difference between a phase of the clock signal and a phase of the first plurality of pulses; and
adding the phase correction signal to a center frequency of an oscillator
generating the clock signal.

6. The method of claim 2, wherein the extracting step comprises the steps of:

generating a frequency correction signal proportional to a difference between a frequency of the clock signal and a frequency of the first plurality of pulses; and

adding the frequency correction signal to a center frequency of an oscillator generating the clock signal.

7. The method of claim 4, wherein the adjusting step comprises the steps of:

generating a voltage signal corresponding to the determined difference; and

generating a current signal proportional to the voltage signal, wherein the current signal controls the duration of each of the second plurality of pulses.

8. A method for recovering a clock signal from an input signal having a variable bit rate, said method comprising the steps of:

estimating a minimum time interval between transitions in the input signal;

generating a first plurality of pulses corresponding respectively to transitions in the input signal;

adjusting duration of each of the first plurality of pulses based on the estimated minimum time interval and inputting into a narrow-band filter the adjusted first plurality of pulses;

determining a center frequency of the narrow-band filter based on the estimated minimum time interval; and



extracting in the narrow-band filter the clock signal from the adjusted first plurality of pulses.

9. The method of claim 8, wherein the estimating step comprises the steps of:

generating a set of delayed input signals by passing the input signal serially through a set of delay segments, wherein the set of delay segments delay the input signal based on a set of predetermined delay times, respectively;

comparing the input signal with the set of generated delayed input signals; and

generating a control signal based on a sum of the predetermined delay times that are less than the minimum time interval between transitions in the input signal.

10. The method of claim 8, wherein the estimating step comprises the steps of:

generating a set of delayed input signals by passing the input signal serially through a set of programmable delay segments, wherein the set of programmable delay segments delay the input signal based on a set of pre-determined delay times, respectively;

comparing the input signal with the set of generated delayed input signals; and

generating a control signal based on a sum of the pre-determined delay times that are less than the minimum time interval between transitions in the input signal.

11. The method of claim 8, wherein the estimating step comprises the steps of:

generating one or more delayed transitions by passing the input signal through a programmable time interval generator, wherein the delayed transitions are generated based on a set of delay time values, respectively;

comparing transitions in the input signal with the generated delayed



transitions; and

adjusting one or more of the delay time values, such that one of the delay time values matches the minimum time interval between the transitions in the input signal.

12. An apparatus for recovering a clock signal from an input signal having a variable bit rate, said apparatus comprising:

a rate detector for estimating a minimum time interval between transitions in the input signal;

a transition detector for generating a first plurality of pulses corresponding respectively to transitions in the input signal;

a narrow-band filter for extracting the clock signal from the adjusted first plurality of pulses; and

a rate selector for adjusting, based on the estimated minimum time interval, duration of each of the first plurality of pulses and a center frequency of the narrow-band filter that receives the adjusted first plurality of pulses.

13. The apparatus of claim 12, wherein said rate detector comprises:

a set of delay segments connected in series for generating a set of delayed input signals based on a set of pre-determined delay times, respectively; and

a set of latches connected to the set of delay segments, respectively, for comparing the set of delayed input signals with the input signal and generating a control signal based on a sum of the pre-determined delay times that are less than the minimum time interval between transitions in the input signal.

14. The apparatus of claim 12, wherein said rate detector comprises:

a programmable time interval generator for generating a set of delayed transitions based on a set of delay time values, respectively; and

an edge transition comparator connected to the programmable time interval generator for comparing the set of delayed transitions with transitions in the input signal and adjusting one or more of the delay time values, such that one of the delay time values matches the minimum time interval between the transitions in the



input signal.

15. The apparatus of claim 12 further comprises:

a calibration source for generating a calibration signal having a set of pre-determined reference bit rates, wherein the rate detector estimates the reference bit rate of the calibration signal; and

a response monitor for determining differences between the pre-determined reference bit rates and the estimated reference bit rate and for adjusting the rate selector until the one of the determined differences equals zero.

16. The apparatus of claim 12, wherein the rate detector comprises:

an interval generator for generating a second plurality of transitions that correlate to the transitions in the input signal;

a transition comparator for determining a difference between the duration of each of the second plurality of transitions and a time interval between each of the transitions in the input signal; and

a feedback means for adjusting the duration of each of the second plurality of transitions until the determined difference equals zero.

17. The apparatus of claim 12, wherein the narrow-band filter comprises:

a phase comparator for generating a phase correction signal proportional to a difference between a phase of the clock signal and a phase of the adjusted first plurality of pulses; and

a first adder for adding the phase correction signal to a center frequency of an oscillator generating the clock signal.

18. The apparatus of claim 12, wherein the narrow-band filter further comprises:

a frequency comparator for generating a frequency correction signal proportional to a difference between a frequency of the clock signal and a frequency of the adjusted first plurality of pulses; and

a second adder for adding the frequency correction signal to a center



frequency of an oscillator generating the clock signal.

19. The apparatus of claim 16, wherein the interval generator comprises:
an edge triggered one-shot for generating a second plurality of pulses
that correlate to the transitions in the input signal.
20. The apparatus of claim 16, wherein the interval generator comprises:
one or more resettable edge triggered delay elements for generating a
second plurality of pulses that correlate to the transitions in the input signal.
21. An apparatus for recovering a clock signal from an input signal having
a variable bit rate, said apparatus comprising:
a rate detector for estimating a minimum time interval between
transitions in the input signal;
a rate selector connected to the rate detector;
a transition detector connected to the rate selector; and
a narrow-band filter connected to the transition detector and the rate
selector, such that the rate selector adjusts, based on the estimated minimum time
interval, duration of each of a plurality of pulses generated by the transition detector
and a center frequency of a narrow-band filter for extracting the clock signal from the
input signal.

