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United States Patent	12395417
Kind Code	B2
Date of Patent	August 19, 2025
Inventor(s)	Babitsky; Eliya et al.

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### Circuit and method for timestamp filtering with RLS filter

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#### Abstract

A circuit and corresponding method perform timestamp filtering. The circuit includes recursive filter logic that implements a recursive least-squares (RLS) filter. The circuit (i) generates a filtered timestamp from a received timestamp by filtering the received timestamp via the recursive filter logic. The recursive filter logic applies the RLS filter to a portion of the received timestamp. A number of bits of the portion is less relative to a total number of bits of the received timestamp. The circuit outputs the filtered timestamp generated. Applying the RLS filter to the portion enables the circuit to be more efficient (e.g., smaller adders, fewer flipflops, etc.), thereby reducing area and power consumption of the circuit.

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**Appl. No.:** 17/815652

**Filed:** July 28, 2022

#### Prior Publication Data

Document Identifier	Publication Date
US 20240039822 A1	Feb. 01, 2024

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#### Publication Classification

**Int. Cl.:** H04L43/106 (20220101); H04L43/087 (20220101)

## U.S. Cl.:

CPC     **H04L43/106** (20130101); **H04L43/087** (20130101);

## Field of Classification Search

**CPC:**     H04L (43/106); H04L (43/087); H04L (69/22); H04W (56/0015); H04W (56/00); H04W (56/001); H04B (7/0413); H04B (7/2681)

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## **Background/Summary**

### **BACKGROUND**

(1) Cloud radio access network (C-RAN) is a centralized, cloud computing-based architecture for radio access networks (RANs) that enables large-scale deployment, collaborative radio technology support, and real-time virtualization capabilities. C-RAN is an evolution of the wireless communication system and uses the common public radio interface (CPRI) standard, coarse or dense wavelength division multiplexing (CWDM/DWDM) technology, and millimeter wave (MM wave) transmission for long distance signals. The “C” in C-RAN can alternatively stand for “centralized” or “collaborative.” In the C-RAN architecture, baseband processing units (BBUs) are decoupled from the radio heads and relocated to a centralized control and processing station. C-RANs are significant in the future progress of wireless technology, such as the fifth-generation (5G) and Internet of Things (IoT) wireless technologies for non-limiting examples. C-RAN is one of the key enablers for 5G.

(2) 5G C-RAN-based systems rely on high accuracy time synchronization between radio heads for improved performance. Typically, the Institute of Electrical and Electronics Engineers (IEEE) 1588-2008 standard for precision time protocol (PTP), or a version thereof, is used for such time synchronization. The standard enables heterogeneous systems that include clocks of various inherent precision, resolution, and stability to synchronize to a grandmaster clock. The standard supports system-wide synchronization accuracy in the sub-microsecond range, with minimal network and local clock computing resources.

### **SUMMARY**

(3) According to an example embodiment, a circuit comprises recursive filter logic configured to implement a recursive least-squares (RLS) filter. The circuit is configured to generate a filtered timestamp from a received timestamp by filtering the received timestamp via the recursive filter

logic. The recursive filter logic is configured to apply the RLS filter to a portion of the received timestamp. A number of bits of the portion being less relative to a total number of bits of the received timestamp. The circuit is further configured to output the filtered timestamp generated.

(4) For non-limiting example, the portion may be a least significant bit (LSB) portion of the received timestamp, wherein the LSB portion is of lesser significance relative to a most significant bit (MSB) portion of the received timestamp.

(5) The RLS filter may be configured to generate, based on the LSB portion, an estimated timestamp value of a target (ideal) timestamp. The circuit may be further configured to generate the filtered timestamp based on the estimated timestamp value generated.

(6) The circuit may further comprise input format-conversion logic coupled to the recursive filter logic. The input format-conversion logic may be configured to convert the received timestamp from an original timestamp format to an intermediate timestamp format. The circuit may be configured to input the received timestamp in the intermediate timestamp format to the recursive filter logic. The recursive filter logic may be further configured to apply the RLS filter to the LSB portion of the received timestamp in the intermediate timestamp format and generate the filtered timestamp in the intermediate timestamp format. The circuit may further comprise output format-conversion logic coupled to the recursive filter logic. The output format-conversion logic may be configured to convert the filtered timestamp from the intermediate timestamp format to the original timestamp format and output the filtered timestamp in the original timestamp format.

(7) The original timestamp format may be based on seconds and nanoseconds and the intermediate timestamp format may be based on seconds and fractional seconds for non-limiting example.

(8) The circuit may further comprise rollover detection logic. The RLS filter may be configured to generate, based on the LSB portion, an estimated timestamp value of a target timestamp. The rollover detection logic may be configured to generate a rollover detection signal based on a comparison of the LSB portion and the estimated timestamp value generated. The circuit may be further configured to generate the filtered timestamp based on the estimated timestamp value generated, the rollover detection signal, and the MSB portion.

(9) The circuit may further comprise timestamp adjustment logic. The RLS filter may be configured to generate, based on the LSB portion, an estimated timestamp value of a target timestamp. The timestamp adjustment logic may be configured to generate a filtered timestamp value of the filtered timestamp based on the estimated timestamp value generated and the MSB portion.

(10) The timestamp adjustment logic may be further configured to adjust the estimated timestamp value generated or the MSB portion responsive to the rollover detection signal indicating that a) the estimated timestamp value generated has rolled over prior to roll over of the MSB portion or b) the MSB portion has rolled over prior to roll over of the estimated timestamp value generated, respectively.

(11) In an event the rollover detection signal has indicated a), the timestamp adjustment logic may be further configured to increment, on a cycle-by-cycle basis, the estimated timestamp value generated and, responsive to the rollover detection signal subsequently indicating that the MSB portion has rolled over, to stop incrementing of the estimated timestamp value generated.

(12) In an event the rollover detection signal has indicated (b), the timestamp adjustment logic may be further configured to increment, on a cycle-by-cycle basis, the MSB portion and, responsive to the rollover detection signal subsequently indicating that the estimated timestamp value has rolled over, to stop incrementing the MSB portion.

(13) The recursive filter logic may be further configured to reduce jitter in the filtered timestamp relative to jitter of the received timestamp. The jitter of the received timestamp may represent a deviation of the received timestamp from a target timestamp.

(14) The received timestamp may be received on a cycle-by-cycle basis. The recursive filter logic may be further configured to generate the filtered timestamp in real time, on the cycle-by-cycle

- basis. The cycle-by-cycle basis may be based on a clock cycle of a clock of the circuit.
- (15) The recursive filter logic may be further configured to reduce jitter in the filtered timestamp relative to jitter of the received timestamp. The received timestamp may be a synchronized timestamp, generated from an original timestamp by synchronizing the original timestamp across multiple clock domains. The jitter reduced may be dynamic jitter generated from the synchronizing.
- (16) The circuit may be further configured to output the filtered timestamp generated to a timestamp consumer. The timestamp consumer may be configured to associate an incoming packet, outgoing packet, or combination thereof, with the filtered timestamp generated and output from the circuit.
- (17) According to another example embodiment, a method comprises generating a filtered timestamp from a received timestamp by filtering the received timestamp via recursive filter logic. The recursive filter logic implements a recursive least-squares (RLS) filter. The generating includes applying the RLS filter to a portion of the received timestamp. A number of bits of the portion being less relative to a total number of bits of the received timestamp. The method further comprises outputting the filtered timestamp generated.
- (18) Further alternative method embodiments parallel those described above in connection with the example circuit embodiment.
- (19) According to yet another example embodiment, an apparatus comprises means for generating a filtered timestamp from a received timestamp by filtering the received timestamp via recursive filter logic. The recursive filter logic implements a recursive least-squares (RLS) filter. The generating includes applying the RLS filter to a portion of the received timestamp. A number of bits of the portion being less relative to a total number of bits of the received timestamp. The apparatus further comprises means for outputting the filtered timestamp generated.
- (20) Further alternative apparatus embodiments parallel those described above in connection with the example circuit embodiment.
- (21) It should be understood that example embodiments disclosed herein can be implemented in the form of a method, apparatus, system, or computer readable medium with program codes embodied thereon.
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## Description

### BRIEF DESCRIPTION OF THE DRAWINGS

- (1) The foregoing will be apparent from the following more particular description of example embodiments, as illustrated in the accompanying drawings in which like reference characters refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating embodiments.
- (2) FIG. 1 is a block diagram of an example embodiment of a circuit for timestamp jitter reduction.
- (3) FIG. 2 is a block diagram of an example embodiment of a filter circuit coupled to a timestamp (TS) synchronization circuit.
- (4) FIG. 3A is graph of an example embodiment of an actual timestamp versus an ideal timestamp.
- (5) FIG. 3B is a plot of an example embodiment of jitter in the actual timestamp of FIG. 3A.
- (6) FIG. 4 is a linear representation of an example embodiment of an ideal timestamp.
- (7) FIG. 5 is a graph of an example embodiment of signals over time that visualize an ability of a first-order recursive least squares (RLS) filter to track a first-order signal with noise.
- (8) FIG. 6 is a schematic diagram of an example embodiment of a circuit for timestamp jitter reduction.
- (9) FIG. 7 is a block diagram of an example embodiment of a circuit for filtering a received timestamp.

(10) FIG. **8** is a block diagram of another example embodiment of a circuit for filtering a received timestamp.

(11) FIGS. **9A-E** are graphs of example embodiments of waveforms that show timestamp jitter before and after filtering via an example embodiment of a circuit disclosed herein.

(12) FIG. **10** is a flow diagram of an example embodiment of a method for timestamp jitter reduction.

(13) FIG. **11** is a flow diagram of an example embodiment of a method for filtering a timestamp.

(14) FIG. **12** is a flow diagram of another example embodiment of a method for filtering a timestamp.

#### DETAILED DESCRIPTION

(15) A description of example embodiments follows.

(16) An example embodiment disclosed herein employs recursive filter logic. The recursive filter logic is recursive and, as such, re-uses one or more of its outputs as an input. Further, because the recursive filter logic is recursive, such logic may process new data as soon as it arrives in order to produce an estimate—as opposed to a batch processing technique that operates on all prior received data for each estimate. According to a non-limiting example embodiment, the recursive filter logic may be configured to implement a recursive least-squares (RLS) filter, which is a special case of a Kalman filter, disclosed further below with regard to equations (1) through (5), for non-limiting example. As such, the recursive filter logic that implements such a special case of the Kalman filter may also be referred to interchangeably herein as Kalman-filter-based (KFB) logic.

(17) While an example embodiment disclosed herein may be disclosed within a context of a cloud/centralized radio access network (C-RAN), fifth-generation (5G) C-RAN, the Institute of Electrical and Electronics Engineers (IEEE) 1588-2008 (Precision Time Protocol) standard, a radio head, or a system on a chip (SoC), it should be understood that example embodiments disclosed herein are not limited to same.

(18) 5G C-RAN based systems rely on high accuracy time synchronization between radio heads for good performance. The IEEE 1588-2008 (Precision Time Protocol) is typically used for such time synchronization. In a 5G C-RAN network, it is useful for each endpoint to generate a local clock and timestamp incoming/outgoing packets as accurately as possible. The endpoint may, for non-limiting example, be a radio head that employs a 5G SoC (system on chip) that is configured to perform the timestamping. Modern 5G SoCs have multiple clock domains and, thus, the timestamp may be created in one clock domain of the SoC and used in another clock domain of the SoC. As such, timestamp synchronization is needed due to the clock domain crossing. This synchronization creates jitter, that is, differences in the value of the synchronized timestamp versus the ideal timestamp, as disclosed further below. An example embodiment disclosed herein reduces timestamp differences resulting from such synchronization, thereby improving jitter and, subsequently, 5G performance. An example embodiment of a circuit for timestamp jitter reduction is disclosed below with regard to FIG. **1**.

(19) FIG. **1** is a block diagram of an example embodiment of a circuit **102** that comprises recursive filter logic **104**. The circuit **102** is configured to (i) generate a filtered timestamp **106** from a received timestamp **108** by filtering the received timestamp **108** via the recursive filter logic **104**. The recursive filter logic **104** is configured to reduce jitter (not shown) of the received timestamp **108**. The jitter represents a deviation of the received timestamp **108** from a target (ideal, correct) timestamp (not shown), such as disclosed further below with regard to FIG. **3A** and FIG. **3B**. The circuit **102** is further configured to output the filtered timestamp **106** generated.

(20) The filtered timestamp **106** generated and output is a more accurate representation of the target timestamp, relative to the received timestamp **108**, due to the jitter reduced. According to an example embodiment, the circuit **102** may be incorporated as a part of a system on a chip (SoC). It should be understood, however, that the circuit **102** is not limited thereto and may, for example, be implemented as a stand-alone integrated circuit (IC) chip for non-limiting example.

(21) According to an example embodiment, the jitter may be dynamic jitter that results from timestamp synchronization across clock domains and the received timestamp **108** may be a synchronized timestamp. As is known in the art, a clock domain crossing occurs whenever data is transferred from an electronic circuit element driven by one clock to another electronic circuit element that is driven by another clock. A system on a chip (SoC) is an example of a system that typically has multiple clock domains. A timestamp created in one clock domain of the SoC, and used in another clock domain of the SoC, benefits from synchronization. The synchronization may, however, result in differences in the value of the synchronized timestamp versus an ideal timestamp and such differences represent dynamic jitter. According to an example embodiment, the received timestamp **108** may be a synchronized timestamp, such as the synchronized timestamp **208** of FIG. 2, disclosed below. The circuit **102** may be configured to reduce maximum and/or average jitter resulting from timestamp synchronization across multiple clock domains, as disclosed below with regard to FIG. 2.

(22) FIG. 2 is a block diagram of an example embodiment of a filter circuit **202** coupled to a timestamp (TS) synchronization circuit **221**. The filter circuit **202** may be the circuit **102** of FIG. 1, disclosed above. Continuing with reference to FIG. 2, the filter circuit **202** comprises recursive filter logic **204**. The filter circuit **202** is configured to (i) generate a filtered timestamp **206** from a received timestamp, namely the synchronized timestamp **208**, by filtering the received timestamp (i.e., the synchronized timestamp **208**) via the recursive filter logic **204**. The recursive filter logic **204** is configured to reduce jitter (not shown) of the received timestamp, that is, the synchronized timestamp **208**. The jitter represents a deviation from a target (ideal, correct) timestamp (not shown), such as disclosed further below with regard to FIG. 3A and FIG. 3B. The filter circuit **202** is further configured to output the filtered timestamp **206** generated.

