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(54) **CALIBRATION OVER ASYMMETRIC LINKS**

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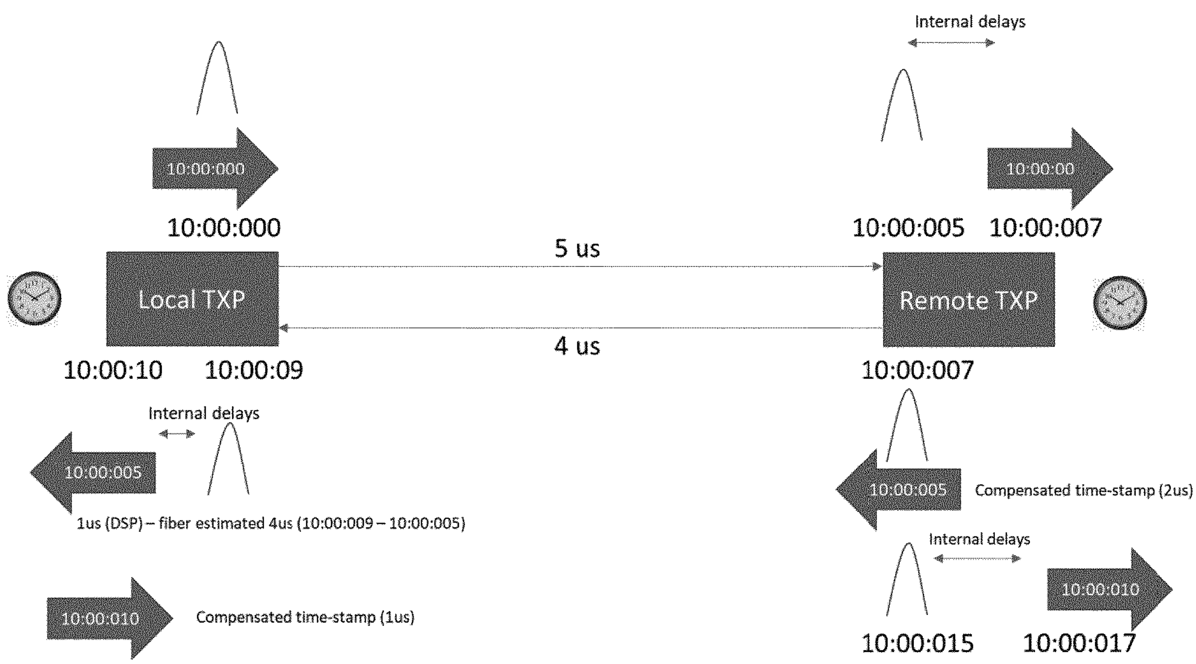
(57) **ABSTRACT**

A first transceiver communicatively coupled to a second transceiver by a first cable and a second cable can transmit a first message to the second transceiver at a first time, T_1, via the first cable. The first transceiver can further receive a second message from the second transceiver via the second cable. The second message includes an indication of a second time, T_2, and an indication of a third time, T_3, associated with when a pulse that is associated with the second message was transmitted by the second transceiver. The first transceiver can further receive the pulse associated with the second message from the second transceiver at a fourth time, T_4, via the first cable. The first transceiver can further determine a first delay associated with the first cable based on the T_1, the T_2, the T_3, and the T_4.



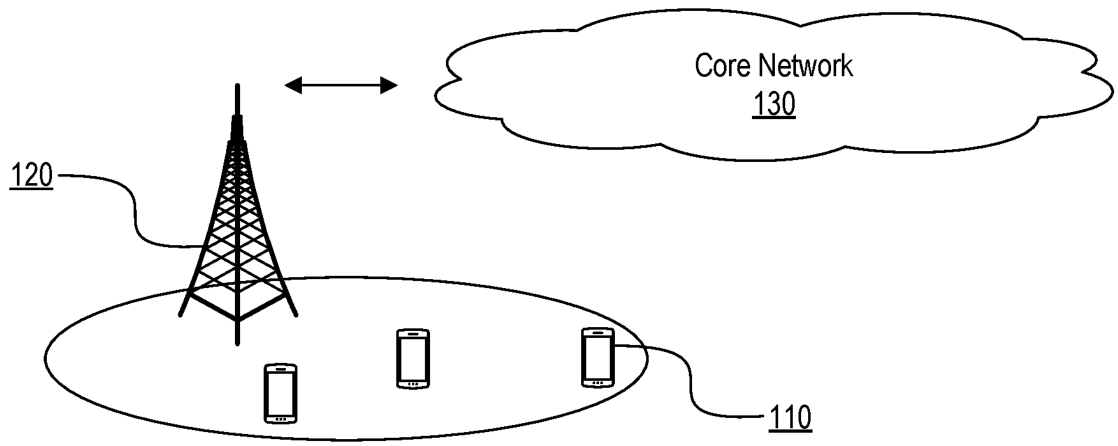

Core Network
130
120
110

FIG. 1

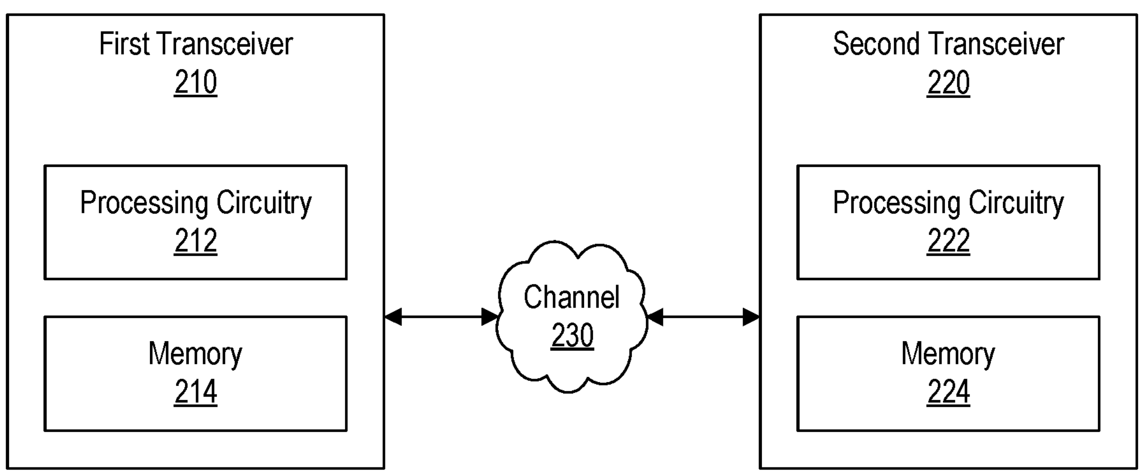

First Transceiver
210
Processing Circuitry
212
Memory
214
Channel
230
Second Transceiver
220
Processing Circuitry
222
Memory
224

