

Single-VCO CDR for TMDS Data at Gigabit Rate

Background of the Invention

Field of the Invention

[0001] This invention relates generally to a circuits and systems for the recovery and regeneration of data and synchronizing clock signals received from a serial transmission channel. More particularly this invention relates to circuits and systems for recovery and regeneration of data and synchronizing clock signals while overcoming skew and jitter within the transmitted data and clock signals.

10 Description of Related Art

[0002] As commercial and cable television has migrated to high definition digital transmission, equipment manufacturers have cooperated to create the specifications such as the High-Definition Multimedia Interface (HDMI[™]) developed by Hitachi, Ltd., Matsushita Electric Industrial Co., Ltd., Philips Consumer Electronics, International B.V., Silicon Image, Inc., Sony Corporation, and Thomson Inc.

[0003] Toshiba Corporation, and the digital visual interface (DVI) specification, as promulgated by the Digital Display Working Group, to describe transmitting digital television audiovisual signals from DVD players, cable television set-top boxes and other audiovisual sources to television sets, projectors and other

video displays. DVI can carry high quality multi-channel audio data and can carry all standard and high-definition consumer electronics video formats. Further, HDMI™ can also carry control and status information in both directions.

5 [0004] Referring to Fig. 1, HDMI™ system architecture is defined to consist of Sources **5** and Sinks **10**. The HDMI™ source device **5** communicates with the over HDMI™ cable and connectors. The HDMI™ cable and connectors carry four differential pairs that make up the Transition Minimized Differential Signaling (TMDS) data and clock channels **15a**, **15b**, **15c**, and **15d**. These
10 channels **15a**, **15b**, **15c**, and **15d** are used to carry video, audio and auxiliary data. In addition, HDMI™ cables and connectors carry a digital data (DDC) channel **20**. The DDC **20** is used for configuration and status exchange between a single Source **5** and a single Sink **10** by reading the Enhanced Extended Display Identification Data (EDID) from the EDID read only memory
15 **40** to retrieve the Sink's configuration and/or capabilities.

[0005] The optional Consumer Electronic Control (CEC) line **55** provides high-level control functions between all of the various audiovisual products in a user's environment.

[0006] Video **45**, audio **50** and auxiliary data is transmitted across the three
20 TMDS data channels **15a**, **15b**, and **15c**. The video pixel clock is transmitted on the TMDS clock channel **15d** and is used by the receiver **35** as a frequency reference for data recovery on the three TMDS data channels **15a**, **15b**, and

15c. Video data is carried as a series of 24-bit pixels on the three TMDS data channels **15a**, **15b**, and **15c**. TMDS encoding converts the 8 bits per channel into the 10 bit DC-balanced, transition minimized sequence which is then transferred by the transmitter **30** serially across the pair at a rate of 10 bits per pixel clock period to the receiver **35**. The receiver **35** acquires and recovers the transmitted data and the synchronizing clock of the data to restore the received video data **55** and the audio data **60**.

[0007] Video pixel rates can range from 25MHz to 165MHz. Video formats with rates below 25MHz (e.g. 13.5MHz for NTSC) can be transmitted using a pixel-repetition scheme. Up to 24 bits per pixel are transferred. In order to transmit audio and auxiliary data across the TMDS channels **15a**, **15b**, and **15c**, HDMI[™] uses a packet structure. In order to attain the higher reliability required of audio and control data, the data is protected with an error correction code and is encoded using a special error reduction coding to produce the 10-bit word that is transmitted

[0008] The transmitter **30**, as shown in Fig. 2 has three encoder and serializers **32a**, **32b**, and **32c** that receive the video components **45a**, **45a**, and **45c**, the audio components **50a**, **50b**, and **50c**, and the control signals **47a**, **47b**, **47c**, and **47d** and convert the signals into the three TMDS link channels **15a**, **15b**, and **15c**. The pixel clock **52** is transmitted on the clock channel **15d** to be the received pixel clock **54**. It should be noted that the pixel clock **52** is the clock for the complete pixel and the bits of the data packets transmitted on the

TMDS link channels **15a**, **15b**, and **15c** are transmitted at a multiple of 10 greater than the pixel clock. The data packets are synchronized by a clock that has a frequency that is ten times greater than the pixel clock **52**. For pixel rates at 165 MHz, the serialized bits of the packet data must be transmitted at a rate of 1.65 Gb/S.

[0009] To ensure that correct capture of the video and audio data **55** and **60** of Fig. 1, the HDMI™ and DVI specifications include standards for inter-conductor data skew and clock jitter. Correct data capture is ensured at receiving end, in one approach, by data over-sampling followed by selecting a bit from over-sampled bits by decision logic as described in U. S. Patent 5,905,769 (Lee, et al.) and U. S. Patent 6,587,525 (Jeong, et al.). Lee, et al. describes a system that receives a multi-channel digital serial encoded signal and converts the signal into a synchronized set of binary characters. A charge pump phase-locked loop receives a transmitted reference clock and derives a multi-phase clock from the reference clock. The multi-phase clock is used to control a plurality of multi-bit block assembly circuits. Each assembly circuit receives one channel of the digital signal and produces a multi-bit block or character. The multi-bit block assembly circuit includes an oversampler, a digital phase-locked loop and a byte synchronizer. The oversampler oversamples the received digital signal under control of the multiphase clock and produces a sequence of oversampled binary data. The digital phase-locked loop receives the oversampled data and selects samples from it depending on the skew characteristics of the sample. The byte synchronizer

assembles a sequence of selected bits into a bit block, or character. An interchannel synchronizer receives as input the characters produced by each of the multi-bit block assembly circuits, and selectively delays output of the received characters in order to synchronize the characters of each channel with one another.

[0010] Jeong, et al. describes a system for transmission and recovery of original digital data. The system includes an encoder, a transmitter, a receiver, a decoder, and an analog phase locked loop. The analog phase locked loop supplies a sender's clock to the transmitter and a receiver's clock to the receiver. The transmit clock frequency is a first integer multiple of the system clock frequency, and the receiver clock frequency is a second integer multiple of the transmit clock frequency within 0.1% tolerance. In a normal flow situation, data frames are output by the receiver in alternate cycles of the system clock. In an overflow situation, data frames are output by the receiver in consecutive cycles of the system clock. In an underflow situation, data frames are output by the receiver in non consecutive or alternate cycles of the system clock.