(23) The filtered timestamp **206** generated and output is a more accurate representation of the target timestamp, relative to the received timestamp (i.e., the synchronized timestamp **208**), due to the jitter reduced. The received timestamp (i.e., the synchronized timestamp **208**) may be received on a cycle-by-cycle basis. The filter circuit **202** may be further configured to generate the filtered timestamp **206** in real time on the cycle-by-cycle basis. The cycle-by-cycle basis may be based on a clock cycle of a clock of the filter circuit **202**, such as clk B of FIG. 2, disclosed below.

(24) According to the example embodiment of FIG. 2, the synchronized timestamp **208** is generated from an original timestamp **207**. The synchronized timestamp **208** is generated by synchronizing the original timestamp **207** across multiple clock domains, such as a first clock domain driven by a first clock **217**, also referred to interchangeably herein as clk A, and a second clock domain driven by a second clock **219**, also referred to interchangeably herein as clk B, for non-limiting example. In the example embodiment of FIG. 2, the received timestamp is the synchronized timestamp **208** that is generated from the original timestamp **207** by synchronizing the original timestamp **207** across the multiple clock domains. The jitter may be dynamic jitter that is generated from such synchronizing.

(25) In the example embodiment of FIG. 2, the TS synchronization circuit **221** is configured to implement the synchronizing and generate the synchronized timestamp **208** from the original timestamp **207**. The TS synchronization circuit **221** may implement any synchronizer technique for multi-clock domains known in the art and is not limited to any particular technique.

(26) There are multiple reasons for a presence of jitter in the synchronized timestamp **208**. A main reason is that, even with a state-of-the-art-synchronization mechanism employed by the TS synchronization circuit **221**, the synchronization mechanism will occasionally have at least one cycle of uncertainty, leading to missed samples. Other reasons for the presence of jitter may include rounding errors and/or initial timestamp generation with a clock (e.g., clk A) that is faster than a minimum increment/resolution of the timestamp for non-limiting examples. In general, a clock that is faster than the minimum increment of the timestamp (and whose period is not an integer multiple of that increment) will add jitter. Slow-clock-to-fast-clock conversions, for example, for cases in

which clk A is slower relative to clk B, may also contribute to jitter as slow-to-fast synchronization results in several (fast) cycles when a timestamp value doesn't change. It should be understood, however, that even fast-to-slow (e.g., clk A is faster relative to clk B) synchronization may suffer from missed samples and rounding. An example embodiment of jitter resulting from the synchronization mechanism is disclosed below with regard to FIG. 3A and FIG. 3B.

(27) FIG. 3A is graph 300 of an example embodiment of an actual timestamp 308 versus an ideal timestamp 333, that is, a target timestamp. The graph 300 plots timestamp values 335 for cycles 337 of a clock of a consumer, that is, a receiver of a timestamp that has been synchronized.

(28) Continuing with reference to FIG. 2 and FIG. 3A, the consumer is the filter circuit 202 and the cycles 337 are cycles of the second clock 219, that is, clk B. In the graph 300, the actual timestamp 308 represents the received timestamp, that is, the synchronized timestamp 208. The actual timestamp 308 differs from the ideal timestamp 333 for reasons such as disclosed above. Errors, such as the missed sample 339, error 341 (e.g., due to inherent uncertainty in the clock domain synchronization), and rounding error 343 are all typical errors of any synchronization mechanism used to produce a synchronized timestamp, such as the synchronized timestamp 208. Such errors cause jitter in the synchronized timestamp 208, represented as the actual timestamp 308 in the graph 300. An example embodiment of the jitter in the actual timestamp 308 is shown in FIG. 3B, disclosed below.

(29) FIG. 3B is a plot of an example embodiment of the jitter 301 in the actual timestamp 308 of FIG. 3A. With reference to FIG. 3A and FIG. 3B, the jitter 301 is represented by the error values 345 over the cycles 337, where the error values 345 are differences between the actual timestamp 308 and the ideal timestamp 333 over the cycles 337. An example embodiment disclosed herein estimates the “correct” timestamp for the actual timestamp 308 (i.e., synchronized timestamp) based on the understanding that the ideal timestamp 333, namely the target timestamp, is a straight line, such as disclosed below with regard to FIG. 4.

(30) FIG. 4 is a linear representation of an example embodiment of an ideal timestamp 433 that may also be referred to interchangeably herein as a target timestamp. The ideal timestamp 433 is a straight line represented by the equation  $y=ax+b$ , where  $y$  denotes the ideal timestamp value,  $a$  is the slope,  $x$  is the clock cycle, and  $b$  denotes the initial ideal timestamp value at clock cycle=0. The slope  $a$  represents a change in the ideal timestamp value that occurs over a number of clock cycles. Actual timestamp values of a synchronized timestamp, such as the actual timestamp values 408a, 408b, 408c, 408d, 408e, and 408f, do not lie on the straight line of the ideal timestamp 433 due to jitter, introduced by synchronization as disclosed above.

(31) If all of the actual timestamp values (e.g., 408a, 408b, 408c, 408d, 408e, and 408f) were known in advance, the “correct” timestamp could be estimated by estimating linear coefficients and using calculus to minimize a sum of the squares of the individual errors in order to obtain the “best” coefficients. That is, a least-square linear fit, also referred to interchangeably herein as a “least squares method,” could be employed. The least squares method is, however, a batch processing technique and, thus, all measurements need to be taken before estimates can be made. In addition, the least squares method relies on matrix multiplications and inversion, both of which are expensive due to the hardware complexity for implementing same. In contrast to a least squares method, an example embodiment estimates the correct (ideal, target) timestamp in real time and with low hardware complexity.

(32) An example embodiment disclosed herein converts the batch processing least squares method to a recursive form and employs a recursive least-squares (RLS) filter to estimate the correct timestamp. An example embodiment disclosed herein employs a special case of a Kalman filter. A Kalman filter is known in the art and details regarding same may be found, for non-limiting example, in “Polynomial Kalman Filters, Fundamentals of Kalman Filtering: A Practical Approach,” IAAC 2010 Workshops, Handouts, Mar. 17, 2017, available via the Internet (e.g., [iaac.technion.ac.il/workshops/2010/KFhandouts/LectKF4.pdf](http://iaac.technion.ac.il/workshops/2010/KFhandouts/LectKF4.pdf)) (hereinafter, “Polynomial Kalman



Filters non-patent-literature (NPL) document”).

(33) In a general Kalman filter, model parameters change over time and, as such, a general Kalman filter line estimation can change over time based on the broad Kalman filter equations. According to an example embodiment of recursive filter logic applied to time estimation as disclosed herein, however, a change in slope does not occur because the timestamp is estimated to be a linear function. According to an example embodiment, timestamp estimation may be based on gains of a first-order RLS filter.

(34) Specifically, according to an example embodiment, a first gain and a second gain, namely  $K_{\text{sub.1.sub.k}}$  and  $K_{\text{sub.2.sub.k}}$ , respectively, may be employed for timestamp estimation, that is, for estimating a target (ideal, correct) timestamp. Equations (1) and (2), disclosed below, may be used to determine the first and second gains, where  $k$  (i.e., the filter step) is incremented on each timestamp update and  $T_{\text{sub.s}}$  is the number of cycles since a last update.

$$(35) \quad K_{1_k} = \frac{2(2k-1)}{k(k+1)}k = 1, 2, \dots, n \quad (1) \quad K_{2_k} = \frac{6}{k(k+1)T_s} \quad (2)$$

(36) Such equations (1) and (2) are disclosed, for example, in the Polynomial Kalman Filters NPL document; however, they are not disclosed in the context of timestamp estimation.

(37) According to an example embodiment disclosed herein, equations of a first order RLS filter may be employed for timestamp estimation and a value of  $k$  employed in equations (1) and (2), disclosed above, represents a current filter step, where  $k$  is incremented on each timestamp update, that is, each time a current timestamp value,  $X_{\text{sub.k}*}$ , is updated by a TS synchronizer, such as the TS synchronization circuit 221 of FIG. 2, disclosed above for non-limiting example. According to an example embodiment,  $T_{\text{sub.s}}$ , as employed in equation (2) above, is a number of clock cycles since the timestamp value of the synchronized timestamp 208 of FIG. 2 was updated by the TS synchronizer 221.

(38) According to an example embodiment, a residual error of the timestamp estimation at a current filter step  $k$  may be defined by:

$$\text{Res.sub.k} = X_{\text{sub.k}*} - \{\text{circumflex over (X)}\}_{\text{sub.k-1}} - \{\text{dot over (\{circumflex over (X)\})}\}_{\text{sub.k-1}} T_{\text{sub.s}} \quad (3)$$

and the RLS filter, based on a first-order polynomial Kalman filter, becomes:

$$\{\text{circumflex over (X)}\}_{\text{sub.k}} = \{\text{circumflex over (X)}\}_{\text{sub.k-1}} + \{\text{dot over (\{circumflex over (X)\})}\}_{\text{sub.k-1}} T_{\text{sub.s}} - K_{\text{sub.1.sub.k}} \text{Res.sub.k} \quad (4)$$

$$\{\text{dot over (\{circumflex over (X)\})}\}_{\text{sub.k}} = \{\text{dot over (\{circumflex over (X)\})}\}_{\text{sub.k-1}} + K_{\text{sub.2.sub.k}} \text{Res.sub.k} \quad (5)$$

where  $k$  is incremented on each timestamp update,  $X^*$  is the current timestamp value from the synchronizer,  $T_{\text{sub.s}}$  is the number of cycles since the last update,  $\{\text{dot over (\{circumflex over (X)\})}\}$  is the estimated line slope of the ideal (target) timestamp, and  $\{\text{circumflex over (X)}\}$  is the estimated timestamp value.

(39) Given a new timestamp value, the RLS filter estimates the best  $\{\text{circumflex over (X)}\}$ , that is, the best estimated timestamp value, based on all values it has seen so far. In between timestamp updates (slow-to-fast), an example embodiment of the RLS filter estimates the timestamp by  $\{\text{circumflex over (X)}\}_{\text{sub.k-1}} + \{\text{dot over (\{circumflex over (X)\})}\}_{\text{sub.k-1}} \times T_{\text{sub.s}}$ . A generic example of a RLS filter tracking a linear signal with noise is disclosed with regard to FIG. 5, disclosed below.

(40) FIG. 5 is a graph 500 of an example embodiment of signals over time that visualize an ability of a first-order recursive least squares (RLS) filter to track a first-order signal with noise. The graph 500 is disclosed in “Recursive Least Squares Filtering,” IAAC 2010 Workshops, Handouts, Mar. 17, 2017, available via the Internet ([iaac.technion.ac.il/workshops/2010/KFhandouts/LectKF3.pdf](http://iaac.technion.ac.il/workshops/2010/KFhandouts/LectKF3.pdf)). Such signals include a measured signal, that is, the measurement 508 that is a noisy signal, a true signal 533, and an estimated signal, namely the estimate 506. The graph 500 is a generic example of a RLS filter tracking a linear signal with noise. An example embodiment disclosed herein

employs an example embodiment of a RLS filter to reduce timestamp jitter as disclosed below with regard to FIG. 6.

(41) FIG. 6 is a schematic diagram of an example embodiment of a circuit **602** for timestamp jitter reduction. The circuit **602** may be employed as the circuit **102** and filter circuit **202**, disclosed above with regard to FIG. 1 and FIG. 2, respectively. The circuit **602** is configured to estimate a “correct” (ideal, target) timestamp in real time and with low hardware complexity. The filtered timestamp **606** represents an estimate of such a correct timestamp. It should be understood that the circuit **602** is simplified for illustrative purpose and is not limited to the elements shown. Further, a circuit for timestamp jitter reduction disclosed herein is not limited to the specific design of the circuit **602**.

(42) The circuit **602** includes recursive filter logic **604**. The circuit **602** is configured to generate the filtered timestamp **606** from a received timestamp **608** by filtering the received timestamp **608** via the recursive filter logic **604**. The recursive filter logic **604** is configured to reduce jitter (not shown) of the received timestamp **608**. The jitter represents a deviation from a target (ideal) timestamp (not shown), such as disclosed above with regard to FIG. 3A and FIG. 3B. The circuit **602** is further configured to output the filtered timestamp **606** generated. The filtered timestamp **606** generated and output is a more accurate representation of the target timestamp relative to the received timestamp **608** based on the jitter reduced.

(43) The jitter of the received timestamp **608** may have a maximum value (not shown) and an average value (not shown) and the recursive filter logic **604** may be further configured to reduce the maximum value of the jitter, average value of the jitter, or a combination thereof.

(44) The circuit **602** may include a plurality of flip-flops (FFs), such as the flip-flop (FF) **612a**, FF **612b**, . . . , and FF **612j**. It should be understood that the circuit **602** may include more or less FFs than shown in FIG. 6. The plurality of FFs may be clocked via a clock (not shown) input to the circuit **602** and may be reset via a filter reset signal **679**. The recursive filter logic **604** may include filter-step control logic **654** configured to generate a filter step value **650**, referred to interchangeably herein as “k,” based on a clock cycle of the clock. The filter-step control logic **654** may be reset via the filter reset signal **679** and may be configured to increment a value **652** for the filter step value **650** (i.e., k) based on a clock cycle of the clock. The filter step value **650** (i.e., k) may be produced by sampling the value **652** via a FF **612e** for non-limiting example.

(45) According to an example embodiment, the filter-step control logic **652** may be configured to increment the filter step value **650** in response to a rising edge or falling edge of the clock and, in an event the filter step value **650** reaches an upper limit (cap, threshold), the filter-step control logic **652** may be configured to stop incrementing the filter step value **650** and to maintain the filter step value **650** at the upper limit (not shown). The upper limit may be sixteen for non-limiting example, as described further below. The filter-step control logic **654** may reset the filter step value **650** responsive to a change in state (e.g., rising edge or falling edge) of the filter reset signal **679** and increment the filter step value **650** in response to a rising edge or falling edge of the clock following same.

(46) According to an example embodiment, the circuit **602** may further comprise output-timestamp selection logic **675** configured to select between the received timestamp **608** and the filtered timestamp **606** generated and output. The output-timestamp selection logic **675** may be configured to output a selected timestamp **678** based on such selection. The output-timestamp selection logic **675** may, for non-limiting example, include an output multiplexer **677** configured to perform the selection based on an enable signal **676** input to the output multiplexer **677**.

(47) The enable signal **676** may be driven by a controller (not shown) for non-limiting example. The controller may drive the enable signal **676** based on a run-time mode of the circuit **602** for non-limiting example. For example, in the run-time mode of the circuit **602**, the enable signal **676** may be configured by the controller to cause the output multiplexer **677** to select the filtered timestamp **606** as the selected timestamp **678**. In a debug mode of the circuit **602**, the enable signal **676** may

be configured by the controller to cause the output multiplexer **677** to select the received timestamp **608** as the selected timestamp **678**.