FIG. 2

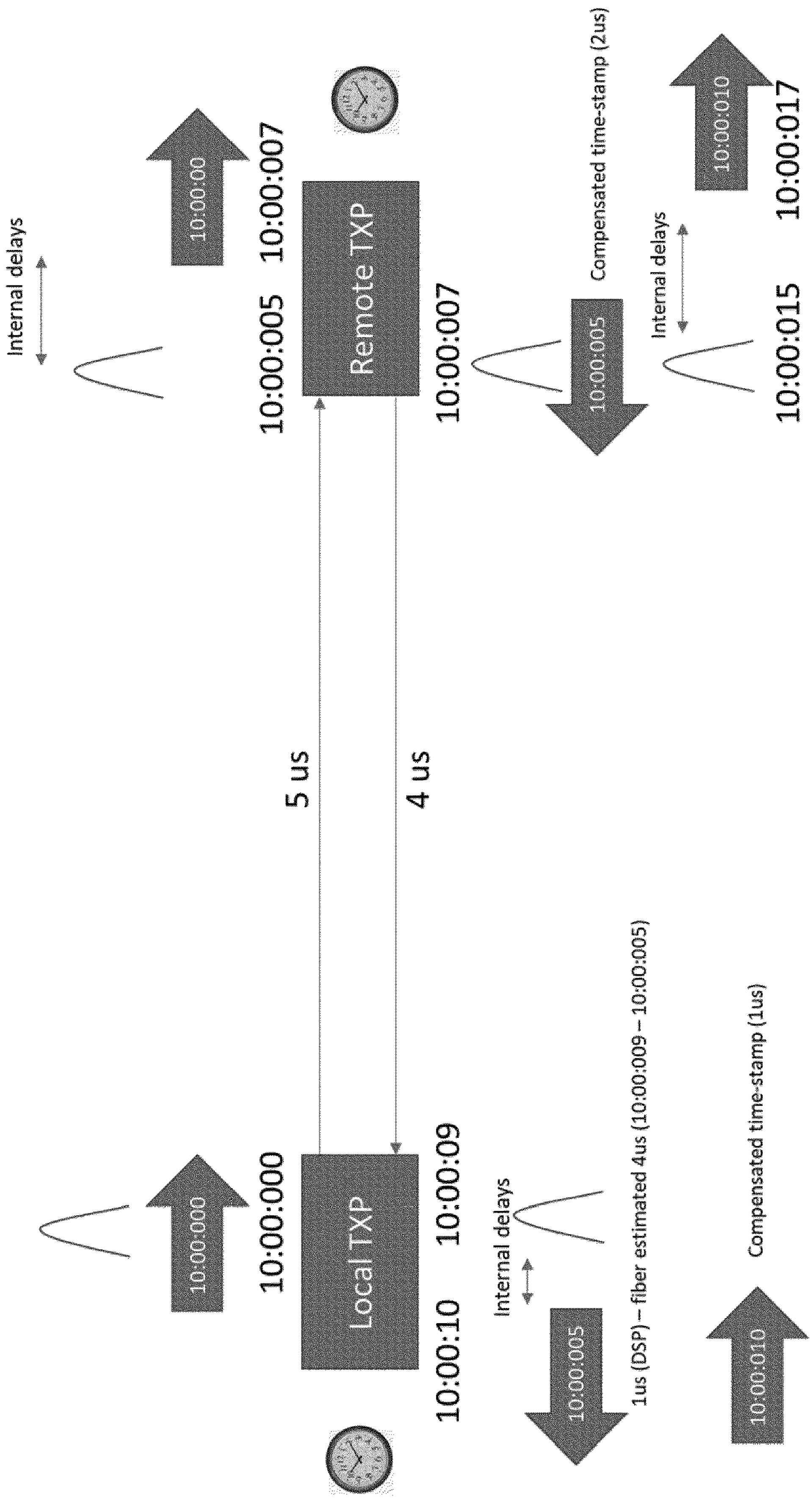

10:00:000
10:00:000
Local TXP
10:00:10
10:00:09
Internal delays
10:00:005
1us (DSP) – fiber estimated 4us (10:00:009 – 10:00:005)
Compensated time-stamp (1us)
10:00:010
5 us
4 us
Internal delays
10:00:00
10:00:005
10:00:007
Remote TXP
10:00:007
10:00:005
Compensated time-stamp (2us)
Internal delays
10:00:015
10:00:010
10:00:017