[0011] In the over-sampling technique, the decision logic is realized by use of a digital phase lock loop (DPLL) whose phase-pointer is adjusted based on transition (boundary) of the input data so that the phase-pointer always points at the center bit of the over-sampled bits. This approach exhibits deteriorated phase quantization error due to the increased phase interval. When the

phase-pointer changes its phase due to change of data boundary, some bits may be selected twice and some may get missed. Therefore careful correction is necessary to remove the repeated bit or add the missing bit, which increases design complexity. Besides, as the clocks and data don't necessarily remain synchronized, error may occur during the over-sampling due to metastability effect. This may cause wrong decision for phase selection in DPLL and result in high bit error rate (BER).

[0012] The advantages of the over-sampling technique for data recovery include the high bandwidth of the DPLL to cope with high data rate of the transmitted TMDS data. The over-sampling technique is relatively easy to implement. It employs a small portion of analog circuitry is mostly digital logic circuitry implemented by using standard cells of a typical application specific integrated circuit process flow.

[0013] Alternately, the over-sampling technique has a large phase quantization error that requires discrete adjustment. Additional data correction logic is required to correct recovered data error due to the quantization error. Further the over-sampling as described above may cause the sampling faults requiring additional error correction complexity. This added complexity contributes to a large power consumption of the circuits employing the over-sampling technique.

[0014] An alternative to the over-sampling technique is the tracking-type of clock and data recovery circuit. The tracking type clock and data recovery

circuit is widely used for data rates in the gigabit per second range. The tracking type clock and data recovery circuit applies a delay to the clock for synchronization between data and clock. One application example is given in Japanese Patent Publication JP2001/203676A (Kazutaka, et al.). Kazutaka, et al. provides a circuit in a chip for receiving data synchronously with a clock that takes synchronization between the data and the clock with high accuracy by delaying only the clock without delaying the data. The circuit synchronizes the data and the clock with a first circuit that detects a phase shift between an input data signal and a clock signal. A second circuit converts the detected phase shift into a control voltage for a delay time. A third circuit produces a delay in response to the control voltage to delay the clock and to produce a sampling clock. A fourth circuit receives the input signal in the timing of the sampling clock. Kazutaka, et al. employs the well known Alexander phase detector for synchronization of the recovered clock and data. It is an acceptable approach with reasonable bit error rate at low data rate and relatively easy to achieve high loop bandwidth using voltage controlled delay line for data/clock synchronization; there are no quantization error and Less Sampling Faults.

[0015] The tracking-type of clock and data recovery circuit requires very sophisticated control circuitry for the voltage controlled delay line to ensure the sufficient delay variation range for variable data rate used in the TMDS link for applications like DVI or HDMI[™]. Error or jitter in edge spacing is introduced because of mismatch between the delay lines and their load capacitances.

This error or jitter requires large devices and careful layout. Further, the tracking-type of clock and data recovery circuit has less tolerance to asymmetric jitter.

[0016] "A 9.9 G-10.8 Gb/S Rate-Adaptive Clock and Data-Recovery with No
5 External Reference Clock for WDM Optical Fiber Transmission", Noguchi, et al., Digest of Technical Papers: IEEE International Solid-State Circuits Conference, ISSCC-2002, 2002, Volume: 1, pp.: 252 - 465 describes a 9.9-10.8 Gb/s rate adaptive clock and data recovery circuit with 1:16 DMUX. A dual-input voltage-controlled oscillator incorporates a fast and a slow tracking
10 loop with a DC gain enhancer.

[0017] U. S. Patent Application 2004/0210790 (Moon et al.) describes a 0.6-2.5 GBaud CMOS tracked 3X over-sampling clock/data recovery. A wide-range multiphase delay-locked loop (DLL) is used for generation of the multiphase clocks for a serializer in the transmitter. A tracked 3X over-sampling technique with dead-zone phase detection is incorporated in the
15 receiver for clock/data recovery in the presence of excessive jitter and inter-symbol interference (ISI). A voltage-controlled oscillator (VCO), based on a folded starved inverter is used for the clock recovery.

[0018] U. S. Patent Application 2004/0042577 (Sumiyoshi et al.) teaches a
20 regenerator circuit extracts proper signals out of signals that have jitter and are skewed. The most stable data rows are selected out of data rows obtained by over-sampling. A serial data regenerator circuit stores serial data as received

for two system clocks, compares special character signals used in transmission with the data as stored for two system clocks, and determines positions (shift numbers) where patterns of the data match the special character signal. Correction for skews is implemented by sampling the data on the basis of information on the positions where matching is determined. Correction for jitter and skew is accomplished by three-times over-sampling serial data as received, dividing the serial data as oversampled into three edge groups, detecting a shift number matching special characters for each of the groups by the process described, selecting an edge group undergoing the least change in shift number, and regenerating the serial data from the edge group.

[0019] U. S. Patent 6,545,507 (Goller) provides a fast locking clock and data recovery circuit (CDR) with high jitter tolerance and elimination of effects caused by metastability. The CDR circuit provides a fast locking (e.g., within 1.5 sync bit times or the first data transition) clock and data recovery. The CDR circuit takes multiple (e.g., 8) phases of the local clock, which are offset (e.g., by 45 degrees), and uses the multiple phases to latch the state of data at multiple times, and uses the latched data to determine which of the multiple phases captured a data transition. The CDR circuit compares the indicated phase to the phase used to capture a previous data transition and uses such information to produce a stable selection of a clock phase. The selected clock phase is then employed to provide a recovered clock and data signals in

association with the incoming serial data stream. The recovered clock and data signals are independent of jitter and free of metastable conditions.

Summary of the Invention

[0020] An object of this invention is to provide a communication system that has clock and data recovery circuit which recovers transmitted data and a synchronizing clock, where the frequency of the clock varies widely over a frequency spectrum.

[0021] Another object of this invention is to provide a clock and data recovery circuit that uses a voltage controlled oscillator to track the data.