(48) The selected timestamp **678** may be output to a different circuit (not shown) that may, for non-limiting example, be configured to timestamp packets based on same. Such timestamping may, for non-limiting example, include inserting the selected timestamp **678** in a field of a packet or appending the selected timestamp **678** to the packet. It should be understood that such selection via the enable signal **676** is for non-limiting example and that the output-timestamp selection logic **675** is optional. For example, the circuit **602** may be configured to output the filtered timestamp **606** directly to the different circuit that may, for non-limiting example, be configured to timestamp packets based on the filtered timestamp **606**. As such, the circuit **602** may be configured to output the filtered timestamp **606** to a timestamp consumer (not shown) that may, in turn, be configured to associate an incoming packet, outgoing packet, or combination thereof, with the filtered timestamp **606** generated and output from the circuit **602**.

(49) Within the context of the circuit **602**, the received timestamp **608** may be referred to interchangeably herein as  $X_{\text{sub}.k+2^*}$ , and may represent the received timestamp **608** at  $k+2$ , that is, at two clock cycles after which a current value of the filter step value **650** (i.e.,  $k$ ) is generated. The received timestamp **608** may be a synchronized timestamp received from a synchronizer, such as the TS synchronizer circuit **221** of FIG. 2, disclosed above for non-limiting example, and, thus, may have jitter present due to synchronization performed by the TS synchronizer circuit **221**, as disclosed above.

(50) Continuing with reference to FIG. 6, the received timestamp **608** may be sampled by the FF **612a** based on the clock to produce a sampled version **609** of the received timestamp **608**. The received timestamp **608** may be received in an original timestamp format (not shown) and the circuit **602** may further comprise input format-conversion logic **614**. The input format-conversion logic **614** may be configured to convert the received timestamp **608**, in the original timestamp format, to an intermediate version **611** of the received timestamp **608**, in an intermediate timestamp format (not shown). Such conversion may be based on an input conversion value **613**. According to an example embodiment, the original timestamp format may be based on seconds and nanoseconds and the intermediate timestamp format may be based on seconds and fractional seconds, as disclosed further below.

(51) For non-limiting example, the input format-conversion logic **614** may include a multiplier configured to multiply the sampled version **609** of the received timestamp **608**, in the original timestamp format, by the input conversion value **613** to produce the intermediate version **611** of the received timestamp **608** in the intermediate timestamp format, as disclosed further below. The intermediate version **611** of the received timestamp **608** may be sampled by the FF **612b** to produce a current timestamp value **616** of the received timestamp **608**. The current timestamp value **616** may be referred to interchangeably herein as  $X_x$ , disclosed above with regard to equations (3) through (5), and may represent the received timestamp **608** in the intermediate timestamp format, at the filter step value **650** (i.e.,  $k$ ). The current timestamp value **616** (i.e.,  $X_{\text{sub}.k^*}$ ) of the received timestamp **608** may be input to the recursive filter logic **604**.

(52) The recursive filter logic **604** may be further configured to implement a recursive least-squares (RLS) filter **610**, disclosed above with regard to equations (1) through (5). The RLS filter **610** may be configured to generate a current estimated timestamp value **638** (i.e.,  $\{\text{circumflex over (X)}\}_{\text{sub}.k}$ ) of the target (ideal) timestamp by generating a current estimated line slope value **637** (i.e.,  $\{\text{circumflex over (X)}\}_{\text{sub}.k}$ ) of a line slope of a linear function (not shown) based on the current timestamp value **616** (i.e.,  $X_{\text{sub}.k^*}$ ) of the received timestamp **608**. The current estimated timestamp value **638** and estimated line slope **637** may be referred to interchangeably herein as  $\{\text{circumflex over (X)}\}_{\text{sub}.k}$  and  $\{\text{dot over } (\{\text{circumflex over (X)}\})\}_{\text{sub}.k}$ , respectively. The linear function may represent the target (ideal) timestamp, as disclosed above with regard to FIG. 3A, FIG. 3B, and FIG. 4.

(53) Continuing with reference to FIG. 6, the current estimated timestamp value **638** (i.e.,  $\{\text{circumflex over (X)}\}.\text{sub.k}$ ) may be sampled by a FF **612c** to produce a previous estimated timestamp value **636** (i.e.,  $\{\text{circumflex over (X)}\}.\text{sub.k-1}$ ) and the current estimated line slope value **637** (i.e.,  $\{\text{dot over } (\{\text{circumflex over (X)}\})\}.\text{sub.k}$ ) may be sampled by a FF **612d** to produce a previous estimated line slope value **646** (i.e.,  $\{\text{dot over } (\{\text{circumflex over (X)}\})\}.\text{sub.k-1}$ ). The circuit **602** may be further configured to generate the filtered timestamp **606** based on the current estimated timestamp value **638** (i.e.,  $\{\text{circumflex over (X)}\}.\text{sub.k}$ ) generated, as disclosed further below. To implement the RLS filter **610** and generate the current estimated timestamp value **638** (i.e.,  $\{\text{circumflex over (X)}\}.\text{sub.k}$ ), the recursive filter logic **604** may be configured to implement equations (3) through (5), disclosed above, optionally based on optimizations, disclosed further below for non-limiting example.

(54) Based on equations (3) through (5), disclosed above, the RLS filter **610** may be configured to generate a current estimated timestamp value **638** (i.e.,  $\{\text{circumflex over (X)}\}.\text{sub.k}$ ) of the target timestamp and generate a current estimated line slope value **637** of a line slope of a linear function, the linear function representing the target timestamp. The current estimated timestamp value **638** may be generated based on a previous estimated timestamp value **636** (i.e.,  $\{\text{circumflex over (X)}\}.\text{sub.k-1}$ ) of the target timestamp and a previous estimated line slope value **646** (i.e.,  $\{\text{dot over } (\{\text{circumflex over (X)}\})\}.\text{sub.k-1}$ ) of the line slope of the linear function. The previous estimated timestamp value **636** (i.e.,  $\{\text{circumflex over (X)}\}.\text{sub.k-1}$ ) and previous estimated line slope value **646** (i.e.,  $\{\text{dot over } (\{\text{circumflex over (X)}\})\}.\text{sub.k-1}$ ) may be generated by the RLS filter **610** prior to generation of the current estimated timestamp value **638** (i.e.,  $\{\text{circumflex over (X)}\}.\text{sub.k}$ ) and current estimated line slope value **637** (i.e.,  $\{\text{dot over } (\{\text{circumflex over (X)}\})\}.\text{sub.k}$ ), respectively.

(55) The previous estimated timestamp value **636** (i.e.,  $\{\text{circumflex over (X)}\}.\text{sub.k-1}$ ) and the previous estimated line slope value **646** (i.e.,  $\{\text{dot over } (\{\text{circumflex over (X)}\})\}.\text{sub.k-1}$ ) may be generated by the RLS filter **610** in a previous clock cycle (e.g.,  $k-1$ ) and the previous clock cycle (e.g.,  $k-1$ ) may immediately precede a current clock cycle (e.g.,  $k$ ) in which the current estimated timestamp value **638** (i.e.,  $\{\text{circumflex over (X)}\}.\text{sub.k}$ ) and current estimated line slope value **637** (i.e.,  $\{\text{dot over } (\{\text{circumflex over (X)}\})\}.\text{sub.k}$ ) are generated.

(56) According to an example embodiment, the received timestamp **608** may be received on the cycle-by-cycle basis. The RLS filter **610** may be configured to generate an estimated timestamp value of the target timestamp, namely the current estimated timestamp value **638** (i.e.,  $\{\text{circumflex over (X)}\}.\text{sub.x}$ ) which is an estimate of the target timestamp, on the cycle-by-cycle basis, and the circuit **602** may be further configured to generate the filtered timestamp **606** on the cycle-by-cycle basis, based on the estimated timestamp value generated, that is, the current estimated timestamp value **638** (i.e.,  $\{\text{circumflex over (X)}\}.\text{sub.k}$ ).

(57) To implement the RLS filter **610**, the recursive filter logic **604** may include received-timestamp filter gain logic **621**, estimated-timestamp filter gain logic **623**, and estimated-line-slope filter gain logic **625**, as disclosed below.

(58) The received-timestamp filter gain logic **621** may be configured to produce a first filter-gain-received-timestamp product **630-1** (i.e.,  $K.\text{sub.1}.\text{sub.k}X.\text{sub.k}^*$ ) and a second filter-gain-received-timestamp product **630-2** (i.e.,  $K.\text{sub.2}.\text{sub.k}X.\text{sub.k}^*$ ). The received-timestamp filter gain logic **621** may be configured to produce the first filter-gain-received-timestamp product **630-1** (i.e.,  $K.\text{sub.1}.\text{sub.k}X.\text{sub.k}^*$ ) by multiplying at least a portion of the current timestamp value **616** (i.e.,  $Xx$ ) with a first filter gain value (i.e.,  $K.\text{sub.1}.\text{sub.k}$ ) (not shown), wherein the first filter gain value is in accordance with equation (1), disclosed above, and based on the filter step value **650**. It should be understood that  $k$ , namely the filter step value **650** is not limited to starting with a value of 1, as indicated with regard to equation (1) and may, for non-limiting example start with a value of 0.

(59) In the example embodiment of FIG. 6, the received-timestamp filter gain logic **621** may be further configured to produce the second filter-gain-received-timestamp product **630-2** by

multiplying the at least a portion of the current timestamp value **616** (i.e.,  $X_{\text{sub.k}}^*$ ) with a second filter gain value (i.e.,  $K_{\text{sub.2.sub.k}}$ ) (not shown), wherein the second filter gain value is in accordance with equation (2), disclosed above, and based on the filter step value **650**.

(60) For non-limiting example, the at least a portion of the current timestamp value **616** (i.e.,  $X_{\text{sub.k}}^*$ ) may be a least-significant bit (LSB) portion **618** of the current timestamp value **616** (i.e.,  $X_{\text{sub.k}}^*$ ), wherein the LSB portion **618** is of lesser significance relative to a most-significant bit (MSB) portion **619** of the current timestamp value **616** (i.e.,  $X_{\text{sub.k}}^*$ ). The at least a portion of the current timestamp value **616** (i.e.,  $X_{\text{sub.k}}^*$ ) may be the least-significant bit (LSB) portion **618** to optimize the circuit **602**, as disclosed further below.

(61) According to an example embodiment, the received-timestamp filter gain logic **621** may include a first received-timestamp multiplexer **626a**. The received-timestamp filter gain logic **621** may be configured to multiply the at least a portion of the current timestamp value **616** (i.e.,  $X_{\text{sub.k}}^*$ ) by a plurality of first filter gain values (not shown) to produce a plurality **620** of first filter-gain-received-timestamp products that may be input to the first received-timestamp multiplexer **626a**.

(62) Each first filter-gain-received-timestamp product of the plurality **620** of first filter-gain-received-timestamp products corresponds to the at least a portion of the current timestamp value **616** (i.e.,  $X_{\text{sub.k}}^*$ ) multiplied by a respective first filter gain value of the plurality of first filter gain values. To multiply the at least a portion of the current timestamp value **616** (i.e.,  $X_{\text{sub.k}}^*$ ) by each respective first filter gain value, the received-timestamp filter gain logic **621** may, for non-limiting example, be configured to shift the at least a portion of the current timestamp value **616** (i.e.,  $X_{\text{sub.k}}^*$ ) by each respective first filter gain value of the plurality of first filter gain values.

(63) For example, the plurality of first filter gain values may include sixteen first filter gain values for  $K_{\text{sub.1}}$  with the following values for  $K_{\text{sub.1}}$  corresponding to  $k=0, \dots, 15$  for non-limiting examples:  $k=0, 1.fwdarw.K_{\text{sub.1}}=1$ ;  $k=2 \dots 5.fwdarw.K_{\text{sub.1}}=0.5$ ;  $k=6 \dots$

$13.fwdarw.K_{\text{sub.1}}=0.25$ ; and  $k=14, 15.fwdarw.K_{\text{sub.1}}=0.125$ . The first and second inputs of to the first received-timestamp multiplexer **626a** (corresponding to a  $\text{select}=k=0, 1$ ) would both be equal to bits  $[N-1:0]$ ; the next four inputs (corresponding to  $k=2 \dots 5$ ) would all be equal to  $[N-1:1]$  (shift right by one, corresponding to  $\cdot 0.5$ ), the next eight inputs would be  $[N-1:2]$ , and the last two would be  $[N-1:3]$ , such inputs representing the plurality **620** of first filter-gain-received-timestamp products for non-limiting example.

(64) The first received-timestamp multiplexer **626a** may be configured to select the first filter-gain-received-timestamp product **630-1** (i.e.,  $K_{\text{sub.1.sub.k}}X_{\text{sub.k}}^*$ ) from the plurality **620** of first filter-gain-received-timestamp products based on the filter step value **650** (i.e.,  $k$ ) and may output the first filter-gain-received-timestamp product **630-1** (i.e.,  $K_{\text{sub.1.sub.k}}X_{\text{sub.k}}^*$ ) selected to an estimated-timestamp producer **634**.

(65) The estimated-timestamp producer **634** may be configured to produce the current estimated timestamp value **638** (i.e.,  $\{\text{circumflex over (X)}\}_{\text{sub.k}}$ ) by combining the first filter-gain-received-timestamp product **630-1** (i.e.,  $K_{\text{sub.1.sub.k}}X_{\text{sub.k}}^*$ ) with a previous estimated timestamp value **636** (i.e.,  $\{\text{circumflex over (X)}\}_{\text{sub.k-1}}$ ), a first filter-gain-previous-estimated-timestamp product **644-1** (i.e.,  $K_{\text{sub.1.sub.k}}\{\text{circumflex over (X)}\}_{\text{sub.k-1}}$ ), a previous estimated line slope value **646** (i.e.,  $\{\text{dot over } (\{\text{circumflex over (X)}\})\}_{\text{sub.k-1}}$ ), and a first filter-gain-previous-estimated-line-slope product **648-1** (i.e.,  $K_{\text{sub.1.sub.k}}\{\text{dot over } (\{\text{circumflex over (X)}\})\}_{\text{sub.k-1}}$ ). The first filter-gain-previous-estimated-line-slope product **648-1** (i.e.,  $K_{\text{sub.1.sub.k}}\{\text{dot over } (\{\text{circumflex over (X)}\})\}_{\text{sub.k-1}}$ ) may be produced via the estimated-line-slope filter gain logic **625**, as disclosed further below.