FIG. 3

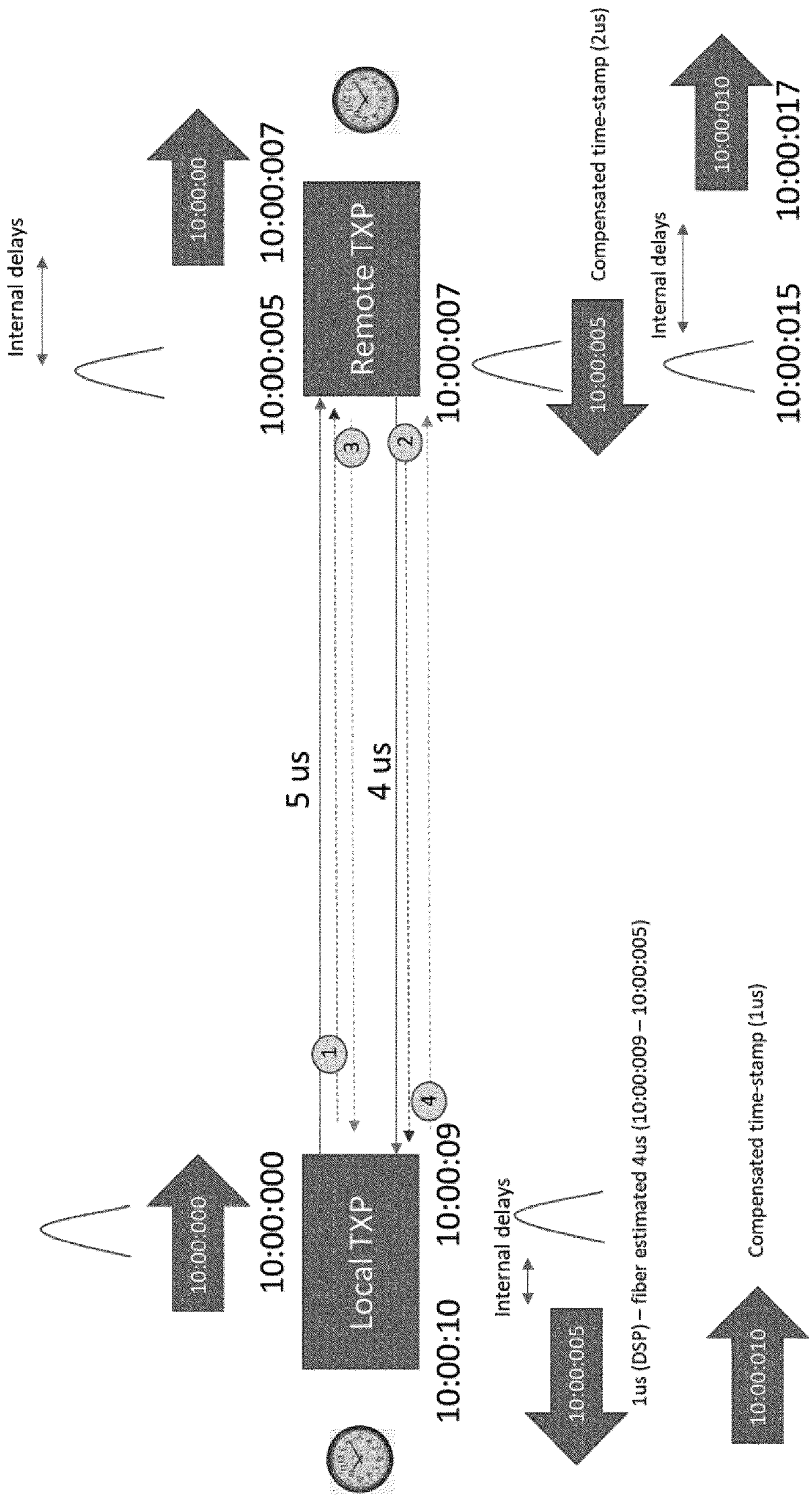

Internal delays
10:00:00
10:00:005
10:00:007
Remote TXP
10:00:007
Compensated time-stamp (2us)
10:00:005
Internal delays
10:00:010
10:00:015
10:00:017
5 us
4 us
1
2
3
4
10:00:000
10:00:000
Local TXP
10:00:10
10:00:09
Internal delays
10:00:005
1us (DSP) – fiber estimated 4us (10:00:009 – 10:00:005)
Compensated time-stamp (1us)
10:00:010