[0022] Further, another object of this invention is to provide a clock and data recovery circuit that has no phase quantization error.

[0023] Even further, another object of this invention is to provide a clock and data recovery circuit that over-samples bits for better jitter tolerance particularly to asymmetric jitter.

[0024] To accomplish at least one of these objects a communication system transmits and receives a synchronizing clock and serialized digital data over a communication medium. The communication system includes a receiver with a clock and data recovery circuit for recovery of the synchronizing clock and serialized digital data from a received communication signal. The clock and data recovery circuit has a data capture device which receives the

communication signal and recovers the serialized digital data. A voltage controlled oscillator is in communication with the data capture device to provide an oscillator clocking signal synchronized to the received communication signal.

5 [0025] A multiple phase generator is in communication with the voltage controlled oscillator to receive and convert the oscillator clocking signal to a plurality of multiple phased clocking signals, each signal being phase shifted from the oscillator clocking signal. The multiple phase generator is in communication with the data capture device to receive the plurality of multiple
10 phased clocking signals, the data capture device acquiring the serialized digital data with each of the plurality of multiple phased clocking signals to create a plurality of acquired multiple phased data signals.

[0026] A phase detector is in communication with the data capture device to receive the recovered serialized data and in communication with the multiple
15 phase generator to acquire the plurality of multiple phased clocking signals, the phase detector determining if the oscillator clocking signal is in phase with the recovered serialized data and providing a lead signal and a lag signal indicating whether the oscillator clocking signal is in phase with the recovered
20 serialized data. A low pass filter is in communication with the phase detector/charge pump to receive and low pass filter the lead lag error signal to develop a frequency adjusting voltage for the voltage controlled oscillator.

[0027] The clock and data recovery circuit further includes a frequency initializing device connected to receive a reference clock signal and in communication with the voltage controlled oscillator employed to assist acquisition of lock of the voltage controlled oscillator to the reference clock signal during initialization. A loop selection device is in communication with the frequency initializing device to receive a frequency increase signal and decrease signal indicating whether the oscillator clocking signal is greater than or lesser than the reference clock signal. The frequency initializing device is further connected to receive a synchronization lost signal. The frequency initializing device is in communication with the low pass filter to switch control of the voltage controlled oscillator from the frequency initializing device after initialization to the phase detector for recovery of the serialized digital data and the synchronizing clock.

[0028] The clock and data recovery circuit further includes a recovered data selector in communication with the data capture device to receive the plurality of acquired multiple phased data signals and in communication with the multiple phase generator to receive the plurality of multiple phased clocking signals, the recovered data selector selecting which of the plurality of acquired multiple phased data signals are to be transferred to external circuitry for further processing. The recovered data selector has at least one mode terminal receiving a selection source indication signal for selecting a mode by which of plurality of acquired multiple phased data signals are selected for to external circuitry for further processing. If the selection source indication

signal indicates that the mode is to be a manual mode, a jitter factor of the recovered data is examined and a grouping of the plurality of acquired multiple phased data signals is selected based on the jitter factor.

[0029] The clock and data recovery circuit has a bit error estimator and
5 synchronization detector in communication with the recovered data selector to
receive the selected plurality of acquired multiple phased data signals,
evaluate the selected plurality of acquired multiple phased data signals for a
bit error rate, and from the bit error rate, transfer a bit error threshold signal to
the recovered data selector to indicate whether the bit error rate is greater or
10 lesser than a desired bit error rate. If the selection source indication signal
indicates that the mode is to be a bit error control wherein the bit error
threshold signal determines which of the plurality of acquired multiple phased
data signals are to be transferred for further processing.

[0030] The bit error estimator and synchronization detector determines
15 whether the plurality of acquired multiple phased data signals are in
synchronization with the reference clock and is not in synchronization
providing the synchronization lost signal to the loop selection device, such that
the loop selection device switches the low pass filter to receive the reference
signal.

Brief Description of the Drawings

[0031] Fig. 1 is a functional block diagram of the High Definition Multimedia Interface (HDMI[™]) architecture of the prior art.

[0032] Fig. 2 is a functional block diagram of the transmitter and receiver of the High Definition Multimedia Interface (HDMI[™]) architecture of the prior art as shown in Fig. 1.

[0033] Fig. 3 is block diagram of the clock data recovery and synchronization circuit of this invention.

[0034] Fig. 4 is a schematic diagram of the voltage controlled oscillator and multiple phase generator of the clock data recovery and synchronization circuit of this invention.

[0035] Fig. 5 is schematic diagram of the data capture circuit of the clock data recovery and synchronization circuit of this invention.

[0036] Fig. 6 is a schematic diagram of the phase detector of the clock data recovery and synchronization circuit of this invention.

[0037] Figs. 7a and 7b are timing diagrams illustrating the operation of the data capture and phase detector of the clock data recovery and synchronization circuit of this invention.

[0038] Fig. 8 is a schematic diagram of the operation of the charge pumping for providing the control voltage of the voltage controlled oscillator of the clock data recovery and synchronization circuit of this invention.

[0039] Fig. 9 is schematic diagram of the loop selection circuit of the clock data recovery and synchronization circuit of this invention.

[0040] Fig. 10 is a block diagram of the bit selector of the clock data recovery and synchronization circuit of this invention.

Detailed Description of the Invention

[0041] In communications systems such as the Transition Minimized Differential Signaling (TMDS) data and clock channels of the HDMI[™], there is a need for clock and data recovery circuits that provide simplicity, low power consumption and small area, while having the ability to operate over a broad range of frequencies. The HDMI[™] has a transmission data rate that varies from 250Mbps to 1.65Gbps. The communication system of this invention includes a clock and data recovery system that has a single voltage controlled oscillator (VCO) to synchronize the TMDS data using a binary (bang-bang) phase detector. The VCO is a ring oscillator having serially connected cross coupled differential amplifiers. Each of the amplifiers has their output cross connected to the inputs of the following differential amplifier. The last differential amplifier is in turned connected to the inputs of the first differential amplifier. The differential amplifiers each have a biasing connection to adjust

the delay of each differential amplifier and thus the frequency of oscillation of the VCO.