(66) According to an example embodiment, the estimated-timestamp producer **634** may be configured to produce the current estimated timestamp value **638** (i.e.,  $\{\text{circumflex over (X)}\}_{\text{sub.k}}$ ) by adding (i) the previous estimated timestamp value **636** (i.e.,  $\{\text{circumflex over (X)}\}_{\text{sub.k-1}}$ ), (ii) the previous estimated line slope value **646** (i.e.,  $\{\text{dot over } (\{\text{circumflex over (X)}\})\}_{\text{sub.k-1}}$ ),

(X))}.sub.k-1) multiplied by a number of cycles T.sub.s since a last timestamp update of the received timestamp **608**, and (iii) the first filter-gain-received-timestamp product **630-1** (i.e., K.sub.1.sub.kX.sub.k\*), and subtracting (iv) the first filter-gain-previous-estimated-timestamp product **644-1** (i.e., K.sub.1.sub.k{circumflex over (X)}.sub.k-1) and (v) the first filter-gain-previous-estimated-line-slope product **648-1** (i.e., K.sub.1.sub.k{dot over ({circumflex over (X))}.sub.k-1) multiplied by the number of cycles T.sub.s, as disclosed above with regard to equations (3) through (5). According to an example embodiment, the number of cycles T.sub.s may be one. In accordance with equation (4), above, the RLS filter **610** may be further configured to generate the current estimated timestamp value **638** (i.e., {circumflex over (X)}.sub.k) based on a product of the previous estimated timestamp value **636** (i.e., {circumflex over (X)}.sub.k-1) and a number of clock cycles that transpired since a last update of the received timestamp **608**.

(67) The received-timestamp filter gain logic **621** may further include a second received-timestamp multiplexer **628a**. The received-timestamp filter gain logic **621** may be configured to multiply the at least a portion of the current timestamp value **616** (i.e., X.sub.k\*) by a plurality of second filter gain values (not shown) to produce a plurality (not shown) of second filter-gain-received-timestamp products input to the second received-timestamp multiplexer **628a**.

(68) Each second filter-gain-received-timestamp product of the plurality of second filter-gain-received-timestamp products may represent the at least a portion of the current timestamp value **616** (i.e., X.sub.k\*) multiplied by a respective second filter gain value of the plurality of second filter gain values. To multiply the at least a portion of the current timestamp value **616** (i.e., X.sub.k\*) by each respective second filter gain value, the received-timestamp filter gain logic **621** may, for non-limiting example, be configured to shift the at least a portion of the current timestamp value **616** (i.e., X.sub.k\*) by each respective second filter gain value.

(69) The second received-timestamp multiplexer **628a** may be configured to select the second filter-gain-received-timestamp product **630-2** (i.e., K.sub.2.sub.kX.sub.k\*) from the plurality of second filter-gain-received-timestamp products and output the second filter-gain-received-timestamp product **630-2** (i.e., K.sub.2.sub.kX.sub.k\*) to an estimated-line-slope producer **635**, as disclosed further below. The second received-timestamp multiplexer **628a** may be configured to select the second filter-gain-received-timestamp product **630-2** (i.e., K.sub.2.sub.kX.sub.k\*) from the plurality of second filter-gain-received-timestamp products based on the filter step value **650** (i.e., k).

(70) As disclosed above, the estimated-timestamp producer **634** may be configured to produce the current estimated timestamp value **638** (i.e., {circumflex over (X)}.sub.k) based on the first filter-gain-previous-estimated-timestamp product **644-1** (i.e., K.sub.1.sub.k{circumflex over (X)}.sub.k-1). The estimated-timestamp filter gain logic **623** may be configured to produce the first filter-gain-estimated-timestamp product **644-1** (i.e., K.sub.1.sub.k{circumflex over (X)}.sub.k-1), input to the estimated-timestamp producer **634**, as disclosed above, and may be further configured to produce a second filter-gain-estimated-timestamp product **644-2** (i.e., K.sub.2.sub.k {circumflex over (X)}.sub.k-1).

(71) The estimated-timestamp filter gain logic **623** may be configured to produce the first filter-gain-estimated-timestamp product **644-1** (i.e., K.sub.1.sub.k{circumflex over (X)}.sub.k-1) by multiplying the previous estimated timestamp value **636** (i.e., X.sub.k-1\*) with the first filter gain value (i.e., K.sub.1.sub.k) of the plurality of first filter gain values. The estimated-timestamp filter gain logic **623** may be further configured to produce the second filter-gain-estimated-timestamp product **644-2** (i.e., K.sub.2.sub.k{circumflex over (X)}.sub.k-1) by multiplying the previous estimated timestamp value **636** (i.e., X.sub.k-1\*) with the second filter gain value (i.e., K.sub.2.sub.k) of the plurality of second filter gain values.

(72) According to an example embodiment, the estimated-timestamp filter gain logic **623** may include a first estimated-timestamp multiplexer **626b**. The estimated-timestamp filter gain logic **623** may be configured to multiply the previous estimated timestamp value **636** (i.e., X.sub.k-1\*)

by each first filter gain value of the plurality of first filter gain values to produce a plurality **622** of first filter-gain-previous-estimated-timestamp products that may be input to the first estimated-timestamp multiplexer **626b**.

(73) Each first filter-gain-estimated-timestamp product of the plurality **622** of first filter-gain-estimated-timestamp products corresponds to the previous estimated timestamp value **636** (i.e.,  $X_{\text{sub.k}-1}$ ) multiplied by a respective first filter gain value of the plurality of first filter gain values. To multiply the previous estimated timestamp value **636** (i.e.,  $X_{\text{sub.k}-1}$ ) by each respective first filter gain value, the estimated-timestamp filter gain logic **623** may, for non-limiting example, be configured to shift the previous estimated timestamp value **636** (i.e.,  $X_{\text{sub.k}-1}$ ) by each respective first filter gain value of the plurality of first filter gain values.

(74) The first estimated-timestamp multiplexer **626b** may be configured to select the first filter-gain-estimated-timestamp product **644-1** (i.e.,  $K_{\text{sub.1.sub.k}}\{\text{circumflex over (X)}\}_{\text{sub.k}-1}$ ) from the plurality **622** of first filter-gain-estimated-timestamp products based on the filter step value **650** (i.e.,  $k$ ) and may output the first filter-gain-estimated-timestamp product **644-1** (i.e.,  $K_{\text{sub.1.sub.k}}\{\text{circumflex over (X)}\}_{\text{sub.k}-1}$ ) selected to the estimated-timestamp producer **634**, disclosed above.

(75) The estimated-timestamp filter gain logic **623** may further include a second estimated-timestamp multiplexer **628b**. The estimated-timestamp filter gain logic **623** may be further configured to multiply the previous estimated timestamp value **636** (i.e.,  $X_{\text{sub.k}-1}$ ) by each second filter gain value of the plurality of second filter gain values to produce a plurality (not shown) of second filter-gain-estimated-timestamp products input to the second estimated-timestamp multiplexer **626b**.

(76) Each second filter-gain-estimated-timestamp product of the plurality of second filter-gain-estimated-timestamp products may represent the previous estimated timestamp value **636** (i.e.,  $X_{\text{sub.k}-1}$ ) multiplied by a respective second filter gain value of the plurality of second filter gain values. To multiply the previous estimated timestamp value **636** (i.e.,  $X_{\text{sub.k}-1}$ ) by each respective second filter gain value, the estimated-timestamp filter gain logic **623** may, for non-limiting example, be configured to shift the previous estimated timestamp value **636** (i.e.,  $X_{\text{sub.k}-1}$ ) by each respective second filter gain value.

(77) The second estimated-timestamp multiplexer **628b** may be configured to select the second filter-gain-estimated-timestamp product **644-2** (i.e.,  $K_{\text{sub.2.sub.k}}\{\text{circumflex over (X)}\}_{\text{sub.k}-1}$ ) from the plurality of second filter-gain-estimated-timestamp products and output the second filter-gain-estimated-timestamp product **644-2** (i.e.,  $K_{\text{sub.2.sub.k}}\{\text{circumflex over (X)}\}_{\text{sub.k}-1}$ ) to the estimated-line-slope producer **635**. The second estimated-timestamp multiplexer **628b** may be configured to select the second filter-gain-estimated-timestamp product **644-2** (i.e.,  $K_{\text{sub.2.sub.k}}\{\text{circumflex over (X)}\}_{\text{sub.k}-1}$ ) from the plurality of second filter-gain-estimated-timestamp products based on the filter step value **650** (i.e.,  $k$ ).

(78) The estimated-line-slope producer **635** may be configured to produce the current estimated line slope value **637** (i.e.,  $\{\text{dot over (}\{\text{circumflex over (X)}\}\}_{\text{sub.k}}\}$ ) by combining the second filter-gain-received-timestamp product **630-2** (i.e.,  $K_{\text{sub.2.sub.k}}X_{\text{sub.k}}$ ), the second filter-gain-estimated-timestamp product **644-2** (i.e.,  $K_{\text{sub.2.sub.k}}\{\text{circumflex over (X)}\}_{\text{sub.k}-1}$ ), the previous estimated line slope value **646** (i.e.,  $\{\text{dot over (}\{\text{circumflex over (X)}\}\}_{\text{sub.k}-1}$ ), and a second filter-gain-estimated-line-slope product **648-2** (i.e.,  $K_{\text{sub.2.sub.k}}\{\text{dot over (}\{\text{circumflex over (X)}\}\}_{\text{sub.k}-1}$ ). The second filter-gain-estimated-line-slope product **648-2** (i.e.,  $K_{\text{sub.2.sub.k}}\{\text{dot over (}\{\text{circumflex over (X)}\}\}_{\text{sub.k}-1}$ ) may be produced via the estimated-line-slope filter gain logic **625**, as disclosed further below.

(79) According to an example embodiment, the estimated-line-slope producer **635** may be configured to produce the current estimated line slope value **637** (i.e.,  $\{\text{dot over (}\{\text{circumflex over (X)}\}\}_{\text{sub.k}}\}$ ) by adding (i) the previous estimated line slope value **646** (i.e.,  $\{\text{dot over (}\{\text{circumflex over (X)}\}\}_{\text{sub.k}-1}$ ) and (ii) the second filter-gain-received-timestamp product **630-2** (i.e.,

K.sub.2.sub.kX.sub.k\*) and subtracting (iii) the second filter-gain-estimated-timestamp product **644-2** (i.e.,  $K_{\text{sub.2.sub.kX.sub.k-1}}$ ) and (iv) second filter-gain-estimated-line-slope product **648-2** (i.e.,  $K_{\text{sub.2.sub.k}\{\dot{\circ}\over(\{\circ\over(X)\})\}\text{sub.k-1}}$ ), multiplied by a number of cycles  $T_{\text{sub.s}}$  since a last timestamp update of the received timestamp **608**, as disclosed above with regard to equations (3) through (5). According to an example embodiment, the number of cycles  $T_{\text{sub.s}}$  may be one. The second filter-gain-estimated-line-slope product **648-2** (i.e.,  $K_{\text{sub.2.sub.k}\{\dot{\circ}\over(\{\circ\over(X)\})\}\text{sub.k-1}}$ ) may be produced via the estimated-line-slope filter gain logic **625**, as disclosed below.

(80) The estimated-line-slope filter gain logic **625** may be configured to produce the first filter-gain-estimated-line-slope product **648-1** (i.e.,  $K_{\text{sub.1.sub.k}\{\dot{\circ}\over(\{\circ\over(X)\})\}\text{sub.k-1}}$ ) and the second filter-gain-estimated-line-slope product **648-2** (i.e.,  $K_{\text{sub.2.sub.k}\{\dot{\circ}\over(\{\circ\over(X)\})\}\text{sub.k-1}}$ ) that are input to the estimated-timestamp producer **634** and estimated-line-slope producer **635**, respectively, as disclosed above.

(81) The estimated-line-slope filter gain logic **625** may be further configured to produce the first filter-gain-estimated-line-slope product **648-1** (i.e.,  $K_{\text{sub.1.sub.k}\{\dot{\circ}\over(\{\circ\over(X)\})\}\text{sub.k-1}}$ ) by multiplying the previous estimated line slope value **646** (i.e.,  $\{\dot{\circ}\over(\{\circ\over(X)\})\}\text{sub.k-1}$ ) with the first filter gain value (i.e.,  $K_{\text{sub.1.sub.k}}$ ) of the plurality of first filter gain values.

(82) The estimated-line-slope filter gain logic **625** may be further configured to produce the second filter-gain-estimated-line-slope product **648-2** (i.e.,  $K_{\text{sub.2.sub.k}\{\dot{\circ}\over(\{\circ\over(X)\})\}\text{sub.k-1}}$ ) by multiplying the previous estimated line slope value **646** (i.e.,  $\{\dot{\circ}\over(\{\circ\over(X)\})\}\text{sub.k-1}$ ) with the second filter gain value (i.e.,  $K_{\text{sub.2.sub.k}}$ ) of the plurality of second filter gain values.

(83) According to an example embodiment, the estimated-line-slope filter gain logic **625** may include a first estimated-line-slope multiplexer **626c**. The estimated-line-slope filter gain logic **625** may be further configured to multiply the previous estimated line slope value **646** (i.e.,  $\{\dot{\circ}\over(\{\circ\over(X)\})\}\text{sub.k-1}$ ) by each first filter gain value of the plurality of first filter gain values to produce a plurality **624** of first filter-gain-estimated-line-slope products that may be input to the first estimated-line-slope multiplexer **626a**.

(84) Each first filter-gain-estimated-line-slope product of the plurality **624** of first filter-gain-estimated-line-slope products corresponds to the previous estimated line slope value **646** (i.e.,  $\{\dot{\circ}\over(\{\circ\over(X)\})\}\text{sub.k-1}$ ) multiplied by a respective first filter gain value of the plurality of first filter gain values. To multiply the previous estimated line slope value **646** (i.e.,  $\{\dot{\circ}\over(\{\circ\over(X)\})\}\text{sub.k-1}$ ) by each respective first filter gain value, the estimated-line-slope filter gain logic **625** may, for non-limiting example, be configured to shift the previous estimated line slope value **646** (i.e.,  $\{\dot{\circ}\over(\{\circ\over(X)\})\}\text{sub.k-1}$ ) by each respective first filter gain value of the plurality of first filter gain values.

