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Apparatus and method for processing receive data in a receive data path including parallel FEC decoding

Abstract

An apparatus comprises a data width converter and a forward error correction (FEC) decoder. The data width converter includes an input to receive an input data stream having an input bit width, a first output to produce a first output data stream having a first output bit width, and a second output to produce a second output data stream having at least a second output bit width. The FEC decoder includes an input to receive the second output data stream having the at least second output bit width. The FEC decoder includes an error correction output to produce one or more error correction values at least partially based on one or more FEC code words in the second output data stream. The one or more error correction values are for correction of one or more symbols, one or more partial symbols, or both, in the first output data stream.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATION (1) This application claims the benefit of the priority date of U.S. Provisional Patent Application No. 63/378,690, filed Oct. 7, 2022, and titled "FEC DECODER IMPLEMENTATION FOR LOW AND CONSTANT LATENCY," the disclosure of which is incorporated herein in its entirety by this reference.

TECHNICAL FIELD
(1) This disclosure relates generally to transceivers, and more particularly to transceiver processing of data for communications including encoding and/or decoding for error correction of data. Additionally, apparatuses and methods are disclosed.
BACKGROUND
(2) Various applications require communications at high data rates over relatively small distances. As one or more examples, automotive in-car systems, certain industrial systems, and smart-home systems would benefit from these types of communications. Several types of protocols and communication media have been proposed and developed for such applications. Innovative, efficient design solutions are often needed to adapt functional components to these developments.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
(1) While this disclosure concludes with claims particularly pointing out and distinctly claiming specific examples, various features and advantages of examples within the scope of this disclosure may be more readily ascertained from the following description when read in conjunction with the accompanying drawings, in which:
(2) FIG. **1** is a schematic block diagram of a transmit physical layer (PHY) of a transmitter that is known by the inventor of this disclosure.
(3) FIG. **2** is a schematic block diagram of a transmit PHY of a transmitter, according to one or more examples of the disclosure.
(4) FIG. **3**A is a flowchart depicting a process to process transmit data in a transmit data path including parallel Forward Error Correction (FEC) encoding, according to one or more examples.
(5) FIG. **3**B is an apparatus to process transmit data in a transmit data path including parallel FEC encoding, according to one or more examples.
(6) FIG. **4** is a table of numbers of transferred data bits per clock cycle associated with operation of a data width converter in the transmit PHY of FIG. **2**, according to one or more examples.
(7) FIG. **5**A is a schematic block diagram of a receive physical layer (PHY) of a receiver that is

known by the inventor of this disclosure.
(8) FIG. **5**B is a schematic block diagram of a FEC decoder of the receive PHY of FIG. **5**A that is known by the inventor of this disclosure.
(9) FIG. **6**A is a schematic block diagram of a receive PHY of a receiver, according to one or more examples of the disclosure.
(10) FIG. **6**B is a block diagram of a circuit portion in the receive PHY of FIG. **6**A, according to one or more examples.
(11) FIG. **6**C is a block diagram of a FEC decoder of FIG. **6**A, according to one or more examples.
(12) FIG. **7**A is a flowchart depicting a process to process receive data in a receive data path including parallel FEC decoding, according to one of more examples.
(13) FIG. **7**B is an apparatus to process receive data in a receive data path including parallel FEC decoding, according to one or more examples.
(14) FIG. **8** is a table of numbers of transferred data bits per clock cycle associated with operation of a data width converter in the receive PHY of FIGS. **6**A-**6**C, according to one or more examples.
(15) FIG. **9** is a look-up table (LUT) for a latency predictor associated with the receive PHY, according to one or more examples.
(16) FIG. **10** is a syndrome calculator associated with the FEC decoder of the receive PHY of FIGS. **6**A-**6**C, according to one or more examples.
(17) FIG. **11** is an example of an error locator polynomial (ELP) algorithm of an error locator associated with the FEC decoder of the receive PHY, according to one or more examples.
(18) FIG. **12** is a timing diagram of communication processing associated with the receive data path having an integrated FEC decoding approach.
(19) FIG. **13** is a timing diagram of communication processing associated with the receive data path having a parallel FEC decoding approach.
(20) FIGS. **14**A and **14**B are timing diagram portions of a timing diagram of communication processing associated with usage of a first clock rate for the receive data path and a second clock rate (i.e., a higher clock rate) for the ELP algorithm.
(21) FIGS. **15**A and **15**B are timing diagram portions of a timing diagram of communication processing associated with the variable symbol syndrome calculation.
(22) FIG. **16** is a block diagram of circuitry that, in some examples, may be used to implement various functions, operations, acts, processes, and/or methods disclosed herein.

DETAILED DESCRIPTION

(23) In the following detailed description, reference is made to the accompanying drawings, which form a part hereof, and in which are shown, by way of illustration, specific examples in which the present disclosure may be practiced. These examples are described in sufficient detail to enable a person of ordinary skill in the art to practice the present disclosure. However, other examples enabled herein may be utilized, and structural, material, and process changes may be made without departing from the scope of the disclosure.
(24) The illustrations presented herein are not meant to be actual views of any particular method, system, device, or structure, but are merely idealized representations that are employed to describe the examples of the present disclosure. In some instances, similar structures or components in the various drawings may retain the same or similar numbering for the convenience of the reader; however, the similarity in numbering does not necessarily mean that the structures or components are identical in size, composition, configuration, or any other property.
(25) The following description may include examples to help enable one of ordinary skill in the art to practice the disclosed examples. The use of the terms “exemplary,” “by example,” and “for example,” means that the related description is explanatory, and though the scope of the disclosure is intended to encompass the examples and legal equivalents, the use of such terms is not intended to limit the scope of an examples or this disclosure to the specified components, steps, features, functions, or the like.

(26) It will be readily understood that the components of the examples as generally described herein and illustrated in the drawings could be arranged and designed in a wide variety of different configurations. Thus, the following description of various examples is not intended to limit the scope of the present disclosure, but is merely representative of various examples. While the various aspects of the examples may be presented in the drawings, the drawings are not necessarily drawn to scale unless specifically indicated.
(27) Furthermore, specific implementations shown and described are only examples and should not be construed as the only way to implement the present disclosure unless specified otherwise herein. Elements, circuits, and functions may be shown in block diagram form in order not to obscure the present disclosure in unnecessary detail. Conversely, specific implementations shown and described are exemplary only and should not be construed as the only way to implement the present disclosure unless specified otherwise herein. Additionally, block definitions and partitioning of logic between various blocks is exemplary of a specific implementation. It will be readily apparent to one of ordinary skill in the art that the present disclosure may be practiced by numerous other partitioning solutions. For the most part, details concerning timing considerations and the like have been omitted where such details are not necessary to obtain a complete understanding of the present disclosure and are within the abilities of persons of ordinary skill in the relevant art.
(28) Those of ordinary skill in the art will understand that information and signals may be represented using any of a variety of different technologies and techniques. Some drawings may illustrate signals as a single signal for clarity of presentation and description. It will be understood by a person of ordinary skill in the art that the signal may represent a bus of signals, wherein the bus may have a variety of bit widths and the present disclosure may be implemented on any number of data signals including a single data signal.
(29) The various illustrative logical blocks, modules, and circuits described in connection with the examples disclosed herein may be implemented or performed with a general purpose processor, a special purpose processor, a digital signal processor (DSP), an Integrated Circuit (IC), an Application Specific Integrated Circuit (ASIC), a Field Programmable Gate Array (FPGA) or other programmable logic device, discrete gate or transistor logic, discrete hardware components, or any combination thereof designed to perform the functions described herein. A general-purpose processor (may also be referred to herein as a host processor or simply a host) may be a microprocessor, but in the alternative, the processor may be any conventional processor, controller, microcontroller, or state machine. A processor may also be implemented as a combination of computing devices, such as a combination of a DSP and a microprocessor, a plurality of microprocessors, one or more microprocessors in conjunction with a DSP core, or any other such configuration. A general-purpose computer including a processor is considered a special-purpose computer while the general-purpose computer is to execute computing instructions (e.g., software code) related to examples of the present disclosure.
(30) The examples may be described in terms of a process that is depicted as a flowchart, a flow diagram, a structure diagram, or a block diagram. Although a flowchart may describe operational acts as a sequential process, many of these acts can be performed in another sequence, in parallel, or substantially concurrently. In addition, the order of the acts may be re-arranged. A process may correspond to a method, a thread, a function, a procedure, a subroutine, a subprogram, other structure, or combinations thereof. Furthermore, the methods disclosed herein may be implemented in hardware, software, or both. If implemented in software, the functions may be stored or transmitted as one or more instructions or code on computer-readable media. Computer-readable media includes both computer storage media and communication media including any medium that facilitates transfer of a computer program from one place to another.
(31) Any reference to an element herein using a designation such as “first,” “second,” and so forth does not limit the quantity or order of those elements, unless such limitation is explicitly stated. Rather, these designations may be used herein as a convenient method of distinguishing between

two or more elements or instances of an element. Thus, a reference to first and second elements does not mean that only two elements may be employed there or that the first element must precede the second element in some manner. In addition, unless stated otherwise, a set of elements may include one or more elements.

(32) As used herein, the term “substantially” in reference to a given parameter, property, or condition means and includes to a degree that one of ordinary skill in the art would understand that the given parameter, property, or condition is met with a small degree of variance, such as, for example, within acceptable manufacturing tolerances. By way of example, depending on the particular parameter, property, or condition that is substantially met, the parameter, property, or condition may be at least 90% met, at least 95% met, or even at least 99% met.

(33) In a traditional approach to the design of an Ethernet physical layer (PHY) transceiver, if a Forward Error Correction (FEC) block is integrated or in-line with the data path, then a majority of the data path operates on integer multiples of the FEC symbol width. However, the outgoing data width is generally not an integer multiple of the FEC symbol width, and therefore one or more additional data width converters (e.g., gearboxes) and read-pause mechanisms may be employed. For Institute of Electrical and Electronics Engineers (IEEE) 802.3ch, 2.5GT1 Automotive Ethernet PHY, for example, the FEC symbol width is ten (10) bits, the data path width may be either seventy (70) bits or eighty (80) bits, and the outgoing data width is sixty-five (65) bits.

(34) Such an approach introduces latency in the communication of Ethernet packets. This latency is a data-dependent latency that may change from one packet to the next, and therefore is a variable latency. The Ethernet packets are timestamped for time synchronization in the network according to IEEE 1588. A packet's timestamp point (a timestamp point is also sometimes referred to as a “reference plane”) is set to be the edge of a device, typically a point that corresponds to the Media Dependent Interface (MDI). Following a packet at the edge of a device may be challenging, so IEEE 802.3 specifies that a first timestamp is generated when a packet crosses the Media Independent interface (MII) and then adjusted by an amount that represents the path data delay to calculate a second, final timestamp corresponding to the MDI reference plane.

(35) For proper timestamping, there should be a guaranteed fixed latency in the PHY, or alternatively, the provision of a predictor logic for calculating the amount of variable latency incurred per packet for adjustment of timing discussed above. For example, a three (3) clock adjustment may be made for a first packet, a ten (10) clock adjustment may be made for a second packet, and so on.

(36) Predictor logic tends to be relatively complex, as it has to estimate the delay of the packet by accurately predicting the start of the Ethernet packet that is transferred through, e.g., two (2) data width converters and the FEC block. Such complex predictor logic is made even more complex when modules are configured to pause the data path. Further, it is often desirable to reduce the overall latency of the packets in the PHY, e.g., for compliance with time-sensitive networking (TSN) standards and real-time communication, without limitation.

(37) Thus, in the traditional approach, multiple data width converters may be utilized. In some implementations of the traditional approach, certain modules may pause communications. This pausing introduces latency, which may further complicate the predictor logic. In a transmit data path, the latency of a frame is at least partially determined by the number of data width converters and the FEC block. Thus, the traditional approach includes multiple sources of variable latency. In a receive data path, the latency of a frame is at least partially determined by the depth of the first-in-first-out (FIFO) buffer, which in turn is determined by the time it takes the FEC decoder to correct the frame. The time it takes the FEC decoder to correct a frame is dominated by an error locator polynomial (ELP) algorithm of an error locator. Further, the FIFO buffer width used in the FEC decoder should align with the FEC symbol width, which results in using several unwanted flops, even though only a single FEC frame must be stored.