[0042] An advantage of the multiple differential amplifiers of the VCO is that equally spaced multiphase clocks are generated. The VCO is so controlled that its output multiphase clocks synchronize with input data. A frequency acquisition aid is employed to help acquire lock to an input reference clock at startup. The VCO actually oscillates at 2.5 times input reference clock frequency. Once the VCO frequency is close enough to the desired clock frequency, the VCO is switched to data tracking loop in which the clock phase is adjusted by charging/discharging VCO control voltage according to the phase error between the clocks and input data transitions. A bang-bang phase detector with dynamic gain-control is introduced to ensure minimum VCO frequency drift in the absence of data transition for TMDS data covering wide variation of data rate. Three time over-sampling provides automatic retiming and bit selection flexibility for better jitter tolerance particularly to asymmetric jitter. An auto-scale frequency detector is incorporated to realize smooth transition from the input reference clock frequency and the timing of the input data transitions.

[0043] The VCO of the clock and data recovery circuit of the invention has an advantage over a delay line of the prior art in that the VCO is controlled to track the data by a simple charge pump circuitry. There is no complicated delay line control circuit which permits much less complexity, resulting in less

area and power consumption. There is no phase quantization error since the clock tracks the data constantly. Simple bit selection logic for the data recovery can be easily implemented using 3x over-sampled bits for better jitter tolerance particularly tolerance to asymmetric jitter.

5 [0044] Refer now to Fig. 3 for a more detailed description of the clock and data recovery circuit of this invention. The clock and data recovery circuit **100** has a voltage controlled oscillator **105** that is composed of a serially connected ring of differential amplifiers **106a**, ..., **106n**. Each of the differential amplifiers **106a**, ..., **106n** have their outputs connected to the input of the succeeding
10 differential amplifiers **106a**, ..., **106n** with the outputs of the last amplifier **106n** connected to the inputs of the first amplifier **106a**. One of the outputs of one of the differential amplifiers **106a**, ..., **106n** (i.e. the last amplifier **106n**) is applied to a buffer (not shown) and becomes the clocking signal **108**.

[0045] The clocking signal **108** is applied to the frequency detector/charge
15 pump **110**. The pixel clock **115** of the HDMI[™] is used as a reference clock and applied as a second input to the frequency detector/charge pump **110**. The pixel clock **115** is compared to the clocking signal **108** to generate up/down error signals **117** and **118**. The up/down error signal **117** is applied through the switch **SW₁**, **119a** to the low pass filter **120**. The low pass filter **120** filters
20 the up/down error signal **117** to remove any high frequency content to create the oscillator correction voltage **122**. The oscillator correction voltage **122** is the signal that adjusts the delay of each of the differential amplifiers **106a**, ...,

106n to adjust the frequency of the clocking signal **108**. The frequency detector/charge pump **110** provides the initialization frequency of the VCO **105**. The VCO **105** actually oscillates at 2.5 times input clock frequency pixel clock **115** for the HDMI[™] application.

5 [0046] The clocking signal **108** is also applied to the multiple phase generator **125** which develops the multiple phase clocks $\phi[0:11]$ **130**. Referring to Fig. 4, the outputs of the differential amplifiers **106a**, ..., **106f** of the voltage controlled oscillator in fact provides each phase of the multiple phase clocks as inputs to the multiple phase clock generator **125**. The multiple phase clock generator

10 **125** is formed of the buffer circuits **127a**, ..., **127l**. The inputs of the each buffer are connected to the appropriately phased output of the differential amplifiers **106a**, ..., **106f**. The outputs of the buffer circuits **127a**, ..., **127l** provide the multiple phase clocks ϕ_0 **130a**, ..., ϕ_{11} **130l**. In the illustration of Fig. 4, as shown, the ring oscillator of the VCO **105** contains six differential

15 amplifiers **106a**, ..., **106f** serially connected output to subsequent input. With the outputs of the last differential amplifier **106f** crossed connected to the inputs of the first differential amplifier **106a**. The out of phase output of the last differential amplifier **106f** is connected to the first buffer circuit **127a** to develop the first phase clock signal ϕ_0 **130a** and the subsequent in phase outputs of

20 the differential amplifiers **106a**, ..., **106e** are connected to the buffer circuits **127b**, ..., **127f** and develop the phased clock signals ϕ_1 **130b**, ..., ϕ_5 **130f**. The in phase output of the last differential amplifier **106f** is connected to the seventh buffer circuit **127g** to develop the seventh phase clock signal ϕ_6 **130g**

and the subsequent out of phase outputs of the differential amplifiers **106a**, ..., **106e** are connected to the buffer circuits **127h**, ..., **127l** and develop the phased clock signals $\phi 7$ **130h**, ..., $\phi 11$ **130l**.

[0047] Returning to Fig. 3, the multiple phase clocks $\phi[0:11]$ **130** are inputs to the data capture device **135**. The data input **140** is the ten bit serialized encoded data from one of the data channels **15a**, **15b**, and **15c** TMDs link of Fig. 2. U. S. Patent 6,762,560 (Guosheng), incorporated herein by reference, illustrates the structure of the data capture device **135** in more detail. A simplified schematic of the data capture device **135** is shown in Fig. 5. The data capture device includes of the latcher circuits **137a**, ..., **137l** that are similar to those shown in Guosheng et al. The input data **140** is applied to the data input terminals of each of the latcher circuits **137a**, ..., **137l**. The multiple phase clocks $\phi 0$ **130a**, ..., $\phi 11$ **130l** are applied to the each of the respective clock terminals of the latcher circuits **137a**, ..., **137l**. The latched data **LD0** **145a**, ..., **LD11** **145l** is presented respectively at the output terminals of each of the latcher circuits **137a**, ..., **137l**.