(85) The first estimated-line-slope multiplexer **626c** may be configured to select the first filter-gain-estimated-line-slope product **648-1** (i.e.,  $K_{\text{sub.1.sub.k}\{\dot{\circ}\over(\{\circ\over(X)\})\}\text{sub.k-1}}$ ) from the plurality **624** of first filter-gain-estimated-line-slope products based on the filter step value **650** (i.e.,  $k$ ) and may output the first filter-gain-estimated-line-slope product **648-1** (i.e.,  $K_{\text{sub.1.sub.k}\{\dot{\circ}\over(\{\circ\over(X)\})\}\text{sub.k-1}}$ ) selected to the estimated-timestamp producer **634** disclosed above.

(86) The estimated-line-slope filter gain logic **625** may further include a second estimated-line-slope multiplexer **628c**. The estimated-line-slope filter gain logic **625** may be configured to multiply the previous estimated line slope value **646** (i.e.,  $\{\dot{\circ}\over(\{\circ\over(X)\})\}\text{sub.k-1}$ ) by each second filter gain value of the plurality of second filter gain values to produce a plurality (not shown) of second filter-gain-estimated-line-slope products input to the second estimated-line-slope multiplexer **626c**.

(87) Each second filter-gain-estimated-line-slope product of the plurality of second filter-gain-



estimated-line-slope products may represent the previous estimated line slope value **646** (i.e.,  $\{\dot{\overline{(X)}}\}_{\text{sub.k}-1}$ ) multiplied by a respective second filter gain value of the plurality of second filter gain values. To multiply the previous estimated line slope value **646** (i.e.,  $\{\dot{\overline{(X)}}\}_{\text{sub.k}-1}$ ) by each respective second filter gain value, the estimated-line-slope filter gain logic **625** may, for non-limiting example, be configured to shift the previous estimated line slope value **646** (i.e.,  $\{\dot{\overline{(X)}}\}_{\text{sub.k}-1}$ ) by each respective second filter gain value.

(88) The second estimated-line-slope multiplexer **628c** may be configured to select the second filter-gain-estimated-line-slope product **648-2** (i.e.,  $K_{\text{sub.2.sub.k}}\{\dot{\overline{(X)}}\}_{\text{sub.k}-1}$ ) from the plurality of second filter-gain-estimate-line-slope products and output the second filter-gain-estimated-line-slope product **648-2** (i.e.,  $K_{\text{sub.2.sub.k}}\{\dot{\overline{(X)}}\}_{\text{sub.k}-1}$ ) to the estimated-line-slope producer **635**. The second estimated-line-slope multiplexer **628c** may be configured to select the second filter-gain-estimated-line-slope product **648-2** (i.e.,  $K_{\text{sub.2.sub.k}}\{\dot{\overline{(X)}}\}_{\text{sub.k}-1}$ ) from the plurality of second filter-gain-estimated-line-slope products based on the filter step value **650** (i.e.,  $k$ ). The second filter-gain-estimated-line-slope product **648-2** (i.e.,  $K_{\text{sub.2.sub.k}}\{\dot{\overline{(X)}}\}_{\text{sub.k}-1}$ ) may be input to the estimated-line-slope producer **635** for generating the current estimated line slope value **637** (i.e.,  $\{\dot{\overline{(X)}}\}_{\text{sub.k}}$ ), as disclosed above.

(89) As disclosed above, the previous estimated line slope value **637** (i.e.,  $\{\dot{\overline{(X)}}\}_{\text{sub.k}-1}$ ) may be used by the estimated-timestamp producer **634** to produce the current estimated timestamp value **638** (i.e.,  $\{\overline{(X)}\}_{\text{sub.k}}$ ) produced by the RLS filter **610**. The filtered timestamp **606** may be generated based on the current estimated timestamp value **638** (i.e.,  $\{\overline{(X)}\}_{\text{sub.k}}$ ) as disclosed below.

(90) According to an example embodiment, the at least a portion of the current timestamp value **616** (i.e.,  $X_{\text{sub.k}}$ ) input to the RLS filter **610** may be the least-significant bit (LSB) portion **618** of the current timestamp value **616**, namely 'N' least significant bits (LSBs) of a total number of bits of the current timestamp value **616** (i.e.,  $X_{\text{sub.k}}$ ), which may be in the intermediate timestamp format based on the input format-conversion logic **614** disclosed above and further below.

(91) In an event the at least a portion of the current timestamp value **616** (i.e.,  $X_{\text{sub.k}}$ ) input to the RLS filter **610** is 'N' bits, the first filter-gain-received-timestamp product **630-1** (i.e.,  $K_{\text{sub.1.sub.k}}X_{\text{sub.k}}$ ), second filter-gain-received-timestamp product **630-2** (i.e.,  $K_{\text{sub.2.sub.k}}X_{\text{sub.k}}$ ), first filter-gain-previous-estimated-timestamp product **644-1** (i.e.,  $K_{\text{sub.1.sub.k}}\{\overline{(X)}\}_{\text{sub.k}-1}$ ), second filter-gain-estimated-timestamp product **644-2** (i.e.,  $K_{\text{sub.2.sub.k}}\{\overline{(X)}\}_{\text{sub.k}-1}$ ), first filter-gain-previous-estimated-line-slope product **648-1** (i.e.,  $K_{\text{sub.1.sub.k}}\{\dot{\overline{(X)}}\}_{\text{sub.k}-1}$ ), second filter-gain-estimated-line-slope product **648-2** (i.e.,  $K_{\text{sub.2.sub.k}}\{\dot{\overline{(X)}}\}_{\text{sub.k}-1}$ ), previous estimated line slope value **646** (i.e.,  $\{\dot{\overline{(X)}}\}_{\text{sub.k}-1}$ ), current estimated line slope value **637** (i.e.,  $\{\dot{\overline{(X)}}\}_{\text{sub.k}}$ ), previous estimated timestamp value **636** (i.e.,  $\{\overline{(X)}\}_{\text{sub.k}-1}$ ), and current estimated timestamp value **638** (i.e.,  $\{\overline{(X)}\}_{\text{sub.k}}$ ), each have a total number of bits that is 'N' bits.

(92) According to an example embodiment, the recursive filter logic **604** may further include rollover detection logic **670** and timestamp adjustment logic **666**. The rollover detection logic **670** may be configured to produce a rollover detection signal **660** based on the LSB portion **618** of the current timestamp value **616** (i.e.,  $X_{\text{sub.k}}$ ) and the current estimated timestamp value **638** (i.e.,  $\{\overline{(X)}\}_{\text{sub.k}}$ ), as disclosed further below. The rollover detection signal **660** may be sampled by the FF **612g** to produce a sampled version **661** of the rollover detection signal **660**. The rollover detection logic **670** and timestamp adjustment logic **666** may be coupled within the circuit **602** and the sampled version **661** of the rollover detection signal **660** may be input to the timestamp adjustment logic **666** and employed by the timestamp adjustment logic **666** as disclosed below.

(93) The timestamp adjustment logic **666** may be configured to produce a filtered timestamp value **668** having a total number of bits of the current timestamp value **616** (i.e.,  $X_{\text{sub.k}}^*$ ). The filtered timestamp value **668** may be based on the current estimated timestamp value **638** (i.e.,  $\{\text{circumflex over (X)}\}_{\text{sub.k}}$ ) and the MSB portion **619** of the current timestamp value **616** (i.e.,  $X_{\text{sub.k}}^*$ ), as disclosed further below. The MSB portion **619** may be sampled by the FF **612f** to produce a sampled version **662** of the MSB portion **619**. The current estimated timestamp value **638** (i.e.,  $\{\text{circumflex over (X)}\}_{\text{sub.k}}$ ) may be sampled by the FF **612h** to produce a sampled version **664** of the current estimated timestamp value **638** (i.e.,  $\{\text{circumflex over (X)}\}_{\text{sub.k}}$ ).

(94) The timestamp adjustment logic **666** may be further configured to produce the filtered timestamp value **668** based on the sampled version **662** of the MSB portion **619** of the current timestamp value **616** (i.e.,  $X_{\text{sub.k}}^*$ ), sampled version **664** of the current estimated timestamp value **638** (i.e.,  $\{\text{circumflex over (X)}\}_{\text{sub.k}}$ ), and sampled version **661** of the rollover detection signal **660**, as disclosed further below.

(95) The filtered timestamp value **668** may be in the intermediate timestamp format and may be sampled by the FF **612i** to produce a sampled version **671** of the filtered timestamp value **668**. The circuit **602** may further comprise output format-conversion logic **672** configured to convert the sampled version **671** of the filtered timestamp value **668**, in the intermediate timestamp format, to a sampled version **674** of the filtered timestamp value **668** in the original timestamp format, as disclosed further below. The sampled version **674** of the filtered timestamp value **668**, in the original timestamp format, may be sampled via the FF **612j** to generate the filtered timestamp **606** that is generated and output by the circuit **602** in the original timestamp format.

(96) According to an example embodiment, the circuit **602** may further comprise reset logic **667**. The reset logic **667** may be configured to assert (activate) the filter reset signal **679** based on the current timestamp value **616** (i.e.,  $X_{\text{sub.k}}^*$ ), in the intermediate timestamp format, and the sampled version **671** of the filtered timestamp value **668**, in the intermediate timestamp format. The filter reset signal **679** may represent an error signal that is asserted, for non-limiting example, based on an absolute difference (not shown) between the current timestamp value **616** (i.e.,  $X_{\text{sub.k}}^*$ ), in the intermediate timestamp format, and the sampled version **671** of the filtered timestamp value **668**, in the intermediate timestamp format, as disclosed in detail further below.

(97) Assertion of the filter reset signal **679** may be represented as an active low state of the filter reset signal **679**, active high state of the filter reset signal **679**, or change in state of the filter reset signal **679** for non-limiting examples. The filter reset signal **679** is not limited to being asserted based on the absolute difference and may, for non-limiting example, be asserted based on an input reset control signal (not shown) driven by a processor (not shown) in response to an instruction(s) executed by the processor and/or based on a reset of a chip (not shown) that incorporates the circuit **602**.

(98) According to an example embodiment, the filter reset signal **679** may be asserted based on the absolute difference such that the circuit **602** is reset in an event the residual error of the RLS filter **610**, namely  $\text{Res}_{\text{sub.k}}$ , disclosed above with regard to equation (3), exceeds an error threshold. The reset logic **667** may be configured to reset the recursive filter logic **604**, automatically, based on the residual error  $\text{Res}_{\text{sub.k}}$  computed, thereby resetting the RLS filter **610**.

(99) As disclosed above, the recursive filter logic **604** may be configured to produce the current estimated line slope value **637** (i.e.,  $\{\text{dot over } (\{\text{circumflex over (X)}\})\}_{\text{sub.k}}$ ) and the current estimated timestamp value **638** (i.e.,  $\{\text{circumflex over (X)}\}_{\text{sub.k}}$ ) based on equations (1) through (5), disclosed above. According to an example embodiment, several optimizations and simplifications to the above-noted equations may be employed for non-limiting example. For example,  $T_{\text{sub.s}}$  may be set to one, reflecting an update of the received timestamp **608** on every clock cycle, according to an example embodiment. According to another example embodiment, a value for  $k$ , that is, the filter step value **650**, may be capped (limited) such that  $k$  does not increment above an upper threshold value, such as sixteen for non-limiting example.

(100) According to an example embodiment, the value for  $k$  may be capped at the upper threshold at which it is determined that the first gain  $K_{\text{sub.1.sub.k}}$  and second gain  $K_{\text{sub.2.sub.k}}$ , disclosed in equations (1) and (2), above, respectively, are small enough to be deemed negligible. For example, if the RLS filter **610** was able to lock onto the target (ideal, correct) timestamp with  $k$  at the capped value, it is understood that it will remain locked. For example, with  $k$  at the capped value, the RLS filter **610** may continue to track the straight line of the target (ideal, correct) timestamp over time even though  $k$  is no longer updating over time. Limiting  $k$  such that a value of same does not increment above an upper threshold value enables hardware logic of the circuit **602** to be simplified.

(101) According to another example embodiment, values for the first gain  $K_{\text{sub.1.sub.k}}$  and second gain  $K_{\text{sub.2.sub.k}}$  may be rounded down to the nearest power-of-2 fraction. Such rounding may cause slightly slower convergence (a few cycles), but significantly simplifies the hardware implementation of the circuit **602**. For non-limiting example, a timestamp format handled within the circuit **602** may be a format that contains 32-bit seconds and 32-bit nanoseconds ( $<10^9$ ). It should be understood, however, that the timestamp format handled by the circuit **602** is not limited to such format. According to an example embodiment, an original timestamp format of the received timestamp **608** may, for non-limiting example, be converted internally, that is, internal to the circuit **602**, to an intermediate timestamp format of 32-bit seconds, 32-bit fractional seconds, to ease rollover (wrap-around) handling, and the output-format conversion logic **672** may be employed for timestamp format conversion such that the filtered timestamp **606** is output in the original timestamp format, as disclosed above and further below.

(102) Rollover Detection and Timestamp Format Conversion

(103) Continuing with reference to FIG. 6, according to an example embodiment, a timestamp format for the received/synchronized timestamp, that is, the received timestamp **608**, may be 64 bits, composed of 32-bit seconds and 32-bit nanoseconds (the nanoseconds part takes values from 0 to  $10^9-1$ ; 0x00000000 to 0x3B9AC9FF in hexadecimal). It should be understood, however, that the timestamp format for the received timestamp **608** is not limited thereto. Further, while the following disclosure related to rollover (wrap-around) and timestamp format conversion may be explained with regard to a 64-bit format, it should be appreciated that such disclosure is not limited thereto and that the concepts with respect to same may be extended to other formats.

(104) The original equations, that is, equations (3)-(5), disclosed above, assume that  $X_{\text{sub.k}^*}$ , that is, the current timestamp value **616** of the received timestamp **608**, changes smoothly. Absent additional special logic disclosed above and below with regard to FIG. 6, a hardware implementation of the RLS filter **610** would not “understand” that a difference between consecutive inputs of, for non-limiting example, 0x000000013B9AC9FF (i.e., 1 s,  $10^9-1$  ns) and 0x0000000200000000 (i.e., 2 s, 0 ns), is just one nanosecond. To the RLS filter **610**, such difference would look like a 0xC4653601 difference (i.e., over 3 billion ns) and, thus, the RLS filter **610** would attempt to (incorrectly) adjust its estimation to match this. This huge difference (i.e., over 3 billion ns) would occur every time the seconds part is incremented; or in other words, when the nanoseconds roll over.

(105) Logic to handle this rollover is relatively complicated and increases the area and power consumption of the implementation. A more efficient solution disclosed herein with regard to FIG. 6 is to convert the received timestamp **608** into a different format, namely an intermediate timestamp format, that has small, bounded increments over the entire range of input values. Such an intermediate timestamp format is advantageously employed in the example embodiment of the circuit **602** of FIG. 6. It should be understood, however, that the circuit **602** is not limited to employing same and that input/output format conversion performed by the circuit **602** is optional.