(38) One or more examples relate, generally, to reducing latency and variation of latency. One or

more examples relate to a transmitter portion of a PHY transceiver capable of reducing latency and variation of latency. In one or more examples, the transmitter portion is capable of reducing the latency and latency variation for compliance with TSN and IEEE 1588. In one or more examples, the transmitter portion includes a latency predictor to determine a latency value that may be utilized to represent a predicted latency. In one or more examples, the latency predictor may be or include a look up table (LUT). In one or more examples, the transmitter portion has a relatively reduced area compared to the traditional approach.
(39) In one or more examples, the transmitter portion includes a FEC encoder in parallel with the transmit data path. In one or more examples, the FEC encoder is operative, at least in substantial part, separately and independently from the transmit data path. In one or more examples, the FEC encoder is operative on a symbol width ("symbol width" is data width in terms of number of symbols) that is different from a symbol width associated with the data path. In one or more examples, the number of data width converters in the transmit data path is one (1) data width converter, which reduces the latency incurred in the transmit data path otherwise caused by additional data width converters. In one or more examples, the transmit data path provides a guaranteed fixed latency in (e.g., most or all, without limitation) modules of the transmitter portion of the PHY transceiver, apart from the (e.g., single, without limitation) data width converter.
(40) One or more examples relate to a receiver portion of a PHY transceiver capable of reducing latency and variation of latency. In one or more examples, the receiver portion is capable of reducing the latency and latency variation for compliance with TSN and IEEE 1588. In one or more examples, the receiver portion includes a latency predictor to determine the latency. In one or more examples, the latency predictor may be or include a look up table (LUT). In one or more examples, the receiver portion of the PHY transceiver has a relatively reduced area as compared to the traditional approach.
(41) In one or more examples, the receiver portion includes a FEC decoder in parallel with the receive data path. In one or more examples, the FEC decoder is operative, at least in substantial part, separately and independently from the receive data path. In one or more examples, the FEC encoder is operative on a symbol width that is different from a symbol width associated with the receive data path. In one or more examples, the number of data width converters in the receiver data path is one (1) data width converter. In one or more examples, the receive data path provides a guaranteed fixed latency in (e.g., most or all, without limitation) modules of the receiver portion of the PHY transceiver apart from the (e.g., single, without limitation) data width converter.
(42) In one or more examples, parallel FEC decoder processing may include a symbol error corrector to correct partial symbols and an error magnitude generator to select the number of bits of error magnitude to provide to the symbol error corrector. Further, in one or more examples, a syndrome calculator of the parallel FEC decoder may be one that operates on a variable number of symbols (e.g., seven (7) or eight (8) FEC symbols per clock). Further, in one or more examples, an ELP algorithm of the FEC decoder may be set to execute at a different (e.g., higher, without limitation) clock rate than the clock rate of the receive data path.
(43) FIG. **1** shows a schematic block diagram of a transmit physical layer (PHY) of a transmitter (referred to herein as a "transmitter portion **100**") that is known by the inventor of this disclosure. The transmitter portion **100** may be at least part of an Ethernet physical layer transceiver (Ethernet PHY) for transmitting data or Ethernet frames. For example, transmitter portion **100** may be compliant with the Institute of Electrical and Electronics Engineers (IEEE) 802.3ch, 2.5GT1 Automotive Ethernet PHY, and more specifically, the "IEEE Standard for Ethernet—Amendment 8: Physical Layer Specifications and Management Parameters for 2.5 Gb/s, 5 Gb/s, and 10 Gb/s Automotive Electrical Ethernet," IEEE 802.3ch-2020, June 2020, for accommodation of the next evolution of in-vehicle networks.
(44) Transmitter portion **100** comprises (from left to right in the figure) a media access control (MAC) interface (I/F) (MAC I/F) **102**, timestamp circuitry **104**, a physical coding sublayer (PCS)

encoder **106**, a data width converter **108** (which may also be referred to herein as a "gearbox **108**"), an FEC encoder **110**, a data width converter **112** (which may also be referred to herein as a "gearbox **112**"), a scrambler **114**, a precoder and mapper **116**, and a transmitter multiplexer (MUX) **118**. Scrambler **114** may include an output **158** to a training top module **120**, which is coupled to transmit MUX **118** for training path selection.

(45) As depicted in FIG. **1**, many of the modules of transmitter portion **100** are in-line (e.g., arranged serially, sequentially, or both without limitation) with a transmit data path **101** for the communication of data from a link layer to a transmission medium (e.g., a shared transmission medium such as a twisted pair, without limitation). In particular, FEC encoder **110** is integrated or in-line with transmit data path **101**. FEC encoder **110** operates (e.g., processes symbols, without limitation) on an FEC symbol width. The FEC symbol width of FEC encoder **110** is ten (10) bits.

(46) Most of transmit data path **101** operates on integer multiples of the FEC symbol width. However, the subsequently-desired or outgoing data width (e.g., seventy-two (72) bits) is not an integer multiple of the FEC symbol width. As the outgoing data width is not an integer multiple of the FEC symbol width, one or more additional data width converters and read-pause mechanisms are employed. For example, transmit data path **101** includes (e.g., the additional) data width converter **112**, and FEC encoder **110** may produce a "read pause" to data width converter **108** via an output **132** when needed.

(47) As shown in FIG. **1**, data width converter **108** includes an input to receive a data stream **150** at a first bit width and an output to produce a data stream **152** at a second bit width. FEC encoder **110** includes an input to receive the data stream **152** at the second bit width and an output to produce a data stream **154** at the (same) second bit width. Data width converter **112** includes an input to receive data stream **154** at the second bit width and an output to produce a data stream **156** at a third bit width.

(48) In support of 2.5GT1, the FEC symbol width is ten (10) bits, the first bit width of data stream **150** is sixty-five (65) bits (e.g., @25.6 ns), the second bit width of data streams **152** and **154** (e.g., to and from FEC encoder **110**, respectively) is seventy (70) bits (e.g., @25.6 ns), and the third bit width of data stream **156** is seventy-two (72) bits (e.g., @25.6 ns).

(49) Prior to processing by FEC encoder **110**, Ethernet packets may be timestamped by timestamp circuitry **104** (named "TS **1588 104**" in FIG. **1**). Timestamping of the Ethernet packets provides for time synchronization in the network for compliance with IEEE 1588 (e.g., Precision Time Protocol (PTP), without limitation). More specifically, timestamp circuitry **104** receives and timestamps Ethernet packets from MAC I/F **102** in a data stream having a bit width of sixty-four (64) bits, according to 10 Gigabit Media Independent Interface (XGMII). XGMII is an interface for high-speed serial data systems for communication between the reconciliation sublayer (RS) and the PCS for 10 Gigabits per second (Gbps) operation.

(50) The modules and arrangement of the modules in transmitter portion **100** introduce latency in the communication of Ethernet packets. This latency is a variable latency that changes from one packet to the next. For compliance with time-sensitive networking (TSN) standards and real-time Ethernet communications, it is desirable to reduce the overall latency of the packets in the PHY. For proper timestamping by timestamp circuitry **104**, there should be a guaranteed fixed latency in the PHY, or alternatively, the provision of a predictor logic for calculating an amount of variable latency incurred per packet to properly adjust the timing.

(51) Transmitter portion **100** includes a latency predictor **122** having an output **130** operably coupled to timestamp circuitry **104** for timing adjustment. However, latency predictor **122** includes complex predictor logic ("1588 predictor logic") to produce, at an output **130**, a predicted variable latency based on multiple sources of variable latency as indicated in the figure. In general, the latency in transmit data path **101** is determined by the number of gearboxes and the FEC block. Latency predictor **122** has relatively complex logic to estimate the delay of the Ethernet packet by determining a start of the packet transferred through the two (2) data width converters **108** and **112**

and FEC encoder **110**. Latency predictor **122** is made even more complex when FEC encoder **110** pauses transmit data path **101** at data width converter **108** via output **132**.

(52) FIG. **2** is a schematic block diagram of a transmit physical layer (PHY) of a transmitter (referred to herein as a "transmitter portion **200**"), according to one or more examples of the disclosure. In one or more examples, transmitter portion **200** may be at least part of an Ethernet physical layer transceiver (Ethernet PHY) for transmitting data (e.g., one or more symbols, without limitation), e.g., of Ethernet frames (e.g., an Ethernet frame is transmitted as a series of symbols on a physical layer, without limitation). In a specific, non-limiting example, transmitter portion **200** is compliant with the IEEE 802.3ch, 2.5GT1 Automotive Ethernet PHY, as described earlier above.

(53) Transmitter portion **200** may include a transmit data path **201** for the communication of data from a link layer to a transmission medium. Transmitter portion **200** comprises (from left to right in the figure) a MAC I/F **202**, timestamp circuit **204**, a PCS encoder **206**, a data width converter **208** (or "gearbox"), an FEC encoder **212**, a scrambler **214**, a precoder and mapper **216**, and a transmit MUX **218**. Precoder and mapper **216** produces pulse-amplitude modulated (PAM) (e.g., 2-level) (PAM-2) signals based on the received data stream. For training, scrambler **214** includes an output to a training top module **222** which is coupled to a selectable input of transmit MUX **218** (a selectable input for selection of a training path). A control signal **220** ("PHY control **220**") from a PHY controller (controller not depicted) is input to transmit MUX **218** for data or training path selection.

(54) As depicted in FIG. **2**, data width converter **208** is in transmit data path **201**, and FEC encoder **212** is in parallel with transmit data path **201**. As an illustrative example, FEC encoder **212** may be arranged in a parallel path **203** that is in parallel with at least a portion of transmit data path **201** and/or data width converter **208**. FEC encoder **212** may operate, at least in substantial part, separately and independently from transmit data path **201**. Given the arrangement, transmit data path **201** provides for a fixed latency in data conveyance.

(55) In one or more examples, transmit data path **201** includes (e.g., only) a single data width converter (i.e., data width converter **208**). Although "single" in transmit data path **201**, data width converter **208** may be made of two or more separate data width converter circuits to produce the two respective output data streams (first and second output data streams **252** and **256**), or alternatively, utilize shared circuitry to produce the different streams.

(56) More specifically as shown in FIG. **2**, an input of data width converter **208** is at least partially responsive to an output of PCS encoder **206**. Data width converter **208** includes an input to receive an input data stream **250** (e.g., input data stream **250** is at least partially based on an output of PCS encoder **206**) at an input bit width, a first output to produce a first output data stream **252** at a first output bit width, and a second output to produce a second output data stream **256** at a second output bit width. In one or more examples, the input bit width, the first output bit width, and the second output bit width are different from each other.

(57) Scrambler **214** includes an input to receive the first output data stream **252** at the first output bit, and includes an output to produce a scrambled output data stream **254** at least partially based on first output data stream **252**. Scrambled output data stream **254** is provided for subsequent processing by precoder and mapper **216** and transmit MUX **218** for transmission. FEC encoder **212** includes an input to receive the second output data stream **256** at the second output bit width, and includes an output to produce parity bits **258** at least partially based on multiple received symbols of the second output data stream **256**. The parity bits **258** are for insertion in the first output data stream **252** having the first output bit width. The first output data stream **252** received at the input of scrambler **214** includes the inserted parity bits from the parity bits **258** produced by FEC encoder **212**.

(58) More particularly, the output of FEC encoder **212** produces parity bits **258** for respective ones of the multiple received symbols of the second output data stream **256**, for insertion at respective intervals of the first output data stream **252**. A parity insertion circuit **210** may insert the parity bits

258. In one or more examples, parity insertion circuit **210** may be part of data width converter **208** or separate therefrom (e.g., an input of parity insertion circuit **210** may receive an output of data width converter **208**, insert respective parity bits **258** in the received output of data width converter **208**, and produce the second output data stream **256** including respective parity bits, without limitation). In one or more examples, parity insertion circuit **210** inserts the generated parity bits at the respective intervals of the first output data stream **252**.

(59) The output of FEC encoder **212** produces the parity bits **258** based on the multiple received symbols (e.g., k symbols, where k=360) received over a number of clock cycles, where respective ones of the k symbols have a symbol width of s bits (e.g., s=10 bits). Thus, in one or more examples, FEC encoder **212** operates on a symbol width that is different from the requirements of transmit data path **201**, and keeps its generated parity bits ready for insertion before the next FEC frame starts. In one or more examples, the second output bit width of second output data stream **256** is an integer multiple of the symbol width of FEC encoder **212**. In one or more examples, the input bit width of input data stream **250** is not an integer multiple of the symbol width, and/or the first output bit width of first output data stream **252** is not an integer multiple of the symbol width.