[0048] Returning to Fig. 3, the latched data **LD[0:11]** **145** from the data capture device **135** is transferred to the phase detector/charge pump **150**. Referring to Fig. 6 for a discussion of the bang-bang phase detector portion of the phase detector/charge pump **150**. The latched data **LD0** **145a**, ..., **LD11** **145l** are input to the exclusive-OR circuits **155a**, ..., **155h**. The latched data **LD0** **145a**, ..., **LD11** **145l** are compared pair wise with the adjacent latched

data and the differences in the periods when the latched data **LD0 145a**, ..., **LD11 145l** are differing causes the exclusive-OR circuits **155a**, ..., **155h** to be activated. The latched data **LD0 145a** and **LD2 145c** are compared with the latched data **LD1 145b**. The latched data **LD3 145d** and **LD5 145f** are compared with the latched data **LD4 145e**. The latched data **LD6 145g** and **LD8 145i** are compared with the latched data **LD7 145h**. The latched data **LD9 145j** and **LD11 145l** are compared with the latched data **LD10 145k**. The transitions that occur between the latched data **LD0 145a**, ..., **LD11 145l** appear at the outputs of the exclusive-OR circuits **155a**, ..., **155g**. The outputs of the exclusive-OR circuits **155a**, ..., **155h** are the data inputs of the data latches **160a**, ..., **160h**. These differences between the pair wise latched data **LD0 145a**, ..., **LD11 145l** are latched by the phase clocks $\phi 1$ **130b**, $\phi 4$ **130e**, $\phi 7$ **130h**, and $\phi 10$ **130k**.

[0049] The phase clocks $\phi 4$ **130e** captures the difference between the latched data **LD0 145a** and the latched data **LD1 145b** in the data latch **160a** and the latched data **LD2 145c** and the latched data **LD1 145b** in the data latch **160b**. The phase clocks $\phi 7$ **130h** captures the difference between the latched data **LD3 145d** and the latched data **LD4 145e** in the data latch **160c** and the latched data **LD5 145f** and the latched data **LD4 145e** in the data latch **160d**. The phase clocks $\phi 10$ **130k** captures the difference between the latched data **LD6 145g** and the latched data **LD7 145h** in the data latch **160e** and the latched data **LD8 145i** and the latched data **LD7 145h** in the data latch **160f**.

The phase clocks $\phi 1$ **130b** captures the difference between the latched data **LD9 145j** and the latched data **LD10 145k** in the data latch **160g** and the latched data **LD11 145l** and the latched data **LD10 145k** in the data latch **160h**. The outputs of the data latches **160a**, **160c**, **160e**, and **160g** provide the indication that the phasing of the voltage controlled oscillator leads the data input **140**. Conversely, the outputs of the data latches **160b**, **160d**, **160f**, and **160h** provide the indication that the phasing of the voltage controlled oscillator lags the data input **140**.

[0050] The bang-bang phase detector **150** suffers a critical drawback for TMD5 encoded data in which transitions are minimized and data rate is variable. The loop gain of the bang-bang phase detector is transition dependant, which leads to dramatic variation in loop gain and results in large jitter inherent in the VCO **105**. The phase detector **150** uses twelve bits of the sampled input data **140** and twelve equally spaced phased clock signals $\phi 0$ **130a**, ..., $\phi 11$ **130l** to ensure the capture of every transition. A simple circuit using two data latches **170a** and **170b** after the OR gates **165a** and **165b** is introduced to dynamically suppress gain at high transitions and reduce VCO jitter as a result for wide range of data rate variation. The lead signals from the data latches **160a**, **160c**, **160e**, and **160g** are the inputs to the OR gate **165a**. The OR'ed lead signals are the clock inputs to the latch **170a**. The data input of the data latches **170a** is connected to a logical one (1) such that a transition of the lead signal causes the lead pulse **152a** to be activated. The lead pulse **152a** is the input to the inverter **172a**. The output of the inverter

5 **172a** is the input to the reset of the data latch **170a** to immediately reset the data latch **170a**. The lag signals from the data latches **160b**, **160d**, **160f**, and **160h** are the inputs to the OR gate **165b**. The OR'ed lead signals are the clock inputs to the latch **170b**. The data input of the data latch **170b** is connected to a logical one (1) such that a transition of the lead signal causes the lag pulse **152b** to be activated. The lag pulse **152b** is the input to the inverter **172b**. The output of the inverter **172b** is the input to the reset of the data latch **170a** to immediately reset the data latch **170a**.

[0051] Referring to Figs. 7a and 7b, the multiple phase clocks [$\phi 0:\phi 11$] 130 latch the serialized input data 140 to generate the latched data [LD0:LD11] 145. The outputs 300 of the exclusive-OR circuits 155a, ..., 155h determine the relative positions of the data and clock phases. The relative positions are captured by the phase clocks $\phi 1$ 130b, $\phi 4$ 130e, $\phi 7$ 130h, and $\phi 10$ 130k in the latches data latches 160a, ..., 160h to generate the Lead signals 305a, ..., 305d and the Lag signals 310a, ..., 310d, which are OR'ed and Latched to generate the Lead Pulse 152a and the Lag Pulse 152b.

[0052] The lead pulse **152a** and lag pulse **152b** are the inputs to the charge pump that provides the oscillator correction voltage **122** for adjusting the voltage controlled oscillator **105**. Referring to Fig. 8, two charge pumps are implemented with their outputs connected through the switches **SW1 119a** and **SW2 119b** to the input control terminal **Vc** of the low pass filter **110**. The first charge pump is incorporated in the frequency detector/charge pump **110** and

is controlled by the up/down signals **255a** and **255b** and the second charge pump is incorporated in the phase detector/charge pump **150** and is controlled by the data phase detector of Fig. 6.

[0053] Upon initialization of the clock and data recovery circuit of this invention, the charge pump incorporated in the phase detector/charge pump **150** is set to a high impedance state with the switch **SW2 119b** being open. The VCO **105** is thus controlled by charge pump incorporated in the frequency detector/charge pump **110** only. Alternately, When the VCO is approximately at the frequency of the data the switch **SW1 119a** is opened to set the charge pump incorporated in the frequency detector/charge pump **110** to a high impedance state and the switch **SW2 119b** is closed such that the VCO **105** is controlled by the data frequency detector/charge pump **110**. The charge pump incorporated in the frequency detector/charge pump **110**. The frequency detector **110** generates the up/down signals **255a** and **255b** that indicate whether the frequency of oscillation of the VCO **105** is less or greater than the reference pixel clock **115**. The up/down signals **255a** and **255b** respectively open and close the switches **SW₅ 255** and **SW₆ 260** to connect and disconnect the current sources **250** and **265** to the low pass filter **110** to provide the oscillator correction voltage **122** to the voltage controlled oscillator **105**.