FIG. 4

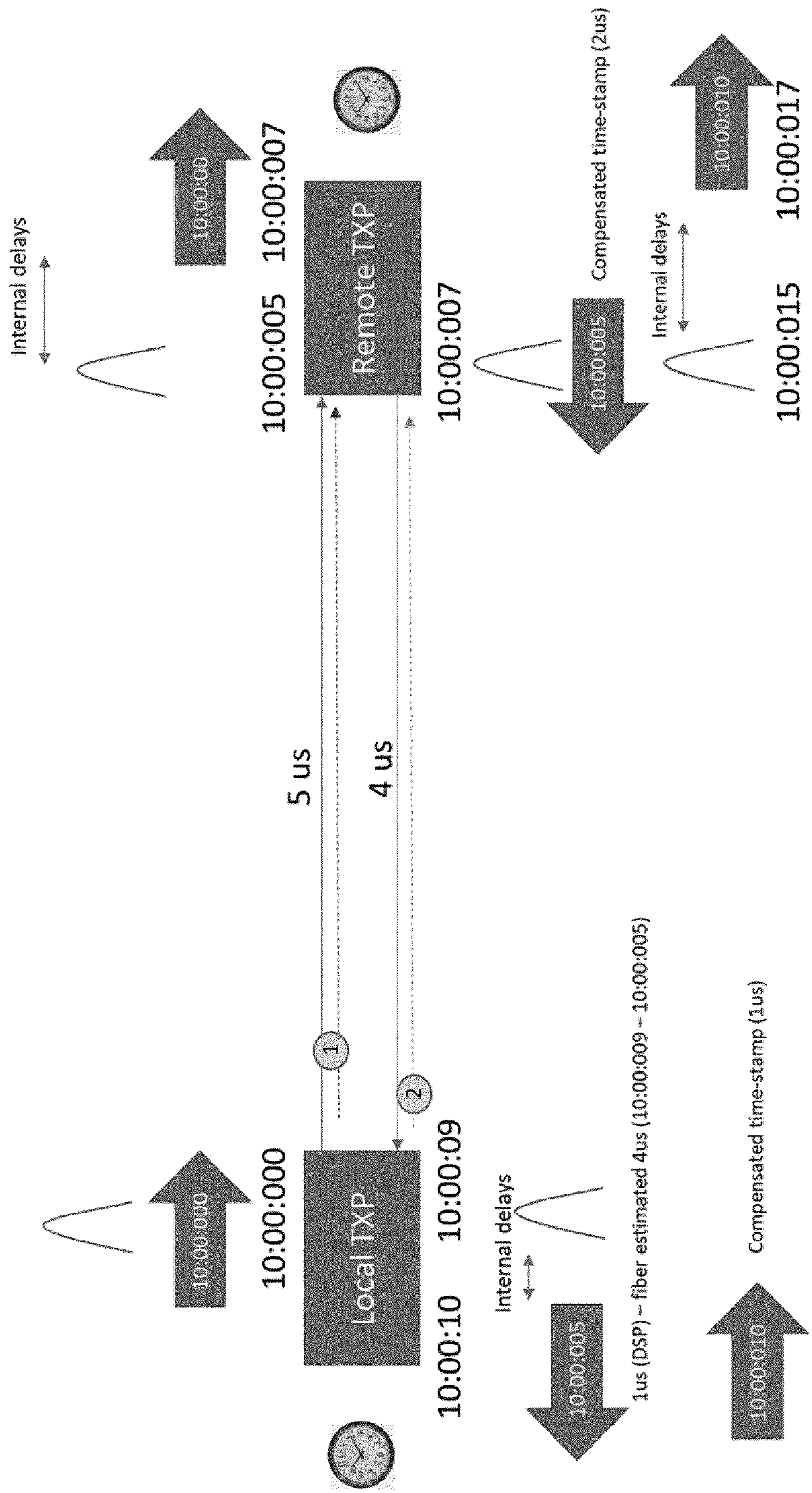

Internal delays
10:00:000
10:00:000
Local TXP
10:00:10
10:00:09
Internal delays
10:00:005
1us (DSP) – fiber estimated 4us (10:00:009 – 10:00:005)
Compensated time-stamp (1us)
10:00:010
1
2
5 us
4 us
10:00:00
10:00:005
10:00:007
Remote TXP
10:00:007
10:00:005
Compensated time-stamp (2us)
Internal delays
10:00:010
10:00:015
10:00:017

FIG. 5

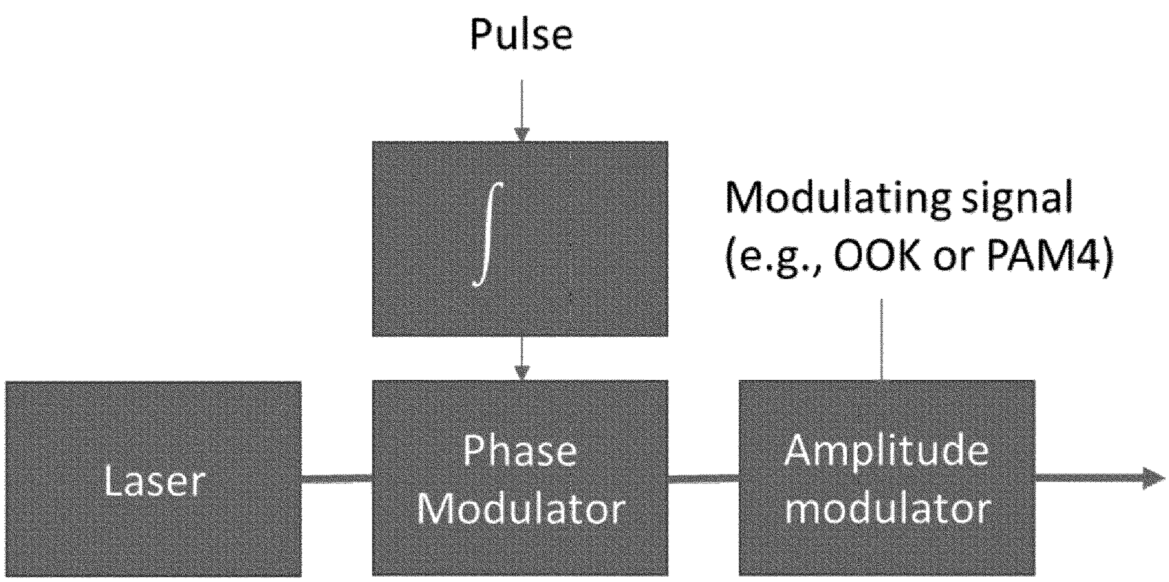

Pulse
$\int$
Modulating signal
(e.g., OOK or PAM4)
Laser
Phase
Modulator
Amplitude
modulator

FIG. 6

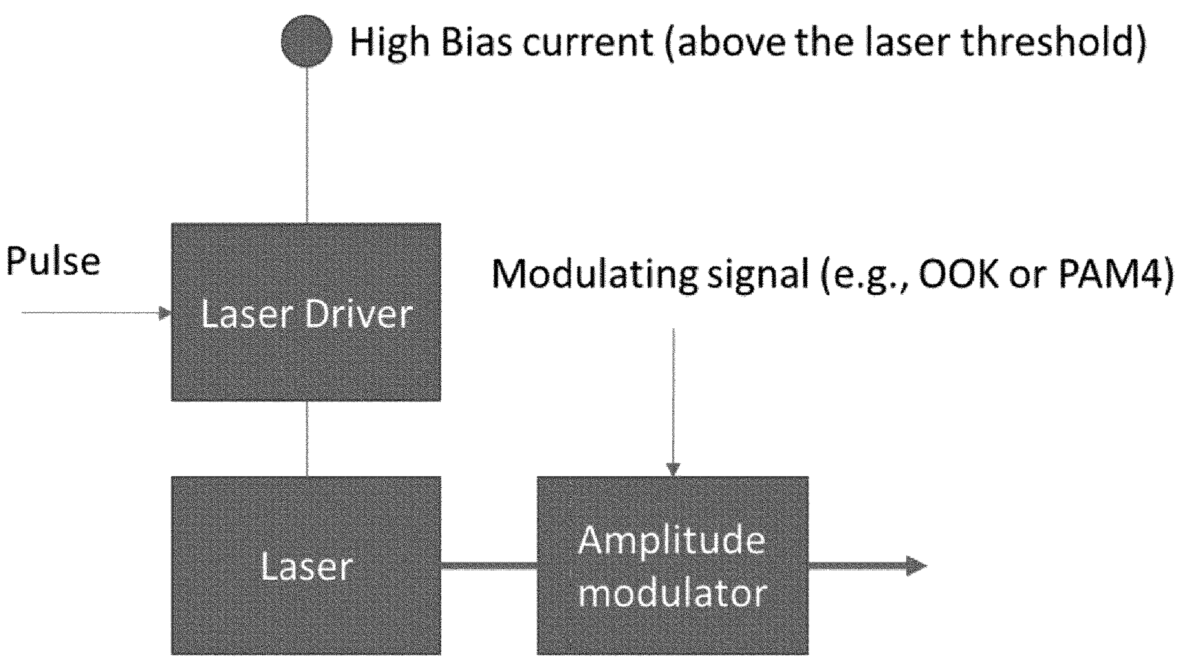

High Bias current (above the laser threshold)
Pulse
Laser Driver
Modulating signal (e.g., OOK or PAM4)
Laser
Amplitude
modulator