(60) In one or more examples, little to no latency is incurred by FEC encoder **212** arranged in parallel path **203**. In one or more examples, the modules and the arrangement of modules in transmitter portion **200** reduce the latency in the communication of Ethernet packets (e.g., by one (1) clock), and/or reduce or eliminate the variability of the latency in transmit data path **201**.

(61) In one or more examples, transmitter portion **200** of the PHY transceiver is configured in accordance with IEEE 802.3ch 2.5GT1. For compliance with 2.5GT1, the symbol width is ten (10) bits, the input bit width of input data stream **250** is sixty-five (65) bits (e.g., @25.6 ns), the first output bit width of first output data stream **252** (e.g., to scrambler **214**) is seventy-two (72) bits (e.g., @25.6 ns), and the second output bit width of second output data stream **256** (e.g., to FEC encoder **212**) is seventy (70) bits (e.g., @25.6 ns). Scrambler **214** outputs the scrambled output data stream **254** also at the first output bit width of seventy-two (72) bits (e.g., @25.6 ns). Each IEEE 802.3ch FEC frame runs for fifty (50) clocks.

(62) In one or more examples, FEC encoder **212** is a Reed-Solomon (RS) FEC encoder utilizing an RS code (e.g., parity bits are an RS code, without limitation). In one or more examples, FEC encoder **212** utilizes an RS code of RS(360,326). In one or more examples, an RS code may be represented by RS(n, k), where n=the total number of symbols in the FEC code word, k=the number of data symbols for data, and (n-k)=the number of parity symbols for parity.

(63) In one or more other examples, transmitter portion **200** is configured in accordance with one or more different standards, bit rates, bit widths, speeds, and/or codes.

(64) In one or more examples, FEC encoder **212** may be a distributed symbol processing FEC encoder, for example, an FEC encoder that operates on a variable number of symbols from one clock (e.g., one or more first clocks) to the next (e.g., one or more second clocks), for matching the incoming data rate. As one example, FEC encoder **212** may operate on seven (7) symbols for one or more first clocks, followed by eight (8) symbols for one or more second clocks. As one example, FEC encoder **212** may operate on six (6) symbols for one or more first clocks, followed by seven (7) symbols for one or more second clocks.

(65) In one or more examples, data width converter **208** may pause FEC encoder **212** (e.g., regularly or periodically), if and as desired or needed, without introducing any variable latency in transmit data path **201**. For example, data width converter **208** may pause FEC encoder **212** once every five (5) or six (6) cycles (e.g., for 2.5GT1). In the traditional approach (i.e., using the integrated FEC encoder in FIG. **1**), any pausing toward the FEC encoder would halt the conveyance of the data downstream, or would not provide sufficient bandwidth for insertion of the parity bits.

(66) Timestamp circuit **204** is in transmit data path **201** to timestamp data stream communications (e.g., per TSN, IEEE 1588 (PTP)). More specifically, timestamp circuit **204** receives and

timestamps Ethernet packets from MAC I/F **202** in a data stream having a bit width of sixty-four (64) bits, according to XGMII. For any latency adjustments, a latency predictor **224** is operably coupled to data width converter **208**, and timestamp circuit **204** is operably coupled to latency predictor **224**. In addition, in one or more examples, latency predictor **224** receives a start of packet (SOP) indication at an output **262** of PCS encoder **206**. Latency predictor **224** selects a latency value responsive to a clock count value provided at an output **260** of data width converter **208**. In one or more examples, latency predictor **224** comprises a look-up table (LUT) of latency values respectively associated with clock count values.

(67) Timestamp circuit **204** receives a latency value **264** (named “predicted latency value **264**” in FIG. **2**) from latency predictor **224**, and adjusts a timing of timestamp circuit **204** at least partially based on the latency value **264**. In one or more examples, the latency values in the look-up table are fixed latency values or predetermined latency values that depend on the (e.g., current, relative) clock count. The current, relative clock count may be relative to a repeating cycle of clock counts, for example, a repeating cycle of 1 to 50 clock counts, or other clock count range. A specific, non-limiting example of such a look-up table for the latency predictor associated with the receiver portion of the PHY transceiver is shown and described later in relation to FIG. **9**.

(68) With reference to the specific, non-limiting example of FIG. **4**, a table **400** of numbers of transferred data bits per clock cycle associated with operation of data width converter **208** of FIG. **2** is shown. The numbers of transferred data bits per clock cycle include the numbers of transferred data bits from the data width converter to the scrambler (“converter-to-scrambler”), and the numbers of transferred data bits from the data width converter to the FEC encoder (“converter-to-FEC-encoder”). The converter-to-scrambler column in table **400** is associated with first output data stream **252** having the first output bit width (FIG. **2**) (e.g., seventy-two (72) bits); and the converter-to-FEC-encoder column in table **400** is associated with second output data stream **256** having the second output bit width (FIG. **2**) (e.g., seventy (70) bits or seven (7) symbols).

(69) The values in the “clock count” column respectively indicate a current clock count associated with a repeating cycle of clock counts, for example, a repeating cycle of 1 to 50 clock counts, or other clock count range. Here, the FEC encoder receives seven (7) symbols per clock cycle at a symbol width of ten (10) bits, for a total of seventy (70) bits per clock cycle. Using the RS code of RS(360, 326), the FEC encoder operates to produce three-hundred and forty (340) parity bits (or thirty-four (34) parity symbols at a 10-bit symbol width) per fifty (50) clock cycles, based on 3260 data bits or 326 10-bit data symbols (i.e., 70 data bits×46 clock cycles+40 data bits×1 clock cycle=3260 data bits or 326 10-bit data symbols). The indication of “P” in the converter-to-FEC-encoder column indicates the insertion of the generated parity bits of the (e.g., first) FEC frame and/or FEC code word. In the clock count cycle that precedes the parity bit insertion of “P,” the FEC encoder receives only forty (40) bits or four (4) symbols. The indication of “Second FEC Frame starts” in the converter-to-scrambler column indicates the start of the next (e.g., second) FEC frame.

(70) FIG. **3**A is a flowchart depicting a process **300** to process transmit data in a transmit data path including parallel FEC encoding, according to one or more examples.

(71) In one or more examples, process **300** may include converting an input data stream having an input bit width to a first output data stream having a first output bit width and to a second output data stream having a second output bit width, in an act **302**. In one or more examples, the input bit width, the first output bit width, and the second output bit width are different from each other. In one or more examples, act **302** may include multiple acts of conversion.

(72) In one or more examples, process **300** may include performing FEC encoding on multiple received symbols of the second output data stream having the second output bit width for generating parity bits, in an act **304**.

(73) In one or more examples, process **300** may include inserting the generated parity bits in the first output data stream, in an act **306**. In one or more examples, process **300** may include

generating parity bits for respective ones of the multiple received symbols of the second output data stream for insertion at respective intervals of the first output data stream.

(74) In one or more examples, converting (e.g., in act **302**) the input data stream having the input bit width to the first output data stream having the first output bit width is performed in a transmit data path, and performing (e.g., in act **304**) at least part of the FEC encoding is performed in parallel with the transmit data path. In one or more examples, the transmit data path provides a fixed latency in communications of the first output data stream.

(75) In one or more examples, the input data stream having the input bit width may be received from a PCS encoder. In one or more examples, the first output data stream having the first output bit width may include the inserted parity bits, and may subsequently be scrambled (e.g., by a scrambler, without limitation).

(76) In one or more examples, performing (e.g., in act **304**) the FEC encoding may involve performing the FEC encoding on the multiple received symbols comprising k symbols (e.g., received over multiple clock cycles), where respective ones of the k symbols comprising a symbol width of s bits. Here, ‘k’ is an integer greater than or equal to 1. In one or more examples, the second output bit width is a multiple of the symbol width of s bits. In one or more examples, the symbol width is ten (10) bits. In one or more examples, the input bit width is sixty-five (65) bits, the first output bit width is seventy-two (72) bits, and the second output bit width is seventy (70) bits.

(77) In one or more examples, process **300** may include signaling a latency predictor with a clock count value. The latency predictor includes a look-up table of latency values respectively associated with clock count values. In one or more examples, process **300** may include adjusting a timing of a timestamping process for timestamping of data stream communications at least partially based on a latency value received from the latency predictor, where the latency value is responsive to the clock count value.

(78) FIG. **3**B is an apparatus **350** to process transmit data in a transmit data path including parallel FEC encoding, according to one or more examples. In one or more examples, apparatus **350** includes a data width converter **352** and an FEC encoder **354**. In one or more examples, data width converter **352** is in a transmit data path **380**, and FEC encoder is in parallel with transmit data path **380** (e.g., in a parallel path **382**).

(79) Data width converter **352** includes an input to receive an input data stream **360** at an input bit width, a first output to produce a first output data stream **362** at a first output bit width, and a second output to produce a second output data stream **364** at a second output bit width. FEC encoder **354** includes an input to receive the second output data stream **364** at the second output bit width. FEC encoder **354** includes an output **366** to produce parity bits at least partially based on multiple received symbols of the second output data stream **364** having the second output bit width. The parity bits are for insertion in the first output data stream **362** having the first output bit width.

(80) FIG. **5**A is a schematic block diagram of a receive physical layer (PHY) of a receiver **500**A (referred to herein as a “receiver portion **500**A”) that is known by the inventor of this disclosure. The receiver portion **500**A may be at least part of an Ethernet physical layer transceiver (Ethernet PHY) for receiving data or Ethernet frames. For example, receiver portion **500**A may be compliant with IEEE 802.3ch, 2.5GT1 Automotive Ethernet PHY, and more specifically, the “IEEE Standard for Ethernet—Amendment 8: Physical Layer Specifications and Management Parameters for 2.5 Gb/s, 5 Gb/s, and 10 Gb/s Automotive Electrical Ethernet,” IEEE 802.3ch-2020, June 2020, for accommodation of the next evolution of in-vehicle networks.

(81) Receiver portion **500**A comprises (from right to left in the figure) a receiver MUX **504**, a symbol decoder **506**, a data width converter **510** (“gearbox **510**”), an FEC decoder **512**, a data width converter **514** (“gearbox **514**”), a PCS decoder **516**, timestamp circuitry **518**, and MAC I/F **520**. From receiver MUX **504**, pulse-amplitude modulated (PAM) (e.g., 4-level) (PAM-4) signals (per clock) are received for processing (e.g., via symbol decoder **506** which is a PAM-symbol

decoder). A training top module **508** is coupled to receive the signals from receiver MUX **504**, for training of the scrambling/descrambling. A PHY controller **502** is input to receiver MUX **504** for data or training path selection.

(82) As depicted in FIG. **5**A, many of the modules of receiver portion **500**A are in-line with a receive data path **501** for processing the incoming data stream from the transmission medium to a link layer for further processing. In particular, FEC decoder **512** is integrated or in-line with receive data path **501**. Note that FEC decoder **512** operates on an FEC symbol width. In one or more examples, the FEC symbol width is ten (10) bits.

(83) Given the above, most of receive data path **501** operates on integer multiples of the symbol width. However, the subsequently-desired data width (e.g., sixty-five (65) bits) is not an integer multiple of the symbol width. As the subsequently-desired data width is not an integer multiple of the symbol width, one or more additional data width converters and read-pause mechanisms may be employed. For example, receive data path **501** may include (the additional) data width converter **514**. Data width converter **514** may further produce a "pause search" signal to FEC decoder **512** at an output **532** when needed. For example, data width converter **514** may produce a pause search signal to pause searching every 9/10/18 clocks, without limitation.

(84) More specifically, data width converter **510** includes an input to receive a data stream **550** at a first bit width and an output to produce a data stream **552** at a second bit width. FEC decoder **512** includes an input to receive the data stream **552** at the second bit width and an output to produce a data stream **554** at the (same) second bit width or an alternative second bit width. Data width converter **514** includes an input to receive data stream **554** at the second bit width (or the alternative second bit width) and an output to produce a data stream **556** at a third bit width.

(85) In support of 2.5GT1, the FEC symbol width is ten (10) bits, the first bit width of data stream **550** is seventy-two (72) bits (e.g., @25.6 ns), the second bit width of data stream **552** is eighty (80) bits (e.g., @25.6 ns), the second bit width of data stream **554** is eighty (80) bits (e.g., @25.6 ns) (or the alternative second bit width of seventy (70) bits), and the third bit width of data stream **556** is sixty-five (65) bits (e.g., @25.6 ns).