[0054] When the frequency is approximately equal to the frequency of the pixel reference signal **115**, the switch **SW1 119a** is opened and the switch **SW2**

119b is closed. The lead pulse **152a** and lag pulse **152b** respectively open and close the switches **SW₇ 275** and **SW₈ 285** to connect and disconnect the current sources **270** and **290** to the low pass filter **110** to provide the oscillator correction voltage **122** to the voltage controlled oscillator **105**.

5 [0055] The loop selector **175**, as shown in Fig. 9, receives the up/down signals **117a** and **117b** from the frequency detector/charge pump **110**, which are applied to the inputs of the exclusive-NOR **200**. The output of the exclusive-NOR **200** is the control signal for the switch **SW₉ 205**. The switch **SW₉ 205** is opened and closed to control the charging of the capacitor **C₁ 215** by the
10 current source **210**. When the frequency of the VCO **105** is not equal to that of the pixel reference clock **115**, the up/down signals **255a** and **255b** are different and the switch **SW₉ 205** is deactivated and the capacitor **C₁ 215** is charged. When the voltage present on the capacitor **C₁ 215** is greater than the threshold of the buffer **217**, switch **SW₁₀ 220** activated discharging the
15 capacitor **C₂ 225** setting the clock input to the flip-flop **240** to a zero level. When the synchronization lost signal **187** is active, the flip-flop **240** is reset and the switch select signal **117** is set to activate the switch **SW₁ 119a** and deactivate the switch **SW₂ 119b** such that the voltage controlled oscillator is controlled by the frequency detector/charge pump **110**.

20 [0056] When the up/down signals **255a** and **255b** from the frequency detector/charge pump **110** indicate that the frequency of the clocking signal **108** of the VCO **105** is nearly equal to the pixel reference clock **115**, the

5 difference of up/down signals **255a** and **255b** become very small and the switch **SW₉ 205** is closed more often and the capacitor **C₁ 215** is not charge sufficiently to reach the threshold of the buffer **217**. The switch **SW₁₀ 220** becomes open and the capacitor **C₂ 225** is charged to a voltage greater than the threshold of the buffer **235** and the logical 1 is clocked through the flip-flop **240**. The switch select signal now deactivates the switch **SW1 119a** and activates the switch **SW2 119b** so that the oscillator correction voltage **122** is then controlled by the phase detector/charge pump **150**.

[0057] Returning to Fig. 3, once the VCO **105** has achieved synchronization,
10 the latched data **LD[0:11] 145** is transferred to the bit selection circuit **180**. The bit selection circuit **182** has two modes of operation that are set by the mode select signal **182**. The modes are a manual operation where an external circuit evaluates the jitter characteristic of the operating clock and data recovery circuit, and an auto-optimized selection mode for optimum bit
15 error rate. The desired sampling location is selected automatically to cope with asymmetric jitter based on feedback from a bit error rate estimator and synchronization detection circuit **185**. The bit error rate estimator and synchronization detection circuit **185** receives a selected set of the latched data **LD[0:11] 145** evaluates the bit error and feed back a bit error control
20 signal **187** to the bit selection circuit **180**.

[0058] Referring to Fig. 10, the bit selection circuit **180** receives the phased clock signals **[ϕ 0: ϕ 11] 130** and the latched data **LD[0:11] 145**. The mode

selection signals **MS1 182a** and **MS2 182b** determine the method of selection of the latched data **LD[0:11] 145** for transmission to the data output **190** for transfer to external circuitry for further processing. In the preferred embodiment of clock and data recovery for an HDMI[™], the data is deserialized into four separate output signals for decoding and recovery of the pixel and audio data. The pixel and audio data is aligned with one of the twelve phased clock signals **[φ0:φ11] 130**. The selected clock is chosen and transferred with the recovered data.

[0059] If the mode selection signals **MS1 182a** and **MS2 182b** indicate that the manual selection is to be used (**MS1=High**), the external evaluation of the jitter determines the data selection by toggling the mode selection signal **MS2 182b**. If the mode selection signal **MS2 182b** is set to a logical 1 (high), the latched data **LD2 145c**, **LD5 145f**, **LD8 145i**, **LD11 145l** are transferred to the data output terminals **190**. Alternately, if the mode selection signal **MS2 182b** is set to a logical 0 (low), the latched data **LD0 145a**, **LD3 145d**, **LD6 145g**, **LD9 145j** are transferred to the data output terminals **190**.

[0060] If the mode selection signals **MS1 182a** and **MS2 182b** indicate that the bit error rate optimization mode is to be used (**MS1=Low**), the bit error control signal **187** provides the selection of the latched data **LD[0:11] 145**. If the bit error control signal **187** is set to a logical 1 (High), latched data **LD2 145c**, **LD5 145f**, **LD8 145i**, **LD11 145l** are transferred to the data output terminals **190**. If the bit error control signal **187** is set to a logical 0 (Low), the latched

data **LD0 145a**, **LD3 145d**, **LD6 145g**, **LD9 145j** are transferred to the data output terminals **190**.

[0061] In summary, the apparatus of this invention performs a process for recovery of a synchronizing clock and serialized digital data from a received communication signal. The process begins by receiving the communication signal and the synchronizing clock that acts as a reference clocking signal. An oscillator is initialized to the reference clocking signal to assist acquisition of lock of the oscillator clocking signal to the reference clock signal during initialization. The serialized digital data is recovered from the communication signal. The oscillator clocking signal is converted to a plurality of multiple phased clocking signals, each signal being phase shifted from the oscillator clocking signal. The plurality of multiple phased clocking signals is then used to generate the recovered data. Upon initializing the oscillator clocking signal, the oscillator clocking signal is then synchronized to the received communication signal. The oscillator clocking signal is determined if it is in phase with the recovered serialized data and providing a lead signal and a lag signal indicating whether the oscillator clocking signal is in phase with the recovered serialized data. The lead and lag signals are then low pass filtered to develop a frequency adjusting voltage for the voltage controlled oscillator. Those of the plurality of acquired multiple phased data signals that are synchronized to the plurality of multiple phased clocking signals are selected to be transferred to external circuitry for further processing.