(106) A non-limiting example of such an intermediate timestamp format is 32-bit seconds and 32-bit fractional seconds (which represents a binary fraction of the form  $M/2^N$ ), where  $M$  represents a value of the fractional seconds part of the received timestamp **608**). To

convert to this intermediate timestamp format, the nanosecond part may be multiplied by  $2^{\lceil \log_2(10^9) \rceil}$  (4.295). As such, the input-timestamp format-conversion logic **614** of the circuit **602** include a multiplier configured to multiply the multiplicand, that is, the sampled version **609** of the received timestamp **608**, by the input conversion value **613**, that is, 4.295 for non-limiting example. Thus, in an event the received timestamp **608** has a value of 0x000000013B9AC9FF (i.e., 1 sec,  $10^9$ -1 ns), such value would be converted by the input format-conversion logic **614** into 0x00000001FFFFFFFB (i.e.,  $1 + 0xFFFFF/2^{32}$  sec; equivalent to 1 sec and 999,999,999 ns). The difference from 0x0000000200000000 (2 sec,  $0/2^{32}$ -0 ns) is then only 0x0000000000000004.

(107) The RLS filter **610** may, advantageously, work on this smoothly incrementing 64-bit input value. The filter's estimated output  $\{ \text{circumflex over (X)} \}.sub.k$ , that is, the current estimated timestamp value **638**, may be used for generating the filtered timestamp **606** in the original timestamp format, that is, “sec, ns” for non-limiting example, based on timestamp format conversion performed by the output format-conversion logic **672** of the circuit **602**. The conversion may be performed by the output-timestamp format-conversion logic **672** before the circuit **602** transmits the filtered timestamp **606** to a timestamp consumer(s) (not shown).

(108) In the non-limiting example embodiment of FIG. 6, the output-timestamp format-conversion logic **672** is a multiplier configured to multiply the multiplicand, that is, the sampled version **671** of the filtered timestamp value **668** in the intermediate timestamp format, by an output conversion value **673**, namely  $10^9/2^{32}$ , such that the output-timestamp format-conversion logic **672** multiplies the fractional seconds by  $10^9/2^{32}$  to convert the sampled version **671** of the filtered timestamp value **668**, in the intermediate timestamp format, to the sampled version **674** of the filtered timestamp value **668**, in the original timestamp format, this is, in turn sampled by the FF **612j** to produce the filtered timestamp **606** that is output by the circuit **602** in the original timestamp format. Such timestamp format conversion enables an additional optimization in the circuit **602**, as disclosed below.

(109) Since the (converted) input to the RLS filter **610** is known to be a smoothly incrementing 64-bit value, an amount (i.e., number N) of its least significant bits (LSBs) is also known to be smoothly incrementing. An example embodiment may run (apply) the RLS filter **610** on those ‘N’ LSBs (and adjust the MSBs as needed), enabling the circuit **602** to be more efficient (e.g., smaller adders, fewer flip-flops, etc.) relative to an implementation in which the RLS filter **610** is applied to the input in its entirety. For such an optimization, it may be useful to make sure that any increment of the current input timestamp **616** (i.e.,  $X.sub.k^*$ ) is by an amount that is much smaller than  $2^N$ —and, thus, a value of N may be chosen accordingly (affected by expected worst-case clock ratios in a chip implementing the circuit **602** and the type of synchronization mechanism used for synchronizing the received timestamp **608** to a clock domain of the circuit **602**).

(110) Theoretically, a similar “trick” of running the RLS filter **610** on ‘N’ LSBs could be employed with the original timestamp format of the received timestamp **608**, however, such implementation would result in having to handle both cases of rollover, that is, one at  $10^9$  and another at  $2^N$ . The  $10^9$  rollover is, however, costly because it's not a power-of-2 and, as such, involves several 30-bit logic elements (while N is typically  $< 30$ ).

(111) An example embodiment disclosed herein considers two types of rollover (values beyond  $2^N$ ): either the input, namely the current input timestamp **616** (i.e.,  $X.sub.k^*$ ), rolls over first, or the filter estimate, namely, the current estimated timestamp value **638** (i.e.,  $\{ \text{circumflex over (X)} \}.sub.k$ ), rolls over first (that depends on whether the filter estimate is currently higher or lower than the input). In either case, according to an example embodiment, the

recursive filter logic **604** may include the rollover detection logic **670** to detect such rollover, and the timestamp adjustment logic **666**, to add  $2\{\text{circumflex over ( )}\}N$  to the value that rolled over first, that is, either the least-significant bit (LSB) portion **618** of the current timestamp value **616** (i.e.,  $X.\text{sub.k}^*$ ) or the current estimated timestamp value **638** (i.e.,  $\{\text{circumflex over (X)}\}.\text{sub.k}$ ), until the other one rolls over as well. This enables continuous computation of the correct difference between the two, as disclosed below where  $N$  is equal to 8 for non-limiting example.

(112) With  $N=8$ , both the input to the RLS filter **610** and the estimate produced by the RLS filter **610** are increasing by 4 on every cycle (just for the sake of the non-limiting example), and the input rolls over first, as shown in Table 1, disclosed below, wherein the difference is incorrectly computed to be  $-247$ .

(113) TABLE-US-00001 TABLE 1 No rollover logic (wrong difference computation). Input (input rolled 246 250 254 over here) 2 6 10 Estimate 237 241 245 249 253 1 Difference 9 9 9  $-247$   $-247$  9

(114) With the rollover detection logic **670**, however, such differences are computed correctly as shown in Table 2, below.

(115) TABLE-US-00002 TABLE 2 With rollover logic (correct difference computation). Input (both rolled over, no need  $2(+2\{\text{circumflex over ( )}\}8 \Rightarrow 6(+2\{\text{circumflex over ( )}\}8 \Rightarrow$  to add  $2\{\text{circumflex over ( )}\}8$  246 250 254 258) 262) anymore) 10 Estimate 237 241 245 249 253 1 Difference 9 9 9 9 9 9

(116) Similar reasoning applies if the filter estimate rolls over first.

(117) In the circuit **602**, the most significant bits (MSBs) of the filter estimate  $\{\text{circumflex over (X)}\}.\text{sub.k}$  (i.e., the current estimated timestamp value **638**) may usually be taken as-is from the filter input  $X.\text{sub.k}^*$ , that is, such bits may usually correspond to the MSB portion **619** of the current timestamp value **616** (i.e.,  $X.\text{sub.k}^*$ ). On rollovers (wrap-arounds), however, an example embodiment of the timestamp adjustment logic **666** may be configured to adjust such MSB bits, as disclosed below.

(118) According to an example embodiment, if the filter estimate  $\{\text{circumflex over (X)}\}.\text{sub.k}$  (i.e., the current estimated timestamp value **638**) has rolled over first, that is, before the LSB portion **618** of the filter input  $X.\text{sub.k}^*$  (i.e., current timestamp value **616**), the timestamp adjustment logic **666** may be configured to increase the MSB portion **619** by one and employ the incremented MSB portion **619** as an MSB portion of the filtered timestamp value **668**. The adjusted timestamp **668** may be sampled via the FF **612i** to produce a sampled version **671** of the adjusted timestamp **668** in the intermediate timestamp format. The filtered timestamp value **668** in the intermediate timestamp format represents the filtered timestamp **606** in the intermediate timestamp format.

(119) According to an example embodiment, if the filter input, namely the LSB portion **618** of the current input timestamp **616** (i.e.,  $X.\text{sub.k}^*$ ) rolls over first, the MSB portion **619** of the filter input  $X_x$  has already been increased by 1. In an event the filter estimate  $\{\text{circumflex over (X)}\}.\text{sub.k}$  (i.e., the current estimated timestamp value **638**) has not rolled over yet, the timestamp adjustment logic **666** may be configured to decrease the MSB portion **619** by one and employ same as the MSB portion of the filtered timestamp value **668**. The filtered timestamp value **668** may be converted from the intermediate timestamp format to the original timestamp format to produce the filtered timestamp **606** that may be output by the circuit **602** as disclosed above.

(120) Filter Reset

(121) Continuing with reference to FIG. 6, as disclosed above, the reset logic **667** may be configured to assert (activate) the filter reset signal **679** based on a) the current timestamp value **616** (i.e.,  $X.\text{sub.k}^*$ ), that is the filter input, and b) the sampled version **671** of the filtered timestamp value **668**, which represents the filter's estimate. According to an example embodiment, the filter estimate and filter input may be 64-bit values {sec, frac sec} and the reset logic **667** may be configured to compute a difference between the filter input and output (its estimation) by subtracting the full 64-bit {sec, frac sec} filter estimate from the 64-bit {sec, frac sec}.

(122) The reset logic **667** may, in turn, check that an amount of MSBs of the difference are the same (either all 1's or all 0's). If they're not, it means that the absolute value of the difference is larger than a threshold (determined by the number of MSBs being checked), and the filter reset signal **679** may be asserted to reset the circuit **602** and, thus, the RLS filter **610**. Checking '64-M' MSB bits will detect a difference outside a range of  $(-2^{\lceil \log_2 M \rceil} \dots 2^{\lceil \log_2 M \rceil} - 1)$ . It should be understood that since the filter reset signal **679** is asserted based on the absolute value of the difference, it doesn't matter if the filter input is subtracted from the filter estimate or vice versa. The following non-limiting examples (1) through (4) are based on a 64-bit difference value in which a number of the MSBs being checked is fifty-six, resulting in detection of a difference outside the range of  $(-256 \dots 255)$ .

(123) Example (1): Input=100=0x64 Output=110=0x6E Difference=100-110=-10=0xFFFFFFFFFFFFFFF6 (bits 63 ... 8 are all 1's)

(124) Example (2): Input=200=0xC8 Output=190=0xBE Difference=200-190=+10=0x000000000000000A (bits 63 ... 8 are all 0's)

(125) Example (3): Input=100=0x64 Output=400=0x190 Difference=100-400=-300=0xFFFFFFFFFFFFFFFED4 (bits 63 ... 8 are NOT all 1's; nor all 0's.fwdarw.difference is outside the desired range)

(126) Example (4): Input=400=0x190 Output=100=0x64 Difference=400-100=+300=0x000000000000012C (bits 63 ... 8 are NOT all 0's; nor all 1's.fwdarw.difference is outside the desired range)

(127) In the non-limiting examples (1) through (4), disclosed above, the differences computed in examples (3) and (4) cause the reset logic **667** to assert the filter reset signal **679**. The reset logic **667** may, for non-limiting example, be employed in the circuit **702** and circuit **802** of FIG. 7 and FIG. 8, respectively, disclosed below.

(128) FIG. 7 is a block diagram of an example embodiment of a circuit **702** for filtering a received timestamp **708**. The circuit comprises input format-conversion logic **714** configured to convert the received timestamp **708** from an original timestamp format to an intermediate timestamp format. The circuit **702** further comprises recursive filter logic **704** coupled to the input format-conversion logic **714**. The recursive filter logic **704** is configured to generate a filtered timestamp **768** in the intermediate timestamp format by filtering the received timestamp **716** in the intermediate timestamp format. The circuit **702** further comprises output format-conversion logic **772** coupled to the recursive filter logic **704**. The output format-conversion logic **772** is configured to convert the filtered timestamp **768** from the intermediate timestamp format to the original timestamp format and output the filtered timestamp **706** in the original timestamp format. The original timestamp format may be based on seconds and nanoseconds and the intermediate timestamp format may be based on seconds and fractional seconds for non-limiting examples, as disclosed above. The circuit **702** may be implemented with reduced area and power consumption due to the format conversion, as disclosed above.

(129) As disclosed above, logic to handle rollover of input values is relatively complicated and increases the area and power consumption of an implementation. A more efficient solution disclosed herein with regard to FIG. 6 and FIG. 7 is to convert the received timestamp (**608**, **708**) into a different format, namely an intermediate timestamp format, that has small, bounded increments over an entire range of input values.

(130) With reference to FIG. 6 and FIG. 7, the input format-conversion logic (**614**, **714**) may include a first multiplier. The first multiplier may be configured to multiply the received timestamp (**608**, **708**) in the original timestamp format by an input conversion value **613** configured to convert the original timestamp format to the intermediate timestamp format. The output format-conversion logic (**672**, **772**) may include a second multiplier. The second multiplier may be configured to multiply the filtered timestamp (**668**, **768**) in the intermediate timestamp format by an output conversion value **673** configured to convert the intermediate timestamp format to the original

timestamp format. The input conversion value and the output conversion value may be configured such that a product of the input conversion value and the output conversion value is one for non-limiting example.

(131) The recursive filter logic (**604, 704**) may be further configured to implement a recursive-least squares (RLS) filter **610**. The RLS filter **610** may be configured to generate an estimated timestamp value, namely the current estimated timestamp value **638** (i.e.,  $\{\text{circumflex over (X)}\}.\text{sub.k}$ ), of a target (ideal) timestamp based on at least a portion of the received timestamp in the intermediate timestamp format (e.g., the current timestamp value **616** (i.e.,  $X.\text{sub.k}^*$ ), **716**). The filtered timestamp (**668, 768**) in the intermediate timestamp format may be generated based on the estimated timestamp value generated. Thus, it follows that the filtered timestamp (**606, 706**) in the original timestamp format may also be generated based on the estimated timestamp value generated, that is, the current estimated timestamp value **638** (i.e.,  $\{\text{circumflex over (X)}\}.\text{sub.k}$ ).

(132) The RLS filter **610** may be further configured to determine a difference in consecutive values of the received timestamp in the intermediate timestamp format (e.g., the current timestamp value **616** (i.e.,  $X.\text{sub.k}^*$ ), **716**), with higher accuracy relative to determining the difference via the consecutive values of the received timestamp (**608, 708**) in the original timestamp format, as disclosed above.

(133) An accuracy of the estimated timestamp value generated, that is, an accuracy of the current estimated timestamp value **638** (i.e.,  $\{\text{circumflex over (X)}\}.\text{sub.k}$ ), may be improved based on conversion of the received timestamp (**608, 708**) from the original timestamp format to the intermediate timestamp format. The accuracy may be improved relative to generating the estimated timestamp value of the target timestamp based on the at least a portion of the received timestamp (**608, 708**) in the original timestamp format, as disclosed above.

(134) Further alternative circuit **702** embodiments may parallel those described above in connection with the example circuit embodiment of FIG. 6. Another example embodiment of a circuit for filtering a timestamp is disclosed below, with regard to FIG. 8.