(86) In FIG. **5**B, a schematic block diagram of FEC decoder **512** of FIG. **5**A is shown. FEC decoder **512** of FIG. **5**B includes a syndrome calculator **560**, an error locator **562** (e.g., using an error locator polynomial (ELP) algorithm), a Chein search module **564**, a synchronous first-in-first-out (FIFO) **566**, and an error corrector **568**, arranged as shown. An output of syndrome calculator **560** is provided to an input of error locator **562**. In one or more examples, error locator **562** runs for thirty-four (34) clocks (e.g., @25.6 ns). Another output **570** from syndrome calculator **560** is provided to synchronous FIFO **566** for communication of the data stream. Chein search module **564** produces correction values at an output **572** to error corrector **568** for the correction of symbols in the data stream. In one or more examples, Chein search module **564** produces an error location in one (1) clock. Chein search module **564** is to produce read enable signals with pauses to synchronous FIFO **566**.

(87) With reference back to FIG. **5**A, Ethernet packets may be timestamped by timestamp circuitry **518**. Timestamping of the Ethernet packets provides for time synchronization in the network for compliance with IEEE 1588 (e.g., PTP, without limitation). More specifically, timestamp circuitry **518** receives and timestamps Ethernet packets in the data stream **556** (e.g., from PCS decoder **516**) having the bit width of sixty-five (65) bits.

(88) Although timestamping is desired, the modules and arrangement of the modules in receiver portion **500**A introduce latency in the communication of Ethernet packets. This latency is a variable latency that changes from one packet to the next. For compliance with TSN standards and real-time Ethernet communications, it is desirable to reduce the overall latency of the packets in the PHY. For proper timestamping by timestamp circuitry **518**, there should be a guaranteed fixed latency in the PHY, or alternatively, the provision of a predictor logic for calculating the amount of variable latency incurred per packet to properly adjust the timing.

(89) Accordingly, receiver portion **500**A includes a latency predictor **522** having an output **534** operably coupled to timestamp circuitry **518** for timing adjustment. However, latency predictor **522** includes complex predictor logic ("1588 predictor logic") to produce, at output **534**, a predicted variable latency based on multiple sources of variable latency, as indicated in the figure.
(90) The latency of the frame in receive data path **501** may be determined by the depth of synchronous FIFO **566** (FIG. **5**B). In turn, the FIFO depth is determined by the time it takes FEC decoder **512** to correct the frame, which is dominated by the ELP algorithm of error locator **562** (FIG. **5**B). The ELP algorithm may execute according to a number of clocks "P" serially (e.g., where P=number of FEC parity symbols). Given the varying FIFO depth, it is difficult to predict the latency when the start of frame (SOF) is written into synchronous FIFO **566**. It is also difficult to keep track of the SOF given the different conversions of the gearboxes.
(91) Even further, the area of receive data path **501** is increased due to the flops that are utilized to align the path with the FEC symbol width. The width of synchronous FIFO **566** should be aligned to the FEC symbol width, even though most of the locations in the FIFO do not need such a large width. Syndrome calculator **560** on the FEC symbol width, so flops are used for data accumulation.
(92) FIG. **6**A is a schematic block diagram of a receive physical layer (PHY) of a receiver (referred to herein as a receiver portion **600**A) according to one or more examples of the disclosure. In one or more examples, receiver portion **600**A may be at least part of an Ethernet physical layer transceiver (Ethernet PHY) for receiving data or Ethernet frames. In a specific, non-limiting example, receiver portion **600**A is compliant with the IEEE 802.3ch, 2.5GT1 Automotive Ethernet PHY, as described earlier above.
(93) Receiver portion **600**A comprises (from right to left in the figure) a receiver MUX **604**, a symbol decoder **606**, a data width converter **610**, a synchronous FIFO **614** (or FIFO, buffer, FIFO buffer, or synchronous FIFO buffer), a symbol error corrector **616**, an FEC decoder **612**, a PCS decoder **618**, timestamp circuit **620**, and a MAC I/F **622**. A training top module **608** is coupled to receive incoming data stream from receiver MUX **604** for training of scrambling/descrambling. A PHY controller **602** is input to receiver MUX **604** for data or training path selection.
(94) As depicted in FIG. **6**A, data width converter **610** is in receive data path **601**, and FEC decoder **612** is in parallel with receive data path **601**. For example, FEC decoder **612** may be arranged in a parallel path **603** that is in parallel with at least a portion of receive data path **601** and/or synchronous FIFO **614**. FEC decoder **612** may operate, at least in substantial part, separately and independently from receive data path **601**. Given the arrangement, receive data path **601** provides for a fixed latency in data conveyance.
(95) In one or more examples, receive data path **601** includes (e.g., only) a single data width converter (i.e., data width converter **610**). Although "single" in receive data path **601**, data width converter **610** may be made of two or more separate data width converter circuits to produce the two respective output data streams (first and second output data streams **652** and **654**), or alternatively, utilize shared circuitry to produce the different streams.
(96) More particularly, data width converter **610** includes an input to receive an input data stream **650** having an input bit width, a first output to produce a first output data stream **652** having a first output bit width, and a second output to produce a second output data stream **654** having at least a second output bit width. In one or more examples, the input bit width, the first output bit width, and the at least second output bit width are different from each other.
(97) In one or more examples, synchronous FIFO **614** has an input to which first output data stream **652** having the first bit width is written into synchronous FIFO **614**. Synchronous FIFO **614** has an output to which a first output data stream **656** having the first bit width is read out from synchronous FIFO **614**. In one or more examples, synchronous FIFO **614** serves as a pipeline stage in receive data path **501**. In one or more examples, synchronous FIFO **614** may receive an "always-on" read-enable signal at an output **630** of symbol error corrector **616**.
(98) In one or more examples, symbol error corrector **616** includes a first input operably coupled to

the output of synchronous FIFO **614**, and a second input operably coupled to an error correction output **655** of FEC decoder **612**. Symbol error corrector **616** includes an output to produce an error-corrected data stream **658** from first output data stream **656** having the first bit width from synchronous FIFO **614**. Error-corrected data stream **658** is produced at least partially based on the one or more error correction values, from error correction output **655**, that correct the one or more symbols, the one or more partial symbols, or both, from the first output data stream **656**.

(99) FEC decoder **612** includes an input to receive the second output data stream **654** having the at least second output bit width. FEC decoder **612** includes an error correction output **655** to produce one or more error correction values at least partially based on one or more FEC code words in the second output data stream **654**. The one or more error correction values are for correction of one or more symbols, one or more partial symbols, or both, in first output data stream **656** having the first bit width from synchronous FIFO **614**.

(100) More particularly, in one or more examples, the error correction output of FEC decoder **612** produces the one or more error correction values for respective ones of the one or more FEC code words in the second output data stream **654**, for correction of respective ones of the one or more symbols, the one or more partial symbols, or both, in the first output data stream **652** having the first bit width.

(101) In one or more examples, receiver portion **600**A of the PHY transceiver is configured in accordance with IEEE 802.3ch 2.5GT1. For compliance with 2.5GT1, the symbol width is ten (10) bits, the input bit width of input data stream **650** is seventy-two (72) bits (e.g., @25.6 ns), the first output bit width of first output data stream **652** (e.g., to synchronous FIFO **614**) is sixty-five (65) bits (e.g., @25.6 ns), and the second output bit width of second output data stream **654** (e.g., to FEC decoder **612**) is seventy (70) or eighty (80) bits (e.g., @25.6 ns). Each IEEE 802.3ch FEC frame runs for fifty (50) clocks.

(102) In one or more examples, FEC decoder **612** is operative on k symbols (e.g., received over multiple clock cycles) in the second output data stream **654** having the at least second bit width. Respective ones of the k symbols comprise a symbol width of s bits. In one or more examples, the at least second output bit width is an integer multiple of the symbol width of s bits (e.g., ten (10) bits).

(103) In one or more examples, FEC decoder **612** is an RS-FEC decoder. In one or more examples, FEC decoder **612** decodes based on an RS code of RS(360,326). In one or more examples, an RS code may be represented by RS(n, k), where n=the total number of symbols in the FEC code word, k=the number of data symbols for data, and (n−k)=the number of parity symbols for parity.

(104) In one or more other examples, receiver portion **600**A is configured in accordance with one or more different standards, bit rates, bit widths, speeds, and/or codes.

(105) In one or more examples, symbol decoder **606** includes an output operably coupled to the input of data width converter **610**. The output of symbol decoder **606** produces the first input data stream **650** having the first bit width to data width converter **610**. In one or more examples, PCS decoder **618** includes an input to receive the error-corrected data stream having the first output bit width.

(106) In FIG. **6**B, a block diagram of a circuit portion **600**B in receive data path **601** of FIG. **6**A is shown, where the circuit portion **600**B includes synchronous FIFO **614** and symbol error corrector **616**.

(107) In FIG. **6**C, a block diagram **600**C of FEC decoder **612** of FIG. **6**A in parallel path **603** is shown, where FEC decoder **612** includes a syndrome calculator **662**, error locator **664** (e.g., using an ELP algorithm), a Chein search module **666**, and an error magnitude generator **668**, arranged as shown.

(108) The at least second output bit width of second output data stream **654** (FIGS. **6**A and **6**C) may be an integer multiple of the symbol width for FEC decoding. On the other hand, the first output bit width of first output data stream **652** (FIGS. **6**A and **6**B) may not be an integer multiple

of the symbol width.
(109) In one or more examples of the disclosure, symbol error corrector **616** (FIGS. **6**A and **6**B) is configured as partial symbol error corrector, and error magnitude generator **668** (FIGS. **6**B and **6**C) is configured as a variable length error magnitude generator (not merely a fixed symbol width error magnitude generator).
(110) With reference to FIG. **6**B, symbol error corrector **616** may receive the one or more error correction values at error correction output **655** for correction of the one or more symbols, the one or more partial symbols, or both, in first output data stream **656** from synchronous FIFO **614**. The output of symbol error corrector **616** produces error-corrected data stream **658** from first output data stream **656** at least partially based on the one or more error correction values.
(111) As symbol error corrector **616** may correct both full symbols and partial symbols, symbol error corrector **616** may be and/or be referred to as a partial symbol error corrector. In one or more examples, a symbol width of a full symbol is ten (10) bits. In one or more examples, a partial symbol width of a partial symbol is five (5) bits. In one or more examples, symbol error corrector **616** corrects both full symbols of ten (10) bits and partial symbols of five (5) bits as needed.
(112) In one or more examples, an error magnitude generator **668** of the FEC decoder in parallel path **603** produces a variable length error magnitude for error correction at symbol error corrector **616**. In one or more examples, error magnitude generator **668** selectively outputs error correction values according to whether a full or partial symbol correction is desired or needed. More particularly, error magnitude generator **668** may selectively output, at error correction output **655**, a selected number of the one or more error correction values (e.g., one or more error magnitude values) for correction of the respective full or partial symbol.
(113) In one or more examples, symbol error corrector **616** includes an XOR circuit **660** for XORing the full/partial symbols in first output data stream **656** with the error correction values.
(114) Symbol error corrector **616** may also produce the always-on read-enable signal at output **630** to synchronous FIFO **614**. In one or more examples, the always-on read enable signal may allow regular or continuous operation of synchronous FIFO **614** during decoding operations. Compare, for example, synchronous FIFO **566** of FIG. **5**B that receives read enable signals with pauses from Chein search module **564**. Accordingly, synchronous FIFO **614** of FIG. **6**A-**6**B may serve as a pipeline stage in receive data path **601**.
(115) With reference to FIG. **6**C, in one or more examples, error magnitude generator **668** may pause the FEC decoding logic (e.g., Chein search module **666**), regularly or periodically, as desired or needed. As error magnitude generator **668** is in parallel path **603**, no variable latency would be incurred by the pausing.
(116) Continuing with FIG. **6**C, syndrome calculator **662** has an input to receive second output data stream **654** having the at least second output bit width, and an output to produce one or more syndromes at least partially based on the one or more FEC code words in the second output data stream **654**. Error locator **664** is operably coupled to the output of syndrome calculator **662**, being provided to an input of error locator **562**. In one or more examples, Chein search module **666** provides error location values to error magnitude generator **668**. In one or more examples, syndrome calculator **560** may operate for fifty (50) clocks to produce a syndrome; error locator **664** may run for seventeen (17) clocks (e.g., @25.6 ns); and Chein search module **666** provides seven (7) error location values in one (1) clock.
(117) In one or more examples, syndrome calculator **662** is operative on k symbols of the second output data stream **654** having the at least second bit width. Respective ones of the k symbols comprise a symbol width of s bits (e.g., ten (10) bits). In one or more examples, the at least second output bit width is an integer multiple of the symbol width.
(118) In one or more examples, syndrome calculator **662** may be or be referred to as a variable-symbol syndrome calculator. In one or more examples, the second output data stream **654** having the at least second output bit width has a second output bit width in one or more first data transfers,

and a third output bit width in one or more second data transfers. In one or more examples, syndrome calculator **662** is operative on a variable number of received symbols, including at the second output bit width where k=7 and at the third output bit width where k=8. In one or more examples, comparing the present approach with the traditional approach of running the syndrome calculator on fixed eight (8) symbols, the buffer savings is from three-hundred-sixty (360) bits to eight (8) bits. A specific, non-limiting example of such a syndrome calculator is shown and described later in relation to FIG. **10**.