[0062] The selecting which of the plurality of acquired multiple phased data signals are synchronized is controlled by a selection source indication signal. The source indication signals selects a mode by which of plurality of acquired multiple phased data signals are selected for to external circuitry for further processing. If the selection source indication signal indicates that the mode is to be a manual mode, a jitter factor of the recovered data is examined and a first grouping of the plurality of acquired multiple phased data signals is selected based on the jitter factor. If the selection source indication signal indicates that the mode is to be a bit error control, a second grouping of the plurality of acquired multiple phased data signals is selected as a function of a bit error rate for further processing. The a bit error rate of the selected plurality of acquired multiple phased data signals is estimated and indicated from the bit error rate transfer signal, whether the bit error rate is greater or lesser than a desired bit error rate.

15 [0063] The plurality of acquired multiple phased data signals are examined to be in synchronization with the reference clock and if not in synchronization connecting the low pass filter to receive the reference clocking signal.

[0064] While this invention has been particularly shown and described with reference to the preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made without departing from the spirit and scope of the invention.

20

CLAIMS

1. A clock and data recovery circuit for recovery of a synchronizing clock and serialized digital data from a received communication signal comprising:
 - a data capture device which receives said communication signal and recovers said serialized digital data;
 - a voltage controlled oscillator in communication with said data capture device to provide an oscillator clocking signal synchronized to said received communication signal;
 - a multiple phase generator in communication with said voltage controlled oscillator to receive and convert said oscillator clocking signal to a plurality of multiple phased clocking signals, each signal being phase shifted from said oscillator clocking signal;
 - a phase detector in communication with the data capture device to receive said recovered serialized data and in communication with said multiple phase generator to acquire said plurality of multiple phased clocking signals, said phase detector determining if said oscillator clocking signal is in phase with said recovered serialized data and providing a lead signal and a lag signal indicating whether said oscillator clocking signal is in phase with said recovered serialized data;

a low pass filter in communication with said phase detector to receive and
low pass filter said lead signal and said lag signal to develop a
frequency adjusting voltage for said voltage controlled oscillator; and
a frequency initializing device connected to receive a reference clock
signal and in communication with said voltage controlled oscillator
employed to assist acquisition of lock of said voltage controlled
oscillator to said reference clock signal during initialization; and
a loop selection device in communication with said frequency initializing
device to receive a frequency increase signal and decrease signal
indicating whether a frequency of said oscillator clocking signal is
greater than or lesser than a frequency of said reference clock signal,
connected to receive a synchronization lost signal, and in
communication with said low pass filter to switch control of said voltage
controlled oscillator from said frequency initializing device after
initialization of said voltage controlled oscillator to said phase detector
for recovery of said serialized digital data and said synchronizing clock;
wherein said data capture device is in communication with said
multiple phase generator to receive said plurality of multiple phased
clocking signals, said data capture device acquiring said serialized
digital data with each of said plurality of multiple phased clocking
signals to create a plurality of acquired multiple phased data signals.

- 1 2. The clock and data recovery circuit of claim 1 further comprising:
- 2 a recovered data selector in communication with said data capture device
- 3 to receive said plurality of acquired multiple phased data signals and in
- 4 communication with said multiple phase generator to receive said
- 5 plurality of multiple phased clocking signals, said recovered data
- 6 selector selecting which of said plurality of acquired multiple phased
- 7 data signals are to be transferred to external circuitry for further
- 8 processing.
- 1 3. The clock and data recovery circuit of claim 2 wherein the recovered data
- 2 selector further comprises:
- 3 at least one mode terminal receiving a selection source indication signal
- 4 for selecting a mode by which of plurality of acquired multiple phased
- 5 data signals are selected for to external circuitry for further processing.
- 1 4. The clock and data recovery circuit of claim 3 wherein if said selection source
- 2 indication signal indicates that said mode is to be a manual mode, a jitter factor
- 3 of said recovered data is examined and a grouping of said plurality of acquired
- 4 multiple phased data signals is selected based on said jitter factor.
- 1 5. The clock and data recovery circuit of claim 3 further comprising:
- 2 a bit error estimator and synchronization detector in communication with
- 3 said recovered data selector to receive said selected plurality of

4 acquired multiple phased data signals, evaluate said selected plurality
5 of acquired multiple phased data signals for a bit error rate, and from
6 said bit error rate transfer a bit error threshold signal to said recovered
7 data selector to indicate whether said bit error rate is greater or lesser
8 than a desired bit error rate.

1 6. The clock and data recovery circuit of claim 5 wherein if said selection source
2 indication signal indicates that said mode is to be a bit error control wherein said
3 bit error threshold signal determines which of said plurality of acquired multiple
4 phased data signals are to be transferred for further processing.

1 7. The clock and data recovery circuit of claim 5 wherein said bit error estimator and
2 synchronization detector determines whether said plurality of acquired multiple
3 phased data signals are in synchronization with said reference clock and is not in
4 synchronization providing said synchronization lost signal to said loop selection
5 device, such that said loop selection device switches said low pass filter to
6 receive said reference signal.

1 8. A communication system for the transmission and reception of a synchronizing
2 clock and serialized digital data over a communication medium comprising:

3 a receiver comprising:

4 a clock and data recovery circuit for recovery of the synchronizing
5 clock and serialized digital data from a received communication
6 signal comprising:

7 a data capture device which receives said communication signal
8 and recovers said serialized digital data;

9 a voltage controlled oscillator in communication with said data
10 capture device to provide an oscillator clocking signal
11 synchronized to said received communication signal;

12 a multiple phase generator in communication with said voltage
13 controlled oscillator to receive and convert said oscillator
14 clocking signal to a plurality of multiple phased clocking
15 signals, each signal being phase shifted from said oscillator
16 clocking signal;

17 a phase detector in communication with the data capture device
18 to receive said recovered serialized data and in
19 communication with said multiple phase generator to acquire
20 said plurality of multiple phased clocking signals, said phase
21 detector determining if said oscillator clocking signal is in
22 phase with said recovered serialized data and providing a
23 lead signal and a lag signal indicating whether said oscillator
24 clocking signal is in phase with said recovered serialized
25 data;