(135) FIG. 8 is a block diagram of another example embodiment of a circuit **802** for filtering a received timestamp **808**. The circuit **802** comprises recursive filter logic **804** configured to implement a recursive least-squares (RLS) filter **810**. The circuit **802** is configured to generate a filtered timestamp **806** from a received timestamp **808** by filtering the received timestamp **808** via the recursive filter logic **804**. The recursive filter logic **804** is configured to apply the RLS filter **810** to the a portion **818** of the received timestamp **808**. A number of bits of the portion **818** is less relative to a total number of bits of the received timestamp. The circuit **802** is further configured to output the filtered timestamp **806** generated. Applying the RLS filter **810** to the portion **818** enables the circuit **802** to be more efficient (e.g., smaller adders, fewer flip-flops, etc.) relative to an implementation in which the RLS filter **810** is applied to the received timestamp **808** in its entirety.

(136) According to a non-limiting example embodiment, the portion **818** may be a least significant bit (LSB) portion of the received timestamp **808**, wherein the LSB portion is of lesser significance relative to a most significant bit (MSB) portion (not shown) of the received timestamp.

(137) With reference to FIG. 6 and FIG. 8, the RLS filter (**610, 810**) may be configured to generate, based on the LSB portion (**618, 818**), an estimated timestamp value of a target (ideal) timestamp (not shown), as disclosed above. The circuit (**602, 802**) may be further configured to generate the filtered (**606, 806**) timestamp based on the estimated timestamp value generated, namely the current estimated timestamp value **638** (i.e.,  $\{\text{circumflex over (X)}\}.\text{sub.k}$ ).

(138) The circuit (**610, 810**) may further comprise input format-conversion logic **614** coupled to the recursive filter logic (**604, 804**). The input format-conversion logic **614** may be configured to convert the received timestamp (**608, 808**) from an original timestamp format to an intermediate timestamp format. The circuit (**602, 802**) may be configured to input the received timestamp in the intermediate timestamp format, that is, the current timestamp value **616** (i.e.,  $X.\text{sub.k}^*$ ), to the recursive filter logic (**608, 808**).

(139) The recursive filter logic (**608, 808**) may be further configured to apply the RLS filter (**610, 810**) to the LSB portion (**618, 818**) of the received timestamp in the intermediate timestamp format, namely the current timestamp value **616** (i.e.,  $X_{\text{sub.k}}$ ), and generate the filtered timestamp in the intermediate timestamp format, namely the filtered timestamp value **668**. The circuit (**602, 802**) may further comprise output format-conversion logic **672** coupled to the recursive filter logic (**608, 808**). The output format-conversion logic **672** may be configured to convert the filtered timestamp from the intermediate timestamp format to the original timestamp format and output the filtered timestamp (**606, 806**) in the original timestamp format.

(140) The circuit (**602, 802**) may further comprise rollover detection logic **670**. The rollover detection logic **670** may be configured to generate a rollover detection signal **660** based on a comparison of the LSB portion (**618, 818**) and the estimated timestamp value generated, that is, the current estimated timestamp value **638** (i.e.,  $\{ \text{circumflex over (X)} \}_{\text{sub.k}}$ ). The circuit (**602, 802**) may be further configured to generate the filtered timestamp (**606, 806**) based on the estimated timestamp value generated, the rollover detection signal **660**, and the MSB portion **619**.

(141) The circuit (**602, 802**) may further comprise timestamp adjustment logic **666**. The timestamp adjustment logic **666** may be configured to generate the filtered timestamp value **668** of the filtered timestamp based on the estimated timestamp value generated, that is, the current estimated timestamp value **638** (i.e.,  $\{ \text{circumflex over (X)} \}_{\text{sub.k}}$ ), and the MSB portion **619**.

(142) As disclosed above, the timestamp adjustment logic **666** may be further configured to adjust the estimated timestamp value generated or the MSB portion **619** responsive to the rollover detection signal **660** indicating that a) the estimated timestamp value generated has rolled over prior to roll over of the MSB portion **619** or b) the MSB portion **619** has rolled over prior to roll over of the estimated timestamp value generated, respectively.

(143) In an event the rollover detection signal **660** has indicated a), the timestamp adjustment logic **666** may be further configured to increment, on a cycle-by-cycle basis, the estimated timestamp value generated and, responsive to the rollover detection signal **660** subsequently indicating that the MSB portion **619** has rolled over, to stop incrementing of the estimated timestamp value generated.

(144) In an event the rollover detection signal **660** has indicated (b), the timestamp adjustment logic **666** may be further configured to increment, on a cycle-by-cycle basis, the MSB portion **619** and, responsive to the rollover detection signal **660** subsequently indicating that the estimated timestamp value has rolled over, to stop incrementing the MSB portion **619**.

(145) Further alternative circuit **802** embodiments may parallel those described above in connection with the example circuit **602** embodiment of FIG. 6. As disclosed above, an example embodiment reduces jitter of receive timestamp. Such jitter reduction is disclosed below with regard to FIGS. 9A-E.

(146) FIGS. 9A-E are graphs of example embodiments of waveforms that show timestamp jitter before and after filtering via an example embodiment of a circuit disclosed herein, such as the circuits **102, 202, 602, 702, and 802**, disclosed above with regard to FIG. 1, FIG. 2, and FIGS. 6-8, respectively. The graphs show differences between ideal and filtered/unfiltered timestamps, as disclosed below. Each of the graphs, namely the graphs **900a-e**, includes an upper waveform and a lower waveform. For example, the graphs **900a, 900b, 900c, 900d, and 900e** include the upper waveforms **908a, 908b, 908c, 908d, and 908e**, respectively, and the lower waveforms **906a, 906b, 906c, 906d, and 906e**, respectively.

(147) The upper waveforms (**908a, 908b, 908c . . . 908e**) represent differences (jitter) between an unfiltered timestamp (not shown) and an ideal timestamp (not shown). The unfiltered timestamp is a synchronized timestamp that is output from a synchronizer, such as the synchronized timestamp **208** that is output from the TS synchronization circuit **221** of FIG. 2, disclosed above. The unfiltered timestamp may be the received timestamp **108**, synchronized timestamp **208**, received timestamp **608**, received timestamp **708**, or received timestamp **808**, disclosed above with regard to FIG. 1, FIG. 2, and FIGS. 6-8, respectively.



(148) With reference to FIG. 2 and FIGS. 9A-E, the unfiltered timestamp is the synchronized timestamp **208** generated by synchronizing the original timestamp **207** across multiple clock domains, that is, from the first clock domain driven by the first clock **217** (i.e., clk A), to the second clock domain driven by the second clock **219** (i.e., clk B). In the example embodiments of FIGS. 9A-E, and with reference to FIG. 2, clk A has a frequency of 350 MHz, 550 MHz, 750 MHz, 1000 MHz, and 1300 MHz, respectively, and clk B has a frequency of 800 MHz. It should be understood, however, that frequencies of clk A and clk B are not limited thereto.

(149) As shown in the graphs **900a-e**, synchronizing from 350 MHz->800 MHz, 550 MHz->800 MHz, 750 MHz->800 MHz, 1000 MHz->800 MHz, and 1300 MHz->800 MHz, respectively, produces a respective synchronized timestamp **208** that has respective jitter represented by the upper waveforms **908a-e**, respectively. By filtering (e.g., via a RLS filter disclosed herein) such an unfiltered timestamp, that is, the synchronized timestamp **208**, via the filter circuit **202**, however, a respective filtered timestamp **206** is produced with the jitter reduced, as represented by the lower waveforms **906a-e**, respectively. The lower waveforms **906a-e** each represent respective differences (jitter) between a respective filtered timestamp **206** and the respective ideal timestamp, where the respective ideal timestamp is a +1/ns counter for non-limiting example.

(150) A comparison between the upper waveforms **908a-e** (jitter out of the synchronizer) and the respective lower waveforms **906a-e** (jitter after filtering via recursive filter logic disclosed herein) shows that the maximum jitter is reduced by up to 50% (1-2 ns in the clock ratios employed in the example embodiments of FIGS. 9A-E) and standard deviation of the jitter is also reduced by 30-50%.

(151) FIG. 10 is a flow diagram **1000** of an example embodiment of a method for timestamp jitter reduction. The method begins (**1002**) and generates a filtered timestamp from a received timestamp by filtering the received timestamp via recursive filter logic, the filtering including reducing jitter of the received timestamp via the recursive filter logic, the jitter representing a deviation from a target timestamp (**1004**). The method outputs the filtered timestamp generated and thereafter ends (**1008**) in the example embodiment.

(152) The outputting may include outputting the filtered timestamp generated to a timestamp consumer. For non-limiting example, the timestamp consumer may associate an incoming packet, outgoing packet, or combination thereof, with the filtered timestamp generated and output.

(153) The method may further comprise receiving the received timestamp on a cycle-by-cycle basis. The generating may include generating the filtered timestamp in real time, on the cycle-by-cycle basis.

(154) The jitter of the received timestamp may have a maximum value and an average value and reducing the jitter may include reducing the maximum value of the jitter, average value of the jitter, or a combination thereof, in the filtered timestamp generated.

(155) The method may further comprise receiving the received timestamp on a cycle-by-cycle basis, generating an estimated timestamp value of the target timestamp on the cycle-by-cycle basis, and generating the filtered timestamp on the cycle-by-cycle basis, based on the estimated timestamp value generated.

(156) The method may further comprise generating an estimated timestamp value of the target timestamp based on the received timestamp and generating the filtered timestamp based on the estimated timestamp value generated.

(157) The method may further comprise generating a current estimated timestamp value of the target timestamp and generating a current estimated line slope value of a line slope of a linear function. The linear function may represent the target timestamp. The current estimated timestamp value may be generated based on a previous estimated timestamp value of the target timestamp and a previous estimated line slope value of the line slope of the linear function. The previous estimated timestamp value and previous estimated line slope value may be generated prior to generation of the current estimated timestamp value and current estimated line slope value, respectively.

(158) The method may further comprise generating, in a previous clock cycle, the previous estimated timestamp value and the previous estimated line slope value. The previous clock cycle may immediately precede a current clock cycle in which the current estimated timestamp value and current estimated line slope value are generated by the RLS filter.

(159) The method may further comprise generating the current estimated timestamp value based on a product of the previous estimated timestamp value and a number of clock cycles that transpired since a last update of the received timestamp. The number of clock cycles may be one for non-limiting example.

(160) The method may further comprise employing a first filter gain and a second filter gain, generating a current estimated timestamp value of the target timestamp, generating a current estimated line slope value of a line slope of a linear function, and generating a residual error. The linear function may represent the target timestamp. The current estimated timestamp value generated may be based on the first filter gain and the residual error. The current estimated line slope value generated may be based on the second filter gain and the residual error.

(161) The method may further comprise generating a filter step value. The first filter gain and the second filter gain may be based on the filter step value generated. Generating the filter step value may include incrementing the filter step value on a cycle-by-cycle basis. The filter step value may be associated with a threshold value. In an event the filter step value reaches the threshold value, generating the filter step value may include maintaining the filter step value at the threshold value.

(162) The method may further comprise generating, in a previous clock cycle, the previous estimated timestamp value and previous estimated line slope value. The previous clock cycle may immediately precede a current clock cycle in which the current estimated timestamp value and current estimated line slope value are generated.

(163) The method may further comprise generating the residual error based on a current timestamp value of the received timestamp, generating a previous estimated timestamp value of the target timestamp, and generating a previous estimated line slope value of a line slope of the linear function. The previous estimated timestamp value and the previous estimated line slope value may be generated prior to generation of the current estimated timestamp value and the current estimated line slope value, respectively.

(164) The method may further comprise generating the residual error based on a number of clock cycles that transpired since a last update of the received timestamp. The number of clock cycles may be one for non-limiting example.

(165) The received timestamp may be a synchronized timestamp of an original timestamp and the method may further comprise computing a residual error and resetting the recursive filter logic, automatically, based on the residual error computed.

(166) FIG. **11** is a flow diagram **1100** of an example embodiment of a method for filtering a timestamp. The method begins (**1102**) and comprises converting a received timestamp from an original timestamp format to an intermediate timestamp format (**1104**). The method comprises generating, via recursive filter logic, a filtered timestamp in the intermediate timestamp format by filtering the received timestamp in the intermediate timestamp format via the recursive filter logic (**1106**). The method comprises converting the filtered timestamp from the intermediate timestamp format to the original timestamp format (**1108**) and outputting the filtered timestamp in the original timestamp format (**1110**). The method thereafter ends (**1112**) in the example embodiment.

(167) The original timestamp format is based on seconds and nanoseconds and wherein the intermediate timestamp format is based on seconds and fractional seconds.

(168) Converting the received timestamp from the original timestamp format to the intermediate timestamp format may include multiplying the received timestamp in the original timestamp format by an input conversion value configured to convert the original timestamp format to the intermediate timestamp format. Converting the filtered timestamp from the intermediate timestamp format to the original timestamp format may include multiplying the filtered timestamp in the

intermediate timestamp format by an output conversion value configured to convert the intermediate timestamp format to the original timestamp format. The input conversion value and the output conversion value may be configured such that a product of the input conversion value and the output conversion value is one.

(169) The method may further comprise determining a difference in consecutive values of the received timestamp, in the intermediate timestamp format, wherein the difference is determined with higher accuracy relative to determining the difference via the consecutive values of the received timestamp, in the original timestamp format.

(170) The method may further comprise generating an estimated timestamp value of a target timestamp based on at least a portion of the received timestamp in the intermediate timestamp format and generating the filtered timestamp based on the estimated timestamp value generated.

(171) The method may further comprise improving accuracy of the estimated timestamp value generated. The accuracy may be improved based on conversion of the received timestamp from the original timestamp format to the intermediate timestamp format. The accuracy may be improved relative to generating the estimated timestamp value of the target timestamp based on the at least a portion of the received timestamp, in the original timestamp format.

(172) Further alternative method embodiments may parallel those described above in connection with the example method embodiment of FIG. 10. Another example embodiment of a method for filtering a timestamp is disclosed below, with regard to FIG. 12.

(173) FIG. 12 is a flow diagram 1200 of another example embodiment of a method for filtering a timestamp. The method begins (1202) and comprises generating a filtered timestamp from a received timestamp by filtering the received timestamp via recursive filter logic (1204). The recursive filter logic implements a recursive least-squares (RLS) filter. The received timestamp includes a most-significant bit (MSB) portion and a least-significant-bit (LSB) portion, the LSB portion of lesser significance relative to the MSB portion. The generating includes applying the RLS filter to the LSB portion of the received timestamp. The method further comprises outputting the filtered timestamp generated (1206) and thereafter ends (1208) in the example embodiment.