(119) As described earlier, error locator **664** may operate according to an ELP algorithm. In one or more examples, the ELP algorithm is provided to perform control channel adjustments according to rIBM (Reformulated Inversion-less Berlekamp Massey algorithm). Note that the ELP algorithm is a relatively independent process as it does not depend on the incoming receive data rate. In addition, the ELP algorithm is not a time critical function, but merely needs to run serially for P-clocks to obtain the polynomial (P=number of parity symbols). To begin processing, the ELP algorithm needs only to obtain a P-symbol syndrome. In one or more examples, for 2.5GT1, P=thirty-four (34) symbols. A specific, non-limiting example of an ELP algorithm of error locator **664** is shown and described later in relation to FIG. **11**.

(120) According to one or more examples, the ELP algorithm of error locator **664** is executed at a relatively higher speed clock speed than that of the receive data path. Here, with respect to FIG. **6**A, data width converter **610** is in receive data path **601**, and at least most of receive data path **601** is responsive to a first clock signal **636** (CLK.sub.DATAPATH) having a first clock frequency. As indicated in FIG. **6**C, error locator **664** utilizing the ELP algorithm may be responsive to a second clock signal **638** (CLK.sub.ELP) having a second clock frequency. In one or more examples, the second clock frequency of second clock signal **638** (CLK.sub.ELP) is greater than the first clock frequency of first clock signal **636** (CLK.sub.DATAPATH).

(121) In one or more examples, the ELP algorithm may run at a clock having a speed that is two (2) times the speed of the receive data path. In one or more examples (e.g., for 2.5GT1), the receive data path may operate at a clock @25.6 ns, whereas the ELP algorithm may execute at a clock @12.8 ns (e.g., two (2) times the speed of the receive data path). Here, the residence time of every FEC frame is reduced from eighty-four (84) clocks to sixty-seventy (67) clocks. In one or more other examples, a different ratio or percentage between clocks (i.e., CLK.sub.ELP and CLK.sub.DATAPATH) is utilized.

(122) In one or more examples, latency predictor **624** is operably coupled to data width converter **610**, and timestamp circuit **620** is operably coupled to latency predictor **624**. In one or more examples, latency predictor **624** selects a latency value responsive to a clock count value provided at an output **632** of data width converter **610**. In one or more examples, latency predictor **624** comprises a look-up table (LUT) of latency values respectively associated with clock count values. Timestamp circuit **620** is in receive data path **601** to timestamp the error corrected data stream. Timestamp circuit **620** receives a latency value at an output **634** of latency predictor **624** and adjusts a timing of timestamp circuit **620** at least partially based on the latency value. In one or more examples, the SOF is relatively easy to predict with use of a look-up table.

(123) In one or more examples relating to latency savings, the residence time of the frame in the receive data path may be reduced from eighty-four (84) clocks to sixty-seven (67) clocks. Thus, the latency may be reduced to 435.2 ns per FEC frame. Due to running a clock at a speed two (2) times the speed of the receive data path, seventeen (17) clock savings may be achieved.

(124) In one or more examples relating to area savings, the FIFO size in the FEC decoder in the traditional approach may have a size of 81×45=3645; whereas the FIFO size in the present approach may be 65×50=3250. By introducing the syndrome calculator, the buffers used in the gearboxes may also be reduced in size (e.g., from 360-bits to 8-bits).

(125) With reference back to FIG. **6**A, receiver portion **600**A may include an Operations, Administrations, and Maintenance (OAM) module **640**. In general, OAM data may be regularly or

periodically inserted in the data stream, in what may be referred to as an in-band data exchange. For 2.5GT1, an OAM symbol of ten (10) bits is included at a fixed position in every FEC frame (e.g., at the **326***t* h symbol). Here, received OAM data may be analyzed for monitoring link operation, such as PHY link health status or other.

(126) In one or more examples, OAM module **640** may be coupled to symbol error corrector **616** and/or the output of FEC decoder **612**. In one or more examples, OAM data is processed via parallel path **603** separately from the processing in receive data path **601**. For example, data width converter **610** may set up an OAM channel in parallel path **603**, so that OAM data is passed through parallel path **603** and not through synchronous FIFO **614** of receive data path **601**. The one or more correction values of error magnitude generator **668** may be applied directly to the last symbol for correction of the OAM data.

(127) FIG. **7**A is a flowchart depicting a process **700** to process receive data in a receive data path including parallel FEC decoding, according to one of more examples.

(128) In one or more examples, process **700** may include converting an input data stream having an input bit width to a first output data stream having a first output bit width and to a second output data stream having at least a second output bit width, in an act **702**. In one or more examples, the input bit width, the first output bit width, and the at least second output bit width are different from each other. In one or more examples, act **702** may include multiple acts of conversion.

(129) In one or more examples, process **700** may include performing FEC decoding process on one or more FEC code words of the second output data stream having the at least second output bit width, for producing one or more error correction values, in an act **704**.

(130) In one or more examples, process **700** may include correcting one or more symbols, one or more partial symbols, or both, in the first output data stream having the first output bit width at least partially based on the one or more error correction values, in an act **706**.

(131) In one or more examples, converting (e.g., in act **702**) the input data stream having the input bit width to the first output data stream having the first output bit width is performed in a receive data path, and performing (e.g., in act **704**) the FEC decoding process involves performing at least part of the FEC decoding process in parallel with the receive data path. In one or more examples, the receive data path provides a fixed latency in communication of the first output data stream.

(132) In one or more examples, the first output data stream having the first bit width is written into a synchronous FIFO in the receive data path, and the first output data stream having the first bit width read out from the synchronous FIFO.

(133) In one or more examples, performing (e.g., in act **704**) the at least part of the FEC decoding process comprises performing on k symbols in the second output data stream having the at least second bit width, where respective ones of the k symbols comprise a symbol width of ten (10) bits. In one or more examples, correcting (e.g., in act **706**) the one or more symbols, the one or more partial symbols, or both, comprises correcting the one or more partial symbols. In one or more examples, correcting the one or more partial symbols involves correcting the one or more partial symbols having a partial symbol width of five (5) bits.

(134) In one or more examples, performing (e.g., in act **704**) the at least part of the FEC decoding process comprises generating one or more error magnitude values comprising the one or more error correction values. In one or more examples, generating the one or more error magnitude values comprises selectively providing a selected number of the one or more error magnitude values comprising the one or more error correction values.

(135) In one or more examples, performing (e.g., in act **704**) the at least part of the FEC decoding process comprises calculating one or more syndromes at least partially based on the one or more FEC code words in the second output data stream having the at least second bit width. In one or more examples, respective ones of k symbols in the second output data stream comprise a symbol width of ten (10) bits. In one or more examples, process **300** may include calculating the one or more syndromes with respect to k symbols of the second output data stream, wherein k=7, and

calculating the one or more syndromes with respect to k symbols of the second output data stream, wherein k=8.
(136) In one or more examples, process **700** may include signaling a latency predictor with a clock count value, where the latency predictor comprises a look-up table of latency values respectively associated with clock count values. In one or more examples, process **300** may include adjusting a timing of a timestamping process for timestamping at least partially based on a latency value received from the latency predictor, the latency value being responsive to the clock count value.
(137) FIG. **7**B is an apparatus **750** to process receive data in a receive data path including parallel FEC decoding, according to one or more examples. In one or more examples, apparatus **750** includes a data width converter **752** and an FEC decoder **754**. In one or more examples, data width converter **752** is in a receive data path **780**, and at least a portion of FEC decoder **754** is in parallel with receive data path **780** (e.g., in a parallel path **782**).
(138) Data width converter **752** includes an input to receive an input data stream **760** having an input bit width, a first output to produce a first output data stream **762** having a first output bit width, and a second output to produce a second output data stream **764** having at least a second output bit width. FEC decoder **754** includes an input to receive the second output data stream **764** having the at least second output bit width. FEC decoder **754** includes an error correction output **766** to produce one or more error correction values at least partially based on one or more FEC code words in the second output data stream **764**. The one or more error correction values are for correction of one or more symbols, one or more partial symbols, or both, in the first output data stream **762** having the first output bit width.
(139) With reference to the specific, non-limiting example of FIG. **8**, a table **800** of numbers of transferred data bits per clock cycle associated with operation of data width converter **610** of FIG. **6**A is shown. In FIG. **8**, the clock count indicates a current, relative clock count that is relative to a repeating cycle of clock counts, for example, a repeating cycle of 1 to 50 clock counts, or other clock count range. Here, the numbers of transferred data bits per clock cycle include the numbers of transferred data bits from the data width converter to the synchronous FIFO ("converter-to-FIFO"), and the numbers of transferred data bits from the data width converter to the FEC decoder/syndrome calculator ("converter-to-syndrome-calculator"). The converter-to-FIFO column in table **800** is associated with first output data stream **652** having the first output bit width (FIG. **6**A) (e.g., sixty-five (65) bits); and the converter-to-syndrome-calculator column in table **800** is associated with second output data stream **654** having the second output bit width (FIG. **6**A) (e.g., seventy (70) bits or seven (7) symbols; or eighty (80) bits or eight (8) symbols).
(140) As indicated in the example of FIG. **8**, the syndrome calculator of the FEC decoder receives seven (7) symbols at a symbol width of ten (10) bits per clock cycle, for a total of seventy (70) bits per clock cycle. This occurs for respective ones of four (4) consecutive clock cycles. Then, the syndrome calculator receives eight (8) symbols at a symbol width of ten (10) bits for the next (single) clock cycle, for a total of eighty (80) bits for the clock cycle. This process then repeats with the syndrome calculator again receiving seventy (70) bits per clock cycle for four (4) consecutive clock cycles and then receiving eighty (80) bits for the next clock cycle, and so on. The syndrome calculator may output one or more syndromes when a full FEC code word is received and processed.
(141) FIG. **9** is a look-up table (LUT) **900** for a latency predictor associated with a receiver portion of a receive PHY, according to one or more examples. LUT **900** is a look-up table of latency values respectively associated with clock count values. In one or more examples, the latency values in LUT **900** are fixed or predetermined latency values that depend upon the clock count. The clock count to be input is a current, relative clock count that is relative to a repeating cycle of clock counts, for example, a repeating cycle of 1 to 50 clock counts, or other clock count range.
(142) Data width converter (or other component or mechanism) signals the latency predictor having LUT **900** with a (current, relative) clock count. In response, LUT **900** outputs a selected