FIG. 7

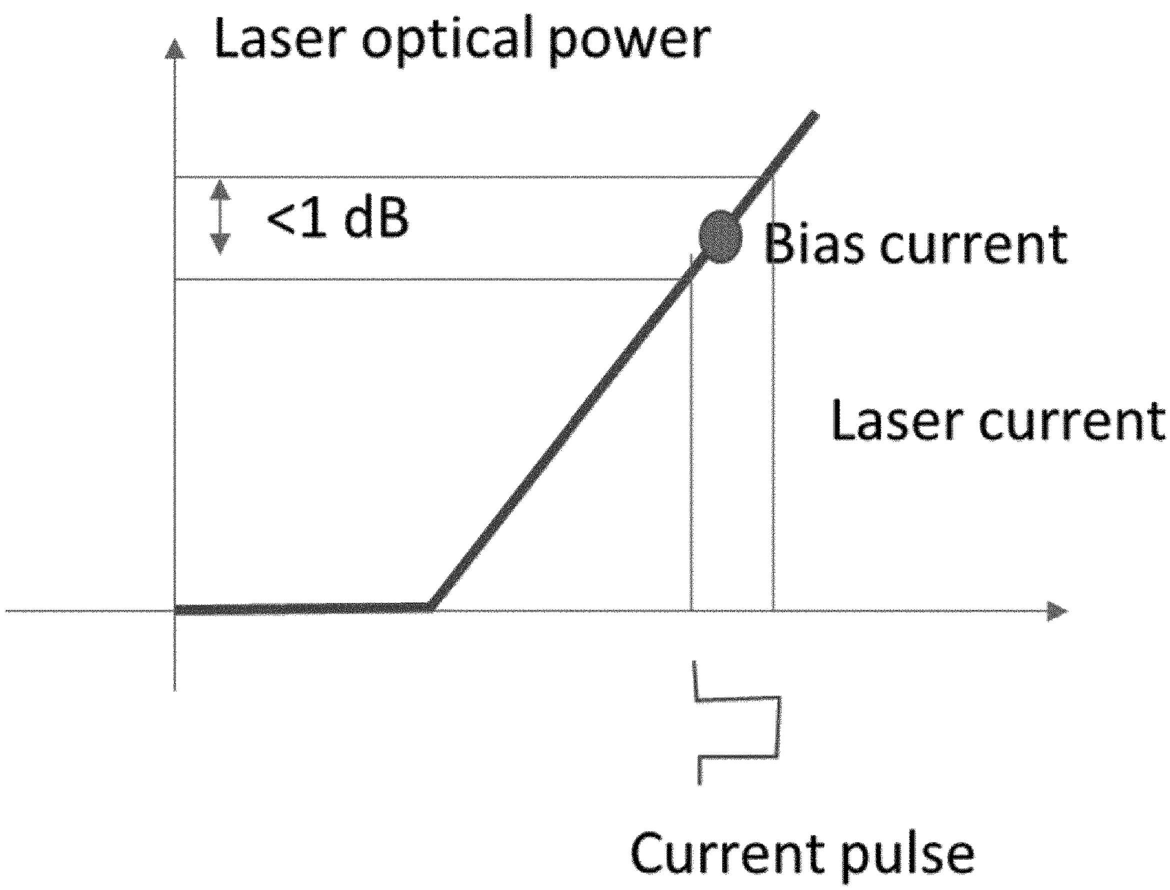


FIG. 8

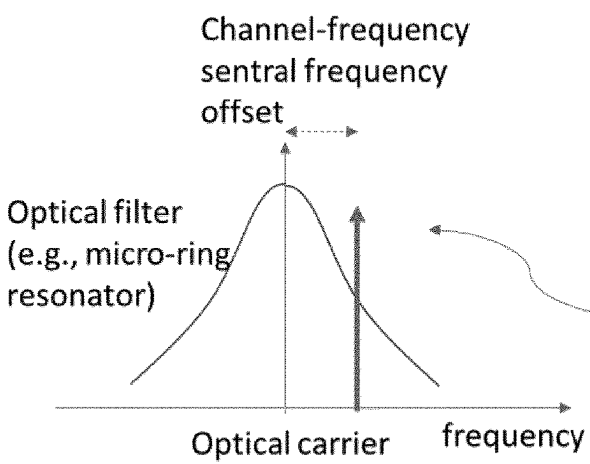


FIG. 9

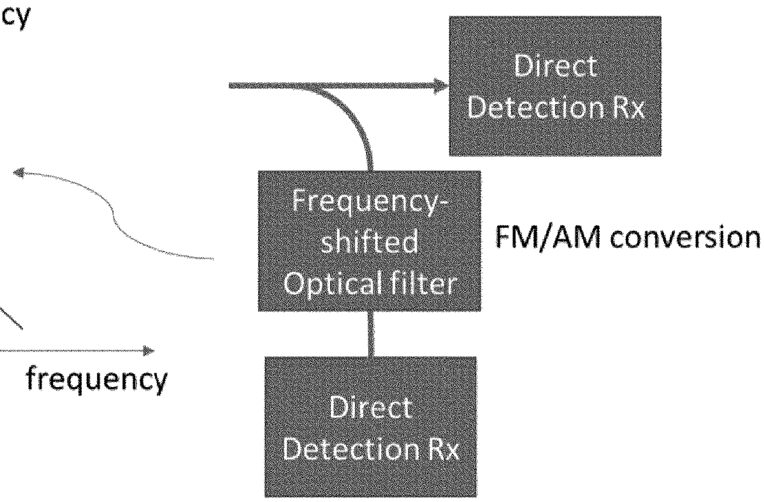


FIG. 10

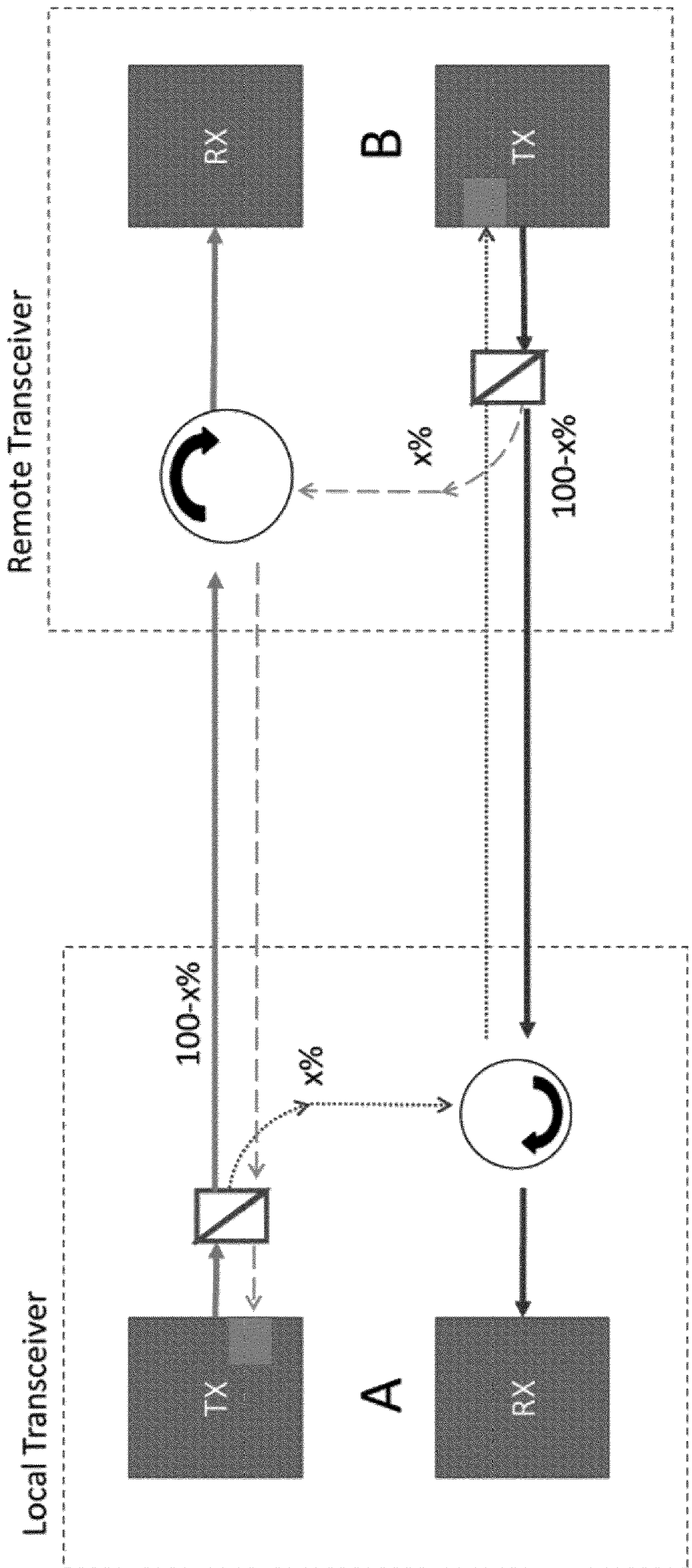

Remote Transceiver
RX
B
TX
x%
100-x%
Local Transceiver
TX
A
RX
100-x%
x%

FIG. 11

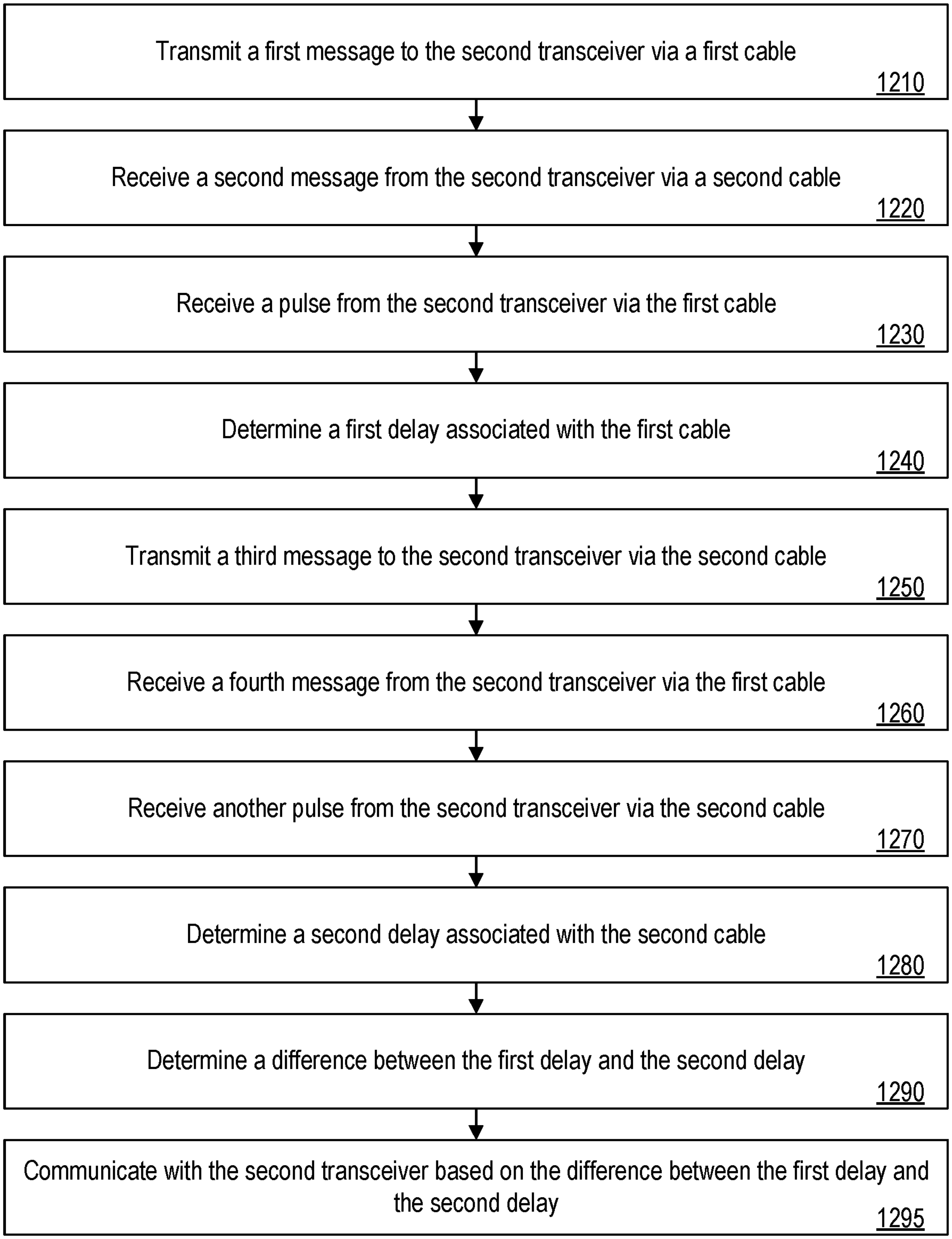

Transmit a first message to the second transceiver via a first cable
1210
Receive a second message from the second transceiver via a second cable
1220
Receive a pulse from the second transceiver via the first cable
1230
Determine a first delay associated with the first cable
1240
Transmit a third message to the second transceiver via the second cable
1250
Receive a fourth message from the second transceiver via the first cable
1260
Receive another pulse from the second transceiver via the second cable
1270
Determine a second delay associated with the second cable
1280
Determine a difference between the first delay and the second delay
1290
Communicate with the second transceiver based on the difference between the first delay and the second delay
1295