(174) The method may further comprise generating, based on the LSB portion, an estimated timestamp value of a target timestamp via the RLS filter and generating the filtered timestamp based on the estimated timestamp value generated.

(175) The method may further comprise converting the received timestamp from an original timestamp format to an intermediate timestamp format and inputting the received timestamp in the intermediate timestamp format to the recursive filter logic. The applying may include applying the RLS filter to the LSB portion of the received timestamp in the intermediate timestamp format. The generating may include generating the filtered timestamp in the intermediate timestamp format. The method may further comprise converting the filtered timestamp from the intermediate timestamp format to the original timestamp format and outputting the filtered timestamp in the original timestamp format.

(176) The method may further comprise generating, based on the LSB portion, an estimated timestamp value of a target timestamp via the RLS filter. The method may further comprise generating a rollover detection signal based on a comparison of the LSB portion and the estimated timestamp value generated. The method may further comprise generating the filtered timestamp based on the estimated timestamp value generated, the rollover detection signal, and the MSB portion.

(177) The method may further comprise generating, based on the LSB portion, an estimated timestamp value of a target timestamp via the RLS filter and generating a filtered timestamp value of the filtered timestamp based on the estimated timestamp value generated and the MSB portion.

(178) The method may further comprise generating a rollover detection signal based on a comparison of the LSB portion and the estimated timestamp value generated. The method may further comprise adjusting the estimated timestamp value generated or the MSB portion responsive

to the rollover detection signal indicating that (a) the estimated timestamp value generated has rolled over prior to roll over of the MSB portion or (b) the MSB portion has rolled over prior to roll over of the estimated timestamp value generated, respectively.

(179) In an event the rollover detection signal has indicated (a), the adjusting includes incrementing, on a cycle-by-cycle basis, the estimated timestamp value generated and responsive to the rollover detection signal subsequently indicating that the MSB portion has rolled over, stopping the incrementing.

(180) In an event the rollover detection signal has indicated (b), the adjusting includes incrementing, on a cycle-by-cycle basis, the MSB portion and, responsive to the rollover detection signal subsequently indicating that the estimated timestamp value has rolled over, stopping the incrementing. Further alternative method embodiments may parallel those described above in connection with the example method embodiment of FIG. 10.

(181) Further example embodiments disclosed herein may be configured using a computer program product; for example, controls may be programmed in software for implementing example embodiments. Further example embodiments may include a non-transitory, computer-readable medium containing instructions that may be executed by a processor, and, when loaded and executed, cause the processor to complete methods described herein. It should be understood that elements of the block and flow diagrams may be implemented in software or hardware, firmware, a combination thereof, or other similar implementation determined in the future.

(182) In addition, the elements of the block and flow diagrams described herein may be combined or divided in any manner in software, hardware, or firmware. If implemented in software, the software may be written in any language that can support the example embodiments disclosed herein. The software may be stored in any form of computer readable medium, such as random-access memory (RAM), read only memory (ROM), compact disk read-only memory (CD-ROM), and so forth. In operation, a general purpose or application-specific processor or processing core loads and executes software in a manner well understood in the art. It should be understood further that the block and flow diagrams may include more or fewer elements, be arranged or oriented differently, or be represented differently. It should be understood that implementation may dictate the block, flow, and/or network diagrams and the number of block and flow diagrams illustrating the execution of embodiments disclosed herein.

(183) The teachings of all patents, published applications and references cited herein are incorporated by reference in their entirety.

(184) While example embodiments have been particularly shown and described, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the scope of the embodiments encompassed by the appended claims.

## Claims

1. A circuit comprising: recursive filter logic configured to implement a recursive least-squares (RLS) filter, the circuit configured to: (i) generate a filtered timestamp from a received timestamp by filtering the received timestamp via the recursive filter logic, the recursive filter logic configured to apply the RLS filter to a portion of the received timestamp, a number of bits of the portion being less than a total number of bits of the received timestamp, and (ii) output the filtered timestamp generated.
2. The circuit of claim 1, wherein the portion is a least significant bit (LSB) portion of the received timestamp, wherein the LSB portion is of lesser significance relative to a most significant bit (MSB) portion of the received timestamp, wherein the RLS filter is configured to generate, based on the LSB portion, an estimated timestamp value of a target timestamp and wherein the circuit is further configured to generate the filtered timestamp based on the estimated timestamp value generated.

3. The circuit of claim 1, wherein the portion is a least significant bit (LSB) portion of the received timestamp, wherein the LSB portion is of lesser significance relative to a most significant bit (MSB) portion of the received timestamp, and wherein the circuit further comprises: input format-conversion logic coupled to the recursive filter logic, the input format-conversion logic configured to convert the received timestamp from an original timestamp format to an intermediate timestamp format, the circuit configured to input the received timestamp in the intermediate timestamp format to the recursive filter logic, the recursive filter logic configured to apply the RLS filter to the LSB portion of the received timestamp in the intermediate timestamp format and generate the filtered timestamp in the intermediate timestamp format; and output format-conversion logic coupled to the recursive filter logic, the output format-conversion logic configured to convert the filtered timestamp from the intermediate timestamp format to the original timestamp format and output the filtered timestamp in the original timestamp format.
4. The circuit of claim 3, wherein the original timestamp format is based on seconds and nanoseconds and wherein the intermediate timestamp format is based on seconds and fractional seconds.
5. The circuit of claim 1, wherein the portion is a least significant bit (LSB) portion of the received timestamp, wherein the LSB portion is of lesser significance relative to a most significant bit (MSB) portion of the received timestamp, wherein the circuit further comprises rollover detection logic and wherein: the RLS filter is configured to generate, based on the LSB portion, an estimated timestamp value of a target timestamp; the rollover detection logic is configured to generate a rollover detection signal based on a comparison of the LSB portion and the estimated timestamp value generated; and the circuit is further configured to generate the filtered timestamp based on the estimated timestamp value generated, the rollover detection signal, and the MSB portion.
6. The circuit of claim 1, wherein the portion is a least significant bit (LSB) portion of the received timestamp, wherein the LSB portion is of lesser significance relative to a most significant bit (MSB) portion of the received timestamp, wherein the circuit further comprises timestamp adjustment logic and wherein: the RLS filter is configured to generate, based on the LSB portion, an estimated timestamp value of a target timestamp; and the timestamp adjustment logic is configured to generate a filtered timestamp value of the filtered timestamp based on the estimated timestamp value generated and the MSB portion.
7. The circuit of claim 6, wherein the portion is a least significant bit (LSB) portion of the received timestamp, wherein the LSB portion is of lesser significance relative to a most significant bit (MSB) portion of the received timestamp, wherein the circuit further comprises rollover detection logic, and wherein: the rollover detection logic is configured to generate a rollover detection signal based on a comparison of the LSB portion and the estimated timestamp value generated; and the timestamp adjustment logic is further configured to adjust the estimated timestamp value generated or the MSB portion responsive to the rollover detection signal indicating that (a) the estimated timestamp value generated has rolled over prior to roll over of the MSB portion or (b) the MSB portion has rolled over prior to roll over of the estimated timestamp value generated, respectively.
8. The circuit of claim 7, wherein, in an event the rollover detection signal has indicated (a), the timestamp adjustment logic is further configured to: increment, on a cycle-by-cycle basis, the estimated timestamp value generated; and responsive to the rollover detection signal subsequently indicating that the MSB portion has rolled over, stop incrementing of the estimated timestamp value generated.
9. The circuit of claim 8, wherein, in an event the rollover detection signal has indicated (b), the timestamp adjustment logic is further configured to: increment, on a cycle-by-cycle basis, the MSB portion; and responsive to the rollover detection signal subsequently indicating that the estimated timestamp value has rolled over, stop incrementing the MSB portion.
10. The circuit of claim 1, wherein the recursive filter logic is further configured to reduce jitter in the filtered timestamp relative to jitter of the received timestamp, the jitter of the received

timestamp representing a deviation of the received timestamp from a target timestamp.

11. The circuit of claim 1, wherein the received timestamp is received on a cycle-by-cycle basis, wherein the recursive filter logic is further configured to generate the filtered timestamp in real time, on the cycle-by-cycle basis, and wherein the cycle-by-cycle basis is based on a clock cycle of a clock of the circuit.

12. The circuit of claim 1, wherein: the recursive filter logic is further configured to reduce jitter in the filtered timestamp relative to jitter of the received timestamp; the received timestamp is a synchronized timestamp, generated from an original timestamp by synchronizing the original timestamp across multiple clock domains; and the jitter reduced is dynamic jitter generated from the synchronizing.

13. The circuit of claim 1, wherein the circuit is further configured to output the filtered timestamp generated to a timestamp consumer and wherein the timestamp consumer is configured to associate an incoming packet, outgoing packet, or combination thereof, with the filtered timestamp generated and output from the circuit.

14. A method comprising: generating a filtered timestamp from a received timestamp by filtering the received timestamp via recursive filter logic, the recursive filter logic implementing a recursive least-squares (RLS) filter, the generating including applying the RLS filter to a portion of the received timestamp, a number of bits of the portion being less than a total number of bits of the received timestamp; and outputting the filtered timestamp generated.

15. The method of claim 14, wherein the portion is a least significant bit (LSB) portion of the received timestamp, wherein the LSB portion is of lesser significance relative to a most significant bit (MSB) portion of the received timestamp, and wherein the method further comprises: generating, based on the LSB portion, an estimated timestamp value of a target timestamp via the RLS filter; and generating the filtered timestamp based on the estimated timestamp value generated.

16. The method of claim 14, wherein the portion is a least significant bit (LSB) portion of the received timestamp, wherein the LSB portion is of lesser significance relative to a most significant bit (MSB) portion of the received timestamp, and wherein the method further comprises: converting the received timestamp from an original timestamp format to an intermediate timestamp format, inputting the received timestamp in the intermediate timestamp format to the recursive filter logic, the applying including applying the RLS filter to the LSB portion of the received timestamp in the intermediate timestamp format, the generating including generating the filtered timestamp in the intermediate timestamp format; and converting the filtered timestamp from the intermediate timestamp format to the original timestamp format and outputting the filtered timestamp in the original timestamp format.

17. The method of claim 16, wherein the original timestamp format is based on seconds and nanoseconds and wherein the intermediate timestamp format is based on seconds and fractional seconds.

18. The method of claim 14, wherein the portion is a least significant bit (LSB) portion of the received timestamp, wherein the LSB portion is of lesser significance relative to a most significant bit (MSB) portion of the received timestamp, and wherein the method further comprises: generating, based on the LSB portion, an estimated timestamp value of a target timestamp via the RLS filter; generating a rollover detection signal based on a comparison of the LSB portion and the estimated timestamp value generated; and generating the filtered timestamp based on the estimated timestamp value generated, the rollover detection signal, and the MSB portion.

19. The method of claim 14, wherein the portion is a least significant bit (LSB) portion of the received timestamp, wherein the LSB portion is of lesser significance relative to a most significant bit (MSB) portion of the received timestamp, and wherein the method further comprises: generating, based on the LSB portion, an estimated timestamp value of a target timestamp via the RLS filter; and generating a filtered timestamp value of the filtered timestamp based on the

estimated timestamp value generated and the MSB portion.

20. The method of claim 19, wherein the portion is a least significant bit (LSB) portion of the received timestamp, wherein the LSB portion is of lesser significance relative to a most significant bit (MSB) portion of the received timestamp, and wherein the method further comprises: generating a rollover detection signal based on a comparison of the LSB portion and the estimated timestamp value generated; and adjusting the estimated timestamp value generated or the MSB portion responsive to the rollover detection signal indicating that (a) the estimated timestamp value generated has rolled over prior to roll over of the MSB portion or (b) the MSB portion has rolled over prior to roll over of the estimated timestamp value generated, respectively.

21. The method of claim 20, wherein, in an event the rollover detection signal has indicated (a), the adjusting includes: incrementing, on a cycle-by-cycle basis, the estimated timestamp value generated; and responsive to the rollover detection signal subsequently indicating that the MSB portion has rolled over, stopping the incrementing.

22. The method of claim 21, wherein, in an event the rollover detection signal has indicated (b), the adjusting includes: incrementing, on a cycle-by-cycle basis, the MSB portion; and responsive to the rollover detection signal subsequently indicating that the estimated timestamp value has rolled over, stopping the incrementing.

23. The method of claim 14, further comprising reducing, via the recursive filter logic, jitter in the filtered timestamp relative to jitter of the received timestamp, the jitter of the received timestamp representing a deviation of the received timestamp from a target timestamp.

24. The method of claim 14, wherein the received timestamp is received on a cycle-by-cycle basis, wherein the generating includes generating the filtered timestamp in real time, on the cycle-by-cycle basis, and wherein the cycle-by-cycle basis is based on a clock cycle of a clock of the method.

25. The method of claim 14, further comprising reducing, via the recursive filter logic, jitter in the filtered timestamp relative to jitter of the received timestamp, wherein the received timestamp is a synchronized timestamp, generated from an original timestamp by synchronizing the original timestamp across multiple clock domains, and wherein the jitter reduced is dynamic jitter generated from the synchronizing.

26. The method of claim 14, wherein the outputting includes outputting the filtered timestamp generated to a timestamp consumer and wherein the timestamp consumer is configured to associate an incoming packet, outgoing packet, or combination thereof, with the filtered timestamp generated and output from the method.

27. An apparatus comprising: means for generating a filtered timestamp from a received timestamp by filtering the received timestamp via recursive filter logic, the recursive filter logic implementing a recursive least-squares (RLS) filter, the generating including applying the RLS filter to a portion of the received timestamp, a number of bits of the portion being less than a total number of bits of the received timestamp; and means for outputting the filtered timestamp generated.

28. The circuit of claim 1, wherein the recursive filter logic is further configured to compute a residual error, wherein the circuit further comprises reset logic, and wherein the reset logic is configured to reset the recursive filter logic, automatically, based on the residual error computed.

29. The circuit of claim 1, wherein the RLS filter is configured to employ a first filter gain and a second filter gain.

30. The circuit of claim 29, wherein respective values of the first filter gain and second filter gain are rounded to a nearest power-of-two.

31. The circuit of claim 29, wherein the recursive filter logic includes filter-step control logic configured to generate a filter step value, wherein the first filter gain and the second filter gain are based on the filter step value, wherein the filter-step control logic is further configured to increment the filter step value on a cycle-by-cycle basis, wherein the filter step value is associated with a threshold value, and wherein, in an event the filter step value reaches the threshold value, the filter-

step control logic is further configured to maintain the filter step value at the threshold value.  
32. The circuit of claim 31, wherein the threshold value is sixteen.

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