latency value that corresponds to the clock count. A timestamp circuit receives the selected latency value from LUT **900** and adjusts its timing at least partially based on the selected latency value.
(143) Note that an LUT for a transmitter portion of a transmit PHY may be substantially the same as LUT **900** of FIG. **9**, according to one or more examples. In one or more examples, the latency predictor utilized in the transmit/receive PHY may solely be a look-up table (without any additional circuitry or substantial additional circuitry).
(144) One or more examples relate, generally, to determining variable latency, and reducing complexity as compared to the traditional approaches discussed above. In one or more examples, there is a fixed delay introduced by the modules in the transmit data path (e.g., by modules other than the data width converter). The variable latency introduced by the data width converter may therefore be reduced to a simple LUT, so the latency can be easily determined or selected at least partially based on a current, running clock count in the data width converter.
(145) To better illustrate by example, a data width converter may maintain an internal clock count from 1 to 50 (e.g., each IEEE 802.3ch FEC frame runs for fifty (50) clocks). Also, a pipeline depth between the data width converter and the PCS decoder may exist, for example, as sixty-nine (69) clocks. When an SOF is received in the PCS decoder, the internal clock count of the data width converter may indicate the n.sup.th clock. Inside the data width converter, the clock count is (c=n−69) clocks when it gave out the SOF. Based on this relationship (c=n−69), one can determine the variable delay introduced by data width converter, which is sixty-nine (69) clocks before current clock count. Accordingly, a predictor LUT that outputs a variable latency value may be based on the (c=n−69) relationship.
(146) FIG. **10** is a syndrome calculator **1000** for a FEC decoder of a receive PHY, according to one or more examples. In one or more examples, syndrome calculator **1000** of FIG. **10** may be utilized as syndrome calculator **662** of FEC decoder **612** indicated in FIG. **6**C.
(147) In one or more examples, syndrome calculator **1000** may be or be referred to as a variable-symbol syndrome calculator. In the example shown, syndrome calculator **1000** may include a plurality of input selectors **1004** having a plurality of inputs **1006** (alpha exponents), a plurality of multipliers **1008** for performing multiplication in relation to the selected inputs, an adder **1010**, and a shift register (DFF) array **1012**, arranged as shown. Syndrome calculator **1000** may produce a syndrome at an output **1014**. As indicated, syndrome calculator **1000** utilizes alpha-exponents to calculate the syndrome and these alpha-exponents are manipulated (e.g., per clock), as indicated in the figure. A selector input **1002** is employed (e.g., an incoming bit) to select between the number of symbols to be processed (e.g., syndrome calculator **1000** manipulates the alpha exponents at least partially based on the incoming bit or selection).
(148) FIG. **11** is an example of an error locator polynomial (ELP) algorithm **1100** of an error locator for an FEC decoder of a receive PHY, according to one or more examples. In one or more examples, such an ELP algorithm may be utilized in error locator **664** of FEC decoder **612** of FIG. **6**C. The ELP algorithm **1100** shown in FIG. **11** is one of many different standard algorithms and/or approaches (conventional or otherwise) that may be utilized in an FEC decoder. As shown in FIG. **11**, ELP algorithm **1100** may include an input function **1102** associated with a syndrome polynomial **1104** and output functions **1106** respectively associated with an error locator polynomial **1108** and an error magnitude polynomial **1110**. While specific parameters are indicated in FIG. **11**, these parameters are not intended to be limiting and will depend on the specific application and/or operating conditions.
(149) In one or more examples, ELP algorithm **1100** may execute at a higher clock rate (e.g., a clock rate associated with clock signal CLK.sub.ELP) than the clock rate of the receive data path (e.g., a clock rate associated with clock signal CLK.sub.DATAPATH). For example, the receive data path may be responsive to a first clock signal (e.g., clock signal CLK.sub.DATAPATH) having a first clock frequency, whereas the error locator having ELP algorithm **1100** may be responsive to a second clock signal (e.g., clock signal CLK.sub.ELP) having a second clock frequency, the

second clock frequency being greater than the first clock frequency.
(150) FIG. **12** is a timing diagram **1200** of communication processing associated with the receive data path having the integrated FEC decoding approach (see, e.g., FIGS. **5**A and **5**B). Timing diagram **1200** reveals variable fill levels that occur as a result of necessary pausing. The varying fill levels result in use of a complex predictor logic for predicting latency.
(151) FIG. **13** is a timing diagram **1300** of communication processing associated with the receive data path having the parallel FEC decoding approach (see, e.g., FIGS. **6**A-**6**C). Compare FIG. **13** with previous FIG. **12**. Timing diagram **1300** reveals fixed FIFO fill levels that occur as a result of no pausing.
(152) FIGS. **14**A and **14**B are timing diagram portions **1400**A and **1400**B of a timing diagram of communication processing associated with usage of a first clock rate for the receive data path and a second clock rate (i.e., a higher clock rate) for the ELP algorithm (see, e.g., FIGS. **6**A-**6**C and **11**). As described previously, the ELP algorithm may run at a clock having a speed that is two (2) times the speed (@12.8 ns) of the speed of the receive data path (@25.6 ns). From the time that the syndrome is available to the time that the ELP is provided is 486.4 ns (486.4/25.6 ns=only 19 clocks). The FIFO fill level and the write/read enables are fixed. From the previous figure (FIG. **13**), the maximum FIFO fill level was 66 (@81 bits). In FIGS. **14**A and **14**B, the maximum FIFO fill level is 69 (@65 bits).
(153) FIGS. **15**A and **15**B are timing diagram portions **1500**A and **1500**B of a timing diagram of communication processing associated with the variable symbol syndrome calculation (see, e.g., FIGS. **6**A-**6**C and **10**). The two (2) cursors indicate the boundaries of an FEC frame. “rx_data_x_i” marks the incoming data to the syndrome calculator. “Bit-**80**” indicates whether the valid input data is eighty (80) bits or seventy (70) bits. The syndrome calculator manipulates the alpha exponents based on this incoming bit, “Bit-**80**.”
(154) FIG. **16** is a block diagram of circuitry **1600** that, in some examples, may be used to implement various functions, operations, acts, processes, and/or methods disclosed herein. The circuitry **1600** includes one or more processors **1604** (sometimes referred to herein as “processors **1604**”) operably coupled to one or more data storage devices (sometimes referred to herein as “storage **1606**”). The storage **1606** includes machine-executable code **1608** stored thereon and the processors **1604** include a logic circuit **1610**. The machine-executable code **1608** includes information describing functional elements that may be implemented by (e.g., performed by) the logic circuit **1610**. The logic circuit **1610** is adapted to implement (e.g., perform) the functional elements described by the machine-executable code **1608**. The circuitry **1600**, when executing the functional elements described by the machine-executable code **1608**, should be considered as special purpose hardware for carrying out functional elements disclosed herein. In some examples, the processors **1604** may perform the functional elements described by the machine-executable code **1608** sequentially, concurrently (e.g., on one or more different hardware platforms), or in one or more parallel process streams.
(155) When implemented by logic circuit **1610** of the processors **1604**, the machine-executable code **1608** adapts the processors **1604** to perform operations of examples disclosed herein. For example, the machine-executable code **1608** may be to adapt the processors **1604** to perform at least a portion or a totality of the method of FIG. **3**A and/or the method of FIG. **7**A. As another example, the machine-executable code **1608** may be to adapt the processors **1604** to perform at least a portion or a totality of the operations described in relation to transmitter portion **200** of FIG. **2** and apparatus **350** of FIG. **3**B, and/or receiver portion **600**A of FIG. **6**A and apparatus **750** of FIG. **7**B.
(156) The processors **1604** may include a general purpose processor, a special purpose processor, a central processing unit (CPU), a microcontroller, a programmable logic controller (PLC), a digital signal processor (DSP), an application specific integrated circuit (ASIC), a field-programmable gate array (FPGA) or other programmable logic device, discrete gate or transistor logic, discrete

hardware components, other programmable device, or any combination thereof designed to perform the functions disclosed herein. A general-purpose computer including a processor is considered a special-purpose computer while the general-purpose computer executes functional elements corresponding to the machine-executable code **1608** (e.g., software code, firmware code, hardware descriptions) related to examples of the present disclosure. It is noted that a general-purpose processor (may also be referred to herein as a host processor or simply a host) may be a microprocessor, but in the alternative, the processors **1604** may include any conventional processor, controller, microcontroller, or state machine. The processors **1604** may also be implemented as a combination of computing devices, such as a combination of a DSP and a microprocessor, a plurality of microprocessors, one or more microprocessors in conjunction with a DSP core, or any other such configuration.

(157) In some examples the storage **1606** includes volatile data storage (e.g., random-access memory (RAM)), non-volatile data storage (e.g., Flash memory, a hard disc drive, a solid state drive, erasable programmable read-only memory (EPROM), etc.). In some examples the processors **1604** and the storage **1606** may be implemented into a single device (e.g., a semiconductor device product, a system on chip (SOC), etc.). In some examples the processors **1604** and the storage **1606** may be implemented into separate devices.

(158) In some examples the machine-executable code **1608** may include computer-readable instructions (e.g., software code, firmware code). By way of non-limiting example, the computer-readable instructions may be stored by the storage **1606**, accessed directly by the processors **1604**, and executed by the processors **1604** using at least the logic circuit **1610**. Also by way of non-limiting example, the computer-readable instructions may be stored on the storage **1606**, transferred to a memory device (not shown) for execution, and executed by the processors **1604** using at least the logic circuit **1610**. Accordingly, in some examples the logic circuit **1610** includes electrically configurable logic circuit **1610**.

(159) In some examples the machine-executable code **1608** may describe hardware (e.g., circuitry) to be implemented in the logic circuit **1610** to perform the functional elements. This hardware may be described at any of a variety of levels of abstraction, from low-level transistor layouts to high-level description languages. At a high-level of abstraction, a hardware description language (HDL) such as an IEEE Standard hardware description language (HDL) may be used. By way of non-limiting examples, VERILOG™, SYSTEMVERILOG™ or very large scale integration (VLSI) hardware description language (VHDL™) may be used.

(160) HDL descriptions may be converted into descriptions at any of numerous other levels of abstraction as desired. As a non-limiting example, a high-level description can be converted to a logic-level description such as a register-transfer language (RTL), a gate-level (GL) description, a layout-level description, or a mask-level description. As a non-limiting example, micro-operations to be performed by hardware logic circuits (e.g., gates, flip-flops, registers, without limitation) of the logic circuit **1610** may be described in a RTL and then converted by a synthesis tool into a GL description, and the GL description may be converted by a placement and routing tool into a layout-level description that corresponds to a physical layout of an integrated circuit of a programmable logic device, discrete gate or transistor logic, discrete hardware components, or combinations thereof. Accordingly, in some examples the machine-executable code **1608** may include an HDL, an RTL, a GL description, a mask level description, other hardware description, or any combination thereof.

(161) In examples where the machine-executable code **1608** includes a hardware description (at any level of abstraction), a system (not shown, but including the storage **1606**) may be to implement the hardware description described by the machine-executable code **1608**. By way of non-limiting example, the processors **1604** may include a programmable logic device (e.g., an FPGA or a PLC) and the logic circuit **1610** may be electrically controlled to implement circuitry corresponding to the hardware description into the logic circuit **1610**. Also by way of non-limiting

example, the logic circuit **1610** may include hard-wired logic manufactured by a manufacturing system (not shown, but including the storage **1606**) according to the hardware description of the machine-executable code **1608**.

(162) Regardless of whether the machine-executable code **1608** includes computer-readable instructions or a hardware description, the logic circuit **1610** is adapted to perform the functional elements described by the machine-executable code **1608** when implementing the functional elements of the machine-executable code **1608**. It is noted that although a hardware description may not directly describe functional elements, a hardware description indirectly describes functional elements that the hardware elements described by the hardware description are capable of performing.

(163) As used in the present disclosure, the terms “module” or “component” may refer to specific hardware implementations to perform the actions of the module or component and/or software objects or software routines that may be stored on and/or executed by general purpose hardware (e.g., computer-readable media, processing devices, etc.) of the computing system. In some examples, the different components, modules, engines, and services described in the present disclosure may be implemented as objects or processes that execute on the computing system (e.g., as separate threads). While some of the system and methods described in the present disclosure are generally described as being implemented in software (stored on and/or executed by general purpose hardware), specific hardware implementations or a combination of software and specific hardware implementations are also possible and contemplated.

(164) As used in the present disclosure, the term “combination” with reference to a plurality of elements may include a combination of all the elements or any of various different subcombinations of some of the elements. For example, the phrase “A, B, C, D, or combinations thereof” may refer to any one of A, B, C, or D; the combination of each of A, B, C, and D; and any subcombination of A, B, C, or D such as A, B, and C; A, B, and D; A, C, and D; B, C, and D; A and B; A and C; A and D; B and C; B and D; or C and D.

(165) Terms used in the present disclosure and especially in the appended claims (e.g., bodies of the appended claims) are generally intended as “open” terms (e.g., the term “including” should be interpreted as “including, but not limited to,” the term “having” should be interpreted as “having at least,” the term “includes” should be interpreted as “includes, but is not limited to,” etc.).