FIG. 12

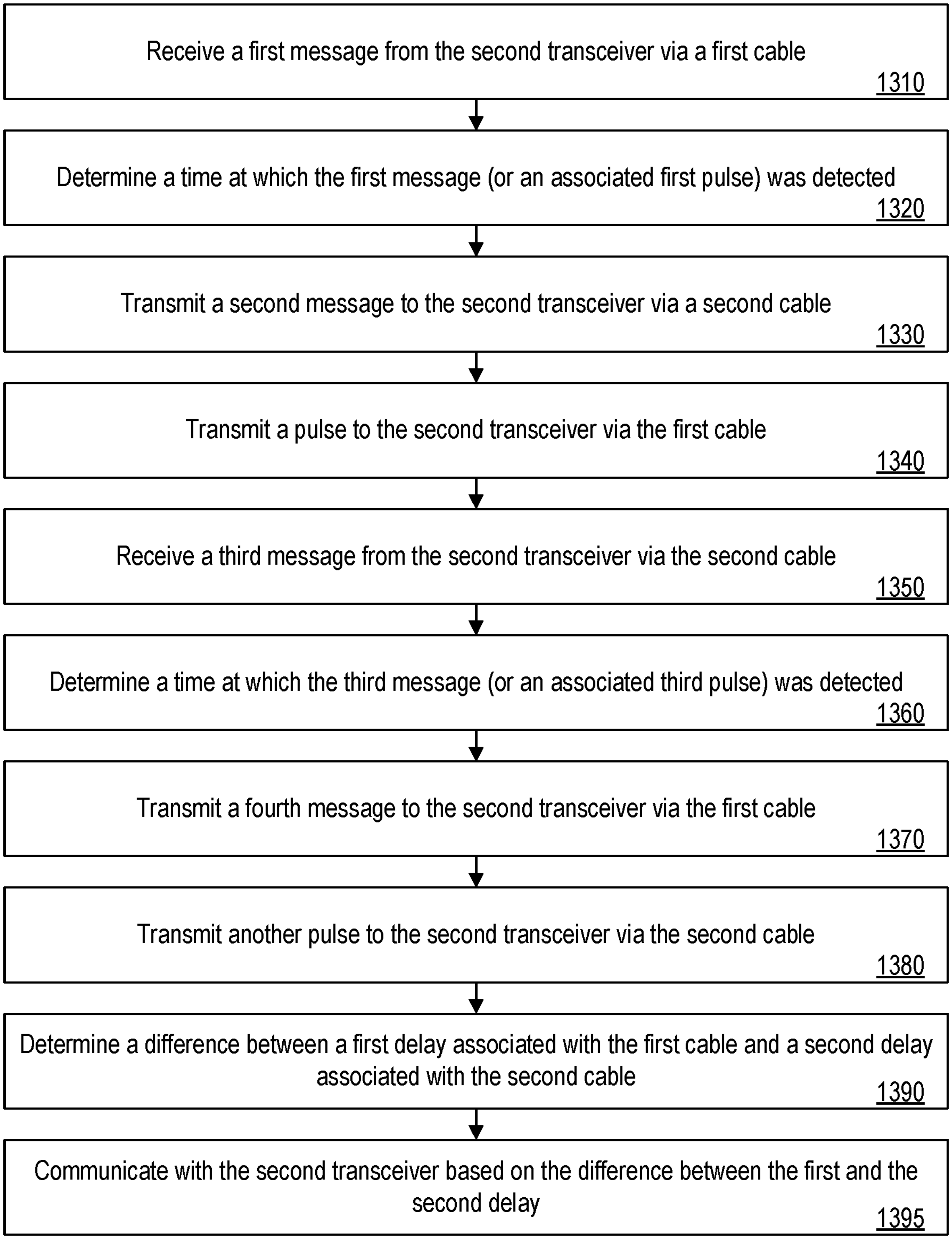

Receive a first message from the second transceiver via a first cable
1310
Determine a time at which the first message (or an associated first pulse) was detected
1320
Transmit a second message to the second transceiver via a second cable
1330
Transmit a pulse to the second transceiver via the first cable
1340
Receive a third message from the second transceiver via the second cable
1350
Determine a time at which the third message (or an associated third pulse) was detected
1360
Transmit a fourth message to the second transceiver via the first cable
1370
Transmit another pulse to the second transceiver via the second cable
1380
Determine a difference between a first delay associated with the first cable and a second delay associated with the second cable
1390
Communicate with the second transceiver based on the difference between the first and the second delay
1395