26 a low pass filter in communication with said phase
27 detector/charge pump to receive and low pass filter said lead

28 signal and said lag signal to develop a frequency adjusting
29 voltage for said voltage controlled oscillator

30 a frequency initializing device connected to receive a reference
31 clock signal and in communication with said voltage
32 controlled oscillator employed to assist acquisition of lock of
33 said voltage controlled oscillator to said reference clock
34 signal during initialization; and

35 a loop selection device in communication with said frequency
36 initializing device to receive a frequency increase signal and
37 decrease signal indicating whether a frequency of said
38 oscillator clocking signal is greater than or lesser than a
39 frequency of said reference clock signal, connected to
40 receive a synchronization lost signal, and in communication
41 with said low pass filter to switch control of said voltage
42 controlled oscillator from said frequency initializing device
43 after initialization of said voltage controlled oscillator to said
44 phase detector for recovery of said serialized digital data and
45 said synchronizing clock; wherein said data capture device is
46 in communication with said multiple phase generator to
47 receive said plurality of multiple phased clocking signals,
48 said data capture device acquiring said serialized digital data

to create a plurality of acquired multiple phased data signals.

9. The communication system of claim 8 wherein the clock and data recovery circuit further comprises:

a recovered data selector in communication with said data capture device to receive said plurality of acquired multiple phased data signals and in communication with said multiple phase generator to receive said plurality of multiple phased clocking signals, said recovered data selector selecting which of said plurality of acquired multiple phased data signals are to be transferred to external circuitry for further processing.

10. The communication system of claim 9 wherein the recovered data selector further comprises:

at least one mode terminal receiving a selection source indication signal
for selecting a mode by which of plurality of acquired multiple phased
data signals are selected for to external circuitry for further processing.

11. The communication system of claim 10 wherein if said selection source indication signal indicates that said mode is to be a manual mode, a jitter factor of said recovered data is examined and a grouping of said plurality of acquired multiple phased data signals is selected based on said jitter factor.

- 1 12. The communication system of claim 10 wherein the clock and data recovery
2 circuit further comprises:
- 3 a bit error estimator and synchronization detector in communication with
4 said recovered data selector to receive said selected plurality of
5 acquired multiple phased data signals, evaluate said selected plurality
6 of acquired multiple phased data signals for a bit error rate, and from
7 said bit error rate transfer a bit error threshold signal to said recovered
8 data selector to indicate whether said bit error rate is greater or lesser
9 than a desired bit error rate.
- 1 13. The communication system of claim 12 wherein if said selection source indication
2 signal indicates that said mode is to be a bit error control wherein said bit error
3 threshold signal determines which of said plurality of acquired multiple phased
4 data signals are to be transferred for further processing.
- 1 14. The communication system of claim 12 wherein said bit error estimator and
2 synchronization detector determines whether said plurality of acquired multiple
3 phased data signals are in synchronization with said reference clock and is not in
4 synchronization providing said synchronization lost signal to said loop selection
5 device, such that said loop selection device switches said low pass filter to
6 receive said reference signal.
- 1 15. The communication system of claim 8 wherein said communication system is
2 selected from a group of communication systems consisting of high definition

3 multimedia interface communication systems and digital video data
4 communication systems.

1 16. The communication system of claim 8 wherein the synchronizing clock and
2 serialized digital data are transmitted on a transition minimized differential
3 signaling link.

1 17. A method for recovery of a synchronizing clock and serialized digital data from a
2 received communication signal comprising the steps of:

3 receiving said communication signal;

4 recovering said serialized digital data from said communication signal;

5 synchronizing an oscillator clocking signal to said received communication
6 signal;

7 converting said oscillator clocking signal to a plurality of multiple phased
8 clocking signals, each signal being phase shifted from said oscillator
9 clocking signal;

10 determining if said oscillator clocking signal is in phase with said
11 recovered serialized data and providing a lead signal and a lag signal
12 indicating whether said oscillator clocking signal is in phase with said
13 recovered serialized data;

14 low pass filtering said lead signal and said lag signal to develop a
15 frequency adjusting voltage for said voltage controlled oscillator; and
16 receiving a reference clock signal;
17 initializing said oscillator clocking signal to assist acquisition of lock of said
18 oscillator clocking signal to said reference clock signal during
19 initialization;
20 upon initializing said oscillator clocking signal, locking said oscillator
21 clocking signal to be synchronized to said received communication
22 signal;
23 acquiring said serialized digital data with each of said plurality of multiple
24 phased clocking signals to create a plurality of acquired multiple
25 phased data signals;
26 selecting which of said plurality of acquired multiple phased data signals
27 are synchronized to said plurality of multiple phased clocking signals
28 and are to be transferred to external circuitry for further processing;
29 and
30 receiving a selection source indication signal for selecting a mode by
31 which of plurality of acquired multiple phased data signals are selected
32 for to external circuitry for further processing; wherein if said selection
33 source indication signal indicates that said mode is to be a manual

34 mode, a jitter factor of said recovered data is examined and a first
35 grouping of said plurality of acquired multiple phased data signals is
36 selected based on said jitter factor.

1 18. The method of claim 17 further comprising the steps of:

2 estimating a bit error rate of said selected plurality of acquired multiple
3 phased data signals, and

4 indicating from said bit error rate transfer, whether said bit error rate is
5 greater or lesser than a desired bit error rate.

1 19. The method of claim 18 further comprising the step of:

2 if said selection source indication signal indicates that said mode is to be a
3 bit error control, selecting a second grouping of said plurality of
4 acquired multiple phased data signals as a function of said bit error
5 rate for further processing.

1 20. The method of claim 17 further comprising the steps of:

2 determining whether said plurality of acquired multiple phased data
3 signals are in synchronization with said reference clock; and

4 if not in synchronization connecting said low pass filter to receive said
5 reference signal.

1 21. The method of claim 17 wherein said communication signal is transmitted within
2 a communication system is selected from a group of communication systems consisting
3 of high definition multimedia interface communication systems and digital video data
4 communication systems.

1 22. The method of claim 17 wherein the synchronizing clock and reference clock are
2 transmitted on a transition minimized differential signaling link.