(166) Additionally, if a specific number of an introduced claim recitation is intended, such an intent will be explicitly recited in the claim, and in the absence of such recitation no such intent is present. For example, as an aid to understanding, the following appended claims may contain usage of the introductory phrases “at least one” and “one or more” to introduce claim recitations. However, the use of such phrases should not be construed to imply that the introduction of a claim recitation by the indefinite articles “a” or “an” limits any particular claim containing such introduced claim recitation to examples containing only one such recitation, even when the same claim includes the introductory phrases “one or more” or “at least one” and indefinite articles such as “a” or “an” (e.g., “a” and/or “an” should be interpreted to mean “at least one” or “one or more”); the same holds true for the use of definite articles used to introduce claim recitations.

(167) In addition, even if a specific number of an introduced claim recitation is explicitly recited, those skilled in the art will recognize that such recitation should be interpreted to mean at least the recited number (e.g., the bare recitation of “two recitations,” without other modifiers, means at least two recitations, or two or more recitations). Furthermore, in those instances where a convention analogous to “at least one of A, B, and C, etc.,” or “one or more of A, B, and C, etc.,” is used, in general such a construction is intended to include A alone, B alone, C alone, A and B together, A and C together, B and C together, or A, B, and C together, etc.

(168) Any disjunctive word or phrase presenting two or more alternative terms, whether in the description, claims, or drawings, should be understood to contemplate the possibilities of including one of the terms, either of the terms, or both terms. For example, the phrase “A or B” should be

understood to include the possibilities of “A” or “B” or “A and B.”

ADDITIONAL NON-LIMITING EXAMPLES OF THE DISCLOSURE INCLUDE

(169) Example 1: An apparatus comprising: a data width converter, the data width converter including an input to receive an input data stream having an input bit width, a first output to produce a first output data stream having a first output bit width, and a second output to produce a second output data stream having at least a second output bit width; and a forward error correction (FEC) decoder, the FEC decoder including an input to receive the second output data stream having the at least second output bit width, the FEC decoder including an error correction output to produce one or more error correction values at least partially based on one or more FEC code words in the second output data stream, the one or more error correction values for correction of one or more symbols, one or more partial symbols, or both, in the first output data stream having the first output bit width.

(170) Example 2: The apparatus according to Example 1, wherein: the data width converter is in a receive data path, and at least a portion of the FEC decoder is in parallel with the receive data path.

(171) Example 3: The apparatus according to Examples 1 and 2, wherein the received data path provides a fixed latency in communication of the first output data stream.

(172) Example 4: The apparatus according to any of Examples 1 to 3, wherein the input bit width, the first output bit width, and the at least second output bit width are different from each other.

(173) Example 5: The apparatus according to any of Examples 1 to 4, comprising: a synchronous first-in-first-out (FIFO), the synchronous FIFO having an input to which the first output data stream having the first bit width is written into the synchronous FIFO, the synchronous FIFO having an output to which the first output data stream having the first bit width is read out from the synchronous FIFO.

(174) Example 6: The apparatus according to any of Examples 1 to 5, wherein the FEC decoder comprises: a symbol error corrector, the symbol error corrector having a first input operably coupled to the output of the synchronous FIFO, a second input operably coupled to the error correction output of the FEC decoder, and an output to produce an error-corrected data stream from the first output data stream having the first bit width at least partially based on the one or more error correction values that correct the one or more symbols, the one or more partial symbols, or both.

(175) Example 7: The apparatus according to any of Examples 1 to 6, wherein the FEC decoder is operative on k symbols in the second output data stream having the at least second output bit width, respective ones of the k symbols comprise a symbol width of s bits, and the symbol width is ten (10) bits, and wherein: the output of the symbol error corrector to produce the error-corrected data stream at least partially based on the one or more error correction values that correct the one or more partial symbols having a partial symbol width of five (5) bits.

(176) Example 8: The apparatus according to any of Examples 1 to 7, wherein the FEC decoder comprises: an error magnitude generator, the error magnitude generator to selectively output, at the error correction output, a selected number of the one or more error correction values for correction of the one or more symbols, the one or more partial symbols, or both, the one or more correction values comprising one or more error magnitude values.

(177) Example 9: The apparatus according to any of Examples 1 to 8, wherein the FEC decoder comprises: a syndrome calculator, the syndrome calculator having an input to receive the second output data stream having the at least second output bit width and an output to produce one or more syndromes at least partially based on the one or more FEC code words in the second output data stream.

(178) Example 10: The apparatus according to any of Examples 1 to 9, wherein the syndrome calculator is operative on k symbols of the second output data stream having the at least second bit width, respective ones of the k symbols comprise a symbol width of ten (10) bits, and the at least second output bit width is an integer multiple of the symbol width of s bits.

(179) Example 11: The apparatus according to any of Examples 1 to 10, wherein the second output data stream having the at least second output bit width has a second output bit width in one or more first data transfers and a third output bit width in one or more second data transfers, and wherein: the syndrome calculator is operative on a variable number of symbols, including at the second output bit width where k=7 and at the third output bit width where k=8.
(180) Example 12: The apparatus according to any of Examples 1 to 11, wherein the data width converter is in a receive data path and the receive data path is responsive to a first clock signal having a first clock frequency, the apparatus comprising: an error locator polynomial generator, the error locator polynomial generator responsive to a second clock signal having a second clock frequency, the second clock frequency greater than the first clock frequency.
(181) Example 13: The apparatus according to any of Examples 1 to 12, wherein: the symbol error corrector includes another output to produce an always-on read enable signal to the synchronous FIFO.
(182) Example 14: The apparatus according to any of Examples 1 to 13, comprising: a latency predictor, the latency predictor operably coupled to the data width converter, the latency predictor comprising a look up table of latency values respectively associated with clock count values.
(183) Example 15: The apparatus according to any of Examples 1 to 14, comprising: a timestamp circuit to timestamp the error corrected data stream, the timestamp circuit to receive a latency value from the latency predictor and to adjust a timing of the timestamp circuit at least partially based on the latency value.
(184) Example 16: The apparatus according to any of Examples 1 to 15, wherein: the error correction output of the FEC decoder to produce the one or more error correction values for respective ones of the one or more FEC code words in the second output data stream for correction of respective ones of the one or more symbols, the one or more partial symbols, or both, in the first output data stream having the first bit width.
(185) Example 17: The apparatus according to any of Examples 1 to 16, wherein: the FEC decoder is operative on k symbols in the second output data stream having at least the second bit width, respective ones of the k symbols comprise a symbol width of s bits, and the at least second output bit width is an integer multiple of the symbol width of s bits.
(186) Example 18: The apparatus according to any of Examples 1 to 17, wherein: the symbol width is ten (10) bits, and the at least second output bit width is seventy (70) bits or eighty (80) bits.
(187) Example 19: The apparatus according to any of Examples 1 to 18, wherein: the input bit width is seventy-two (72) bits, and the first output bit width is sixty-five (65) bits.
(188) Example 20: A method comprising: converting an input data stream having an input bit width to a first output data stream having a first output bit width and to a second output data stream having at least a second output bit width; performing a forward error correction (FEC) decoding process on one or more FEC code words of the second output data stream having the at least second output bit width, for producing one or more error correction values; and correcting one or more symbols, one or more partial symbols, or both, in the first output data stream having the first output bit width at least partially based on the one or more error correction values.
(189) Example 21: The method according to Example 20, wherein: converting the input data stream having the input bit width to the first output data stream having the first output bit width is performed in a receive data path, and performing the FEC decoding process comprises performing at least part of the FEC decoding process in parallel with the receive data path.
(190) Example 22: The method according to Examples 20 and 21, wherein the receive data path provides a fixed latency in communication of the first output data stream.
(191) Example 23: The method according to any of Examples 20 to 22, wherein the input bit width, the first output bit width, and the second output bit width are different from each other.
(192) Example 24: The method according to any of Examples 20 to 23, comprising: writing into a synchronous first-in-first-out (FIFO) the first output data stream having the first bit width; and

reading out from the synchronous FIFO the first output data stream having the first bit width.
(193) Example 25: The method according to any of Examples 20 to 24, wherein correcting the one or more symbols, the one or more partial symbols, or both, comprises correcting the one or more partial symbols.
(194) Example 26: The method according to any of Examples 20 to 25, wherein: performing the at least part of the FEC decoding process comprises performing on k symbols in the second output data stream having the at least second output bit width, wherein respective ones of the k symbols comprise a symbol width of ten (10) bits, and correcting the one or more partial symbols comprises correcting the one or more partial symbols having a partial symbol width of five (5) bits.
(195) Example 27: The method according to any of Examples 20 to 26, wherein performing the at least part of the FEC decoding process comprises: generating one or more error magnitude values comprising the one or more error correction values.
(196) Example 28: The method according to any of Examples 20 to 27, wherein generating comprises: selectively providing a selected number of the one or more error magnitude values comprising the one or more error correction values.
(197) Example 29: The method according to any of Examples 20 to 28, wherein performing the at least part of the FEC decoding process comprises: calculating one or more syndromes at least partially based on the one or more FEC code words in the second output data stream having the at least second bit width.
(198) Example 30: The method according to any of Examples 20 to 29, wherein respective ones of k symbols in the second output data stream comprise a symbol width of ten (10) bits, the method comprising: calculating the one or more syndromes with respect to k symbols of the second output data stream, wherein k=7, and calculating the one or more syndromes with respect to k symbols of the second output data stream, wherein k=8.
(199) Example 31: The method according to any of Examples 20 to 30, comprising: signaling a latency predictor with a clock count value, the latency predictor comprising a look up table of latency values respectively associated with clock count values.
(200) Example 32: The method according to any of Examples 20 to 31, comprising: adjusting a timing of a timestamping process for timestamping at least partially based on a latency value received from the latency predictor, the latency value responsive to the clock count value.
(201) Example 33: An apparatus comprising: a data width converter in a receive data path, the data width converter including an input to receive an input data stream having an input bit width, a first output to produce a first output data stream having a first output bit width, and a second output to produce a second output data stream having at least a second output bit width; a synchronous first-in-first-out (FIFO) in the receive data path, the synchronous FIFO having an input to which the first output data stream having the first bit width is written into the synchronous FIFO, the synchronous FIFO having an output to which the first output data stream having the first bit width is read out from the synchronous FIFO; at least a portion of a forward error correction (FEC) decoder in parallel with the receive data path, the at least portion of the FEC decoder including an input to receive the second output data stream having the at least second output bit width, the at least portion of the FEC decoder including an error correction output to produce one or more error correction values at least partially based on one or more FEC code words in the second output data stream having the at least second output bit width; and a symbol error corrector in the receive data path, the symbol error corrector having a first input operably coupled to the output of the synchronous FIFO, a second input operably coupled to the error correction output of the FEC decoder, and an output to produce an error-corrected data stream from the first output data stream having the first bit width at least partially based on the one or more error correction values that correct one or more symbols, one or more partial symbols, or both, in the first output data stream.
(202) Example 34: The apparatus according to Example 33, wherein: the at least portion of the FEC decoder is operative on k symbols in the second output data stream having the at least second

bit width, and respective ones of the k symbols comprise a symbol width of ten (10) bits, and the output of the symbol error corrector to produce the error-corrected data stream at least partially based on the one or more error correction values for correction of the one or more partial symbols having a partial symbol width of five (5) bits.
(203) Example 35: The apparatus according to Examples 33 and 34, wherein the at least portion of the FEC decoder comprises: an error magnitude generator, the error magnitude generator to selectively output, at the error correction output, a selected number of the one or more correction values for correction of the one or more symbols or the one or more partial symbols, the one or more correction values comprising one or more error magnitude values.
(204) Example 36: The apparatus according to any of Examples 33 to 35, wherein the at least portion of the FEC decoder comprises: a syndrome calculator, the syndrome calculator having an input to receive the second output data stream having the at least second output bit width and an output to produce one or more syndromes at least partially based on the one or more FEC code words.
(205) Example 37: The apparatus according to any of Examples 33 to 36, wherein the syndrome calculator is operative on k symbols of the second output data stream having the at least second bit width, respective ones of the k symbols comprise a symbol width of s bits, and the at least second output bit width is an integer multiple of the symbol width.
(206) Example 38: The apparatus according to any of Examples 33 to 37, wherein the syndrome calculator is operative at a variable number of symbols.
(207) Example 39: The apparatus according to any of Examples 33 to 38, wherein the second output data stream having the at least second output bit width has a second output bit width in one or more first data transfers and a third output bit width in one or more second data transfers, the symbol width is ten (10) bits, and wherein: the syndrome calculator is operative at the variable number of symbols including at the second output bit width where k=7 and at the third output bit width where k=8.
(208) While the present disclosure has been described herein with respect to certain illustrated examples, those of ordinary skill in the art will recognize and appreciate that the present invention is not so limited. Rather, many additions, deletions, and modifications to the illustrated and described examples may be made without departing from the scope of the invention as hereinafter claimed along with their legal equivalents. In addition, features from one example may be combined with features of another example while still being encompassed within the scope of the invention as contemplated by the inventor.