FIG. 13

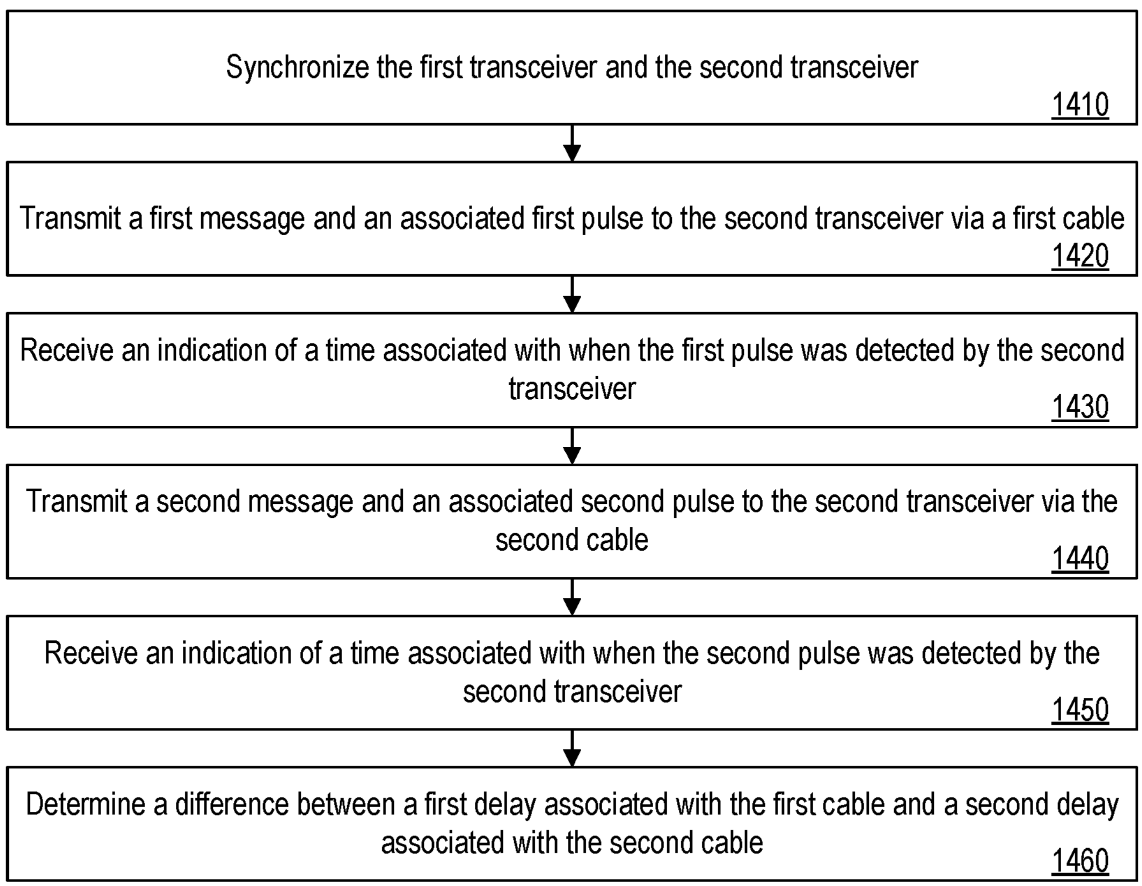

Synchronize the first transceiver and the second transceiver
1410
Transmit a first message and an associated first pulse to the second transceiver via a first cable
1420
Receive an indication of a time associated with when the first pulse was detected by the second transceiver
1430
Transmit a second message and an associated second pulse to the second transceiver via the second cable
1440
Receive an indication of a time associated with when the second pulse was detected by the second transceiver
1450
Determine a difference between a first delay associated with the first cable and a second delay associated with the second cable
1460

FIG. 14

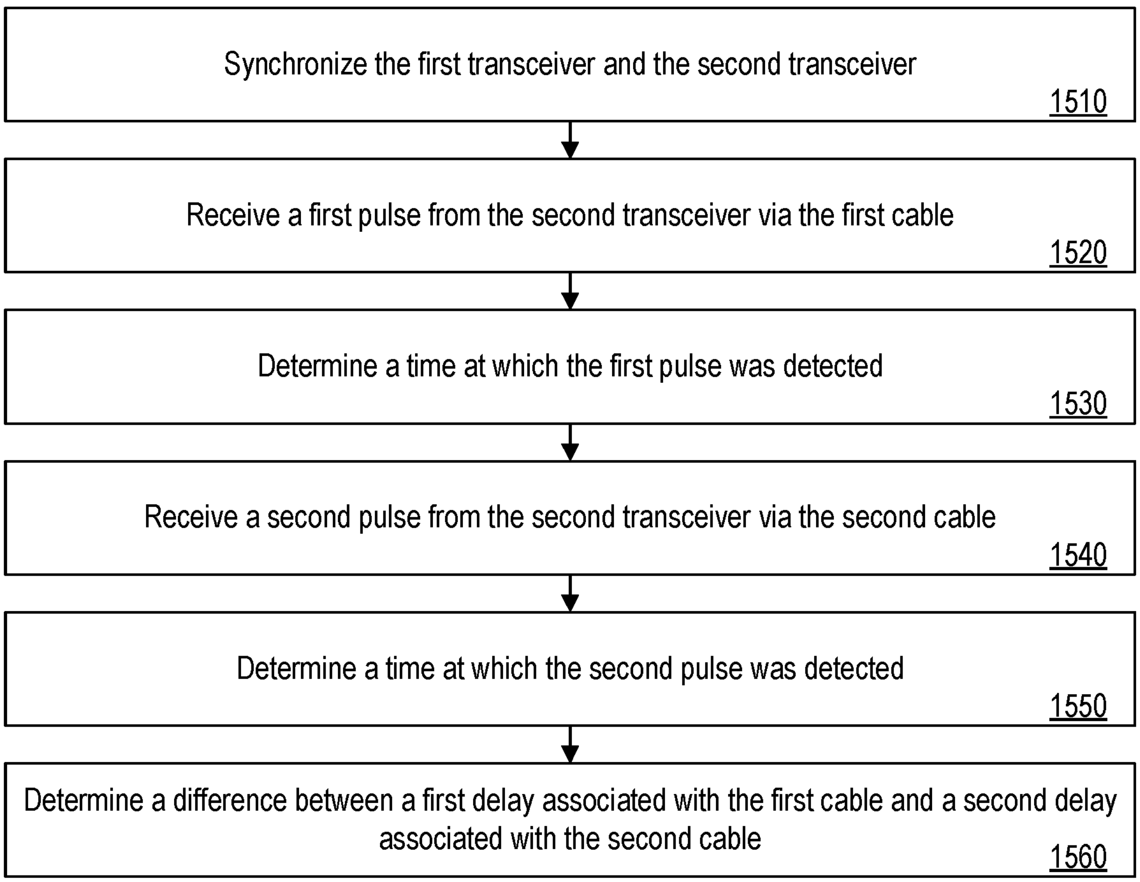

Synchronize the first transceiver and the second transceiver
1510
Receive a first pulse from the second transceiver via the first cable
1520
Determine a time at which the first pulse was detected
1530
Receive a second pulse from the second transceiver via the second cable
1540
Determine a time at which the second pulse was detected
1550
Determine a difference between a first delay associated with the first cable and a second delay associated with the second cable
1560

FIG. 15