Claims

1. An apparatus comprising: a data width converter in a receive data path, the data width converter including an input to receive an input data stream having an input bit width, a first output to produce a first output data stream having a first output bit width, and a second output to produce a second output data stream having a second output bit width; a forward error correction (FEC) decoder, at least a portion of the FEC decoder in parallel with the receive data path, the FEC decoder including an input to receive the second output data stream having the second output bit width, the FEC decoder including an error correction output to produce one or more error correction values at least partially based on one or more FEC code words in the second output data stream, the one or more error correction values for correction of one or more symbols, one or more partial symbols, or both, in the first output data stream having the first output bit width; and a latency predictor, the latency predictor operably coupled to the data width converter, the latency predictor comprising a look up table of latency values respectively associated with clock count values.
2. The apparatus of claim 1, wherein: the data width converter is to provide a clock count value to

the latency predictor, and the latency predictor is to select a latency value at least partially responsive to the clock count value, the latency value for adjustment of timing used for timestamping data stream communications in the receive data path.
3. The apparatus of claim 2, wherein the received data path provides a fixed latency in communication of the first output data stream.
4. The apparatus of claim 1, wherein the input bit width, the first output bit width, and the second output bit width are different from each other.
5. The apparatus of claim 1, comprising: a synchronous first-in-first-out (FIFO), the synchronous FIFO having an input to which the first output data stream having the first bit width is written into the synchronous FIFO, the synchronous FIFO having an output to which the first output data stream having the first bit width is read out from the synchronous FIFO.
6. The apparatus of claim 5, wherein the FEC decoder comprises: a symbol error corrector, the symbol error corrector having a first input operably coupled to the output of the synchronous FIFO, a second input operably coupled to the error correction output of the FEC decoder, and an output to produce an error-corrected data stream from the first output data stream having the first bit width at least partially based on the one or more error correction values that correct the one or more symbols, the one or more partial symbols, or both.
7. The apparatus of claim 6, wherein the FEC decoder is operative on k symbols in the second output data stream having the second output bit width, k is a positive integer, and respective ones of the k symbols comprise a symbol width of ten (10) bits, and wherein: the output of the symbol error corrector to produce the error-corrected data stream at least partially based on the one or more error correction values that correct the one or more partial symbols having a partial symbol width of five (5) bits.
8. The apparatus of claim 7, wherein the FEC decoder comprises: an error magnitude generator, the error magnitude generator to selectively output, at the error correction output, a selected number of the one or more error correction values for correction of the one or more symbols, the one or more partial symbols, or both, the one or more correction values comprising one or more error magnitude values.
9. The apparatus of claim 1, wherein the FEC decoder comprises: a syndrome calculator, the syndrome calculator having an input to receive the second output data stream having the second output bit width and an output to produce one or more syndromes at least partially based on the one or more FEC code words in the second output data stream.
10. The apparatus of claim 9, wherein the syndrome calculator is operative on k symbols of the second output data stream having the second output bit width, respective ones of the k symbols comprise a symbol width of ten (10) bits, k is a positive integer, and the second output bit width is an integer multiple of the symbol width of ten (10) bits.
11. The apparatus of claim 10, wherein the second output data stream has the second output bit width in one or more first data transfers and a third output bit width in one or more second data transfers, and wherein: the syndrome calculator is operative on a variable number of symbols, including at the second output bit width where k=7 and at the third output bit width where k=8.
12. The apparatus of claim 9, wherein the data width converter is in a receive data path and the receive data path is responsive to a first clock signal having a first clock frequency, the apparatus comprising: an error locator polynomial generator, the error locator polynomial generator responsive to a second clock signal having a second clock frequency, the second clock frequency greater than the first clock frequency.
13. The apparatus of claim 6, wherein: the symbol error corrector includes another output to produce a read enable signal to the synchronous FIFO that allows regular or continuous operation of the synchronous FIFO during decoding operations.
14. The apparatus of claim 2, wherein: the data width converter is to provide the clock count value to the latency predictor for respective clock count values of a repeating cycle of clock count values.

15. The apparatus of claim 14, comprising: a timestamp circuit to timestamp the error corrected data stream, the timestamp circuit to receive the latency value from the latency predictor and to adjust the timing at least partially based on the latency value.
16. The apparatus of claim 1, wherein: the error correction output of the FEC decoder to produce the one or more error correction values for respective ones of the one or more FEC code words in the second output data stream for correction of respective ones of the one or more symbols, the one or more partial symbols, or both, in the first output data stream having the first bit width.
17. The apparatus of claim 1, wherein: the FEC decoder is operative on k symbols in the second output data stream having the second output bit width, respective ones of the k symbols comprise a symbol width of s bits, and the second output bit width is an integer multiple of the symbol width of s bits, wherein k and s are positive integers.
18. The apparatus of claim 17, wherein: the symbol width is ten (10) bits, and the at least second output bit width is seventy (70) bits or eighty (80) bits.
19. The apparatus of claim 18, wherein: the input bit width is seventy-two (72) bits, and the first output bit width is sixty-five (65) bits.
20. A method comprising: converting an input data stream having an input bit width to a first output data stream having a first output bit width and to a second output data stream having a second output bit width, the input data stream and the first output data stream in a receive data path; performing a forward error correction (FEC) decoding process on one or more FEC code words of the second output data stream having the second output bit width to produce one or more error correction values, at least a part of the FEC decoding process performed in parallel with the receive data path; correcting one or more symbols, one or more partial symbols, or both, in the first output data stream having the first output bit width at least partially based on the one or more error correction values; and signaling a latency predictor with a clock count value for selection of a latency value, the latency predictor comprising a look up table of latency values respectively associated with clock count values, the latency value for adjustment of timing used for timestamping data stream communications in the receive data path.
21. The method of claim 20, wherein: signaling the latency predictor with the clock count value for selection of the latency value is performed for respective clock count values of a repeating cycle of clock count values.
22. The method of claim 20, comprising: writing into a synchronous first-in-first-out (FIFO) the first output data stream having the first bit width; and reading out from the synchronous FIFO the first output data stream having the first bit width.
23. The method of claim 20, wherein correcting the one or more symbols, the one or more partial symbols, or both, comprises correcting the one or more partial symbols.
24. The method of claim 23, wherein: the at least part of the FEC decoding process performed in parallel with the receive data path is performed on k symbols in the second output data stream having the second output bit width, wherein k is a positive integer, and respective ones of the k symbols comprise a symbol width of ten (10) bits, and correcting the one or more partial symbols comprises correcting the one or more partial symbols having a partial symbol width of five (5) bits.
25. The method of claim 20, wherein the at least part of the FEC decoding process performed in parallel with the receive data path comprises: generating one or more error magnitude values comprising the one or more error correction values.
26. The method of claim 25, wherein generating comprises: selectively providing a selected number of the one or more error magnitude values comprising the one or more error correction values.
27. The method of claim 20, wherein the at least part of the FEC decoding process performed in parallel with the receive data path comprises: calculating one or more syndromes at least partially based on the one or more FEC code words in the second output data stream having the second output bit width.

28. The method of claim 27, wherein respective ones of k symbols in the second output data stream comprise a symbol width of ten (10) bits, the method comprising: calculating the one or more syndromes with respect to k symbols of the second output data stream, wherein k=7, and calculating the one or more syndromes with respect to k symbols of the second output data stream, wherein k=8.
29. The method of claim 21, wherein: signaling the latency predictor with the clock count value is from a data width converter used for converting the input data stream.
30. The method of claim 29, comprising: adjusting the timing of a timestamping process for the timestamping of the data stream communications in the receive data path at least partially based on the latency value received from the latency predictor, the latency value responsive to the clock count value.
31. An apparatus comprising: a data width converter in a receive data path, the data width converter including an input to receive an input data stream having an input bit width, a first output to produce a first output data stream having a first output bit width, and a second output to produce a second output data stream having a second output bit width; a synchronous first-in-first-out (FIFO) in the receive data path, the synchronous FIFO having an input to which the first output data stream having the first bit width is written into the synchronous FIFO, the synchronous FIFO having an output to which the first output data stream having the first bit width is read out from the synchronous FIFO; at least a portion of a forward error correction (FEC) decoder in parallel with the receive data path, the at least portion of the FEC decoder including an input to receive the second output data stream having the second output bit width, the at least portion of the FEC decoder including an error correction output to produce one or more error correction values at least partially based on one or more FEC code words in the second output data stream having the second output bit width; and a symbol error corrector in the receive data path, the symbol error corrector having a first input operably coupled to the output of the synchronous FIFO, a second input operably coupled to the error correction output of the FEC decoder, and an output to produce an error-corrected data stream from the first output data stream having the first bit width at least partially based on the one or more error correction values that correct one or more symbols, one or more partial symbols, or both, in the first output data stream.
32. The apparatus of claim 31, wherein: the symbol error corrector in the receive data path is to: correct the one or more symbols, the one or more partial symbols, or both, including respective symbols of ten (10) bits, and correct the one or more symbols, the one or more partial symbols, or both, including respective partial symbols of five (5) bits.
33. The apparatus of claim 31, wherein the FEC decoder comprises: a syndrome calculator, the syndrome calculator including an input to receive the second output data stream having the second output bit width, the syndrome calculator operative on a variable number of k symbols, the syndrome calculator to: calculate one or more syndromes with respect to k symbols of the second output data stream, where k=7, and calculate one or more syndromes with respect to k symbols of the second output data stream, where k=8.
34. An apparatus comprising: a data width converter, the data width converter including an input to receive an input data stream having an input bit width, a first output to produce a first output data stream having a first output bit width, and a second output to produce a second output data stream having a second output bit width; a synchronous first-in-first-out (FIFO), the synchronous FIFO having an input to which the first output data stream having the first bit width is written into the synchronous FIFO, the synchronous FIFO having an output to which the first output data stream having the first bit width is read out from the synchronous FIFO; and a forward error correction (FEC) decoder, the FEC decoder including an input to receive the second output data stream having the second output bit width, the FEC decoder including an error correction output to produce one or more error correction values at least partially based on one or more FEC code words in the second output data stream, the one or more error correction values for correction of one or more symbols,

one or more partial symbols, or both, in the first output data stream having the first output bit width read out from the synchronous FIFO.

35. The apparatus of claim 34, wherein the FEC decoder comprises: a symbol error corrector, the symbol error corrector having a first input operably coupled to the output of the synchronous FIFO, a second input operably coupled to the error correction output of the FEC decoder, and an output to produce an error-corrected data stream from the first output data stream having the first bit width at least partially based on the one or more error correction values that correct the one or more symbols, the one or more partial symbols, or both, the symbol error corrector to: correct the one or more symbols, the one or more partial symbols, or both, including respective symbols of ten (10) bits, and correct the one or more symbols, the one or more partial symbols, or both, including respective partial symbols of five (5) bits.

36. A method comprising: converting an input data stream having an input bit width to a first output data stream having a first output bit width and to a second output data stream having a second output bit width; writing into a synchronous first-in-first-out (FIFO) the first output data stream having the first output bit width; performing a forward error correction (FEC) decoding process on one or more FEC code words of the second output data stream having the second output bit width to produce one or more error correction values; and correcting one or more symbols, one or more partial symbols, or both, in the first output data stream having the first output bit width, read out from the synchronous FIFO, at least partially based on the one or more error correction values.

37. The method of claim 36, wherein correcting the one or more symbols, the one or more partial symbols, or both, includes correcting respective symbols of ten (10) bits and correcting respective partial symbols of five (5) bits.

38. The method of claim 36, wherein performing the FEC decoding process comprises: calculating one or more syndromes with respect to k symbols of the second output data stream, wherein k=7, and calculating one or more syndromes with respect to k symbols of the second output data stream, wherein k=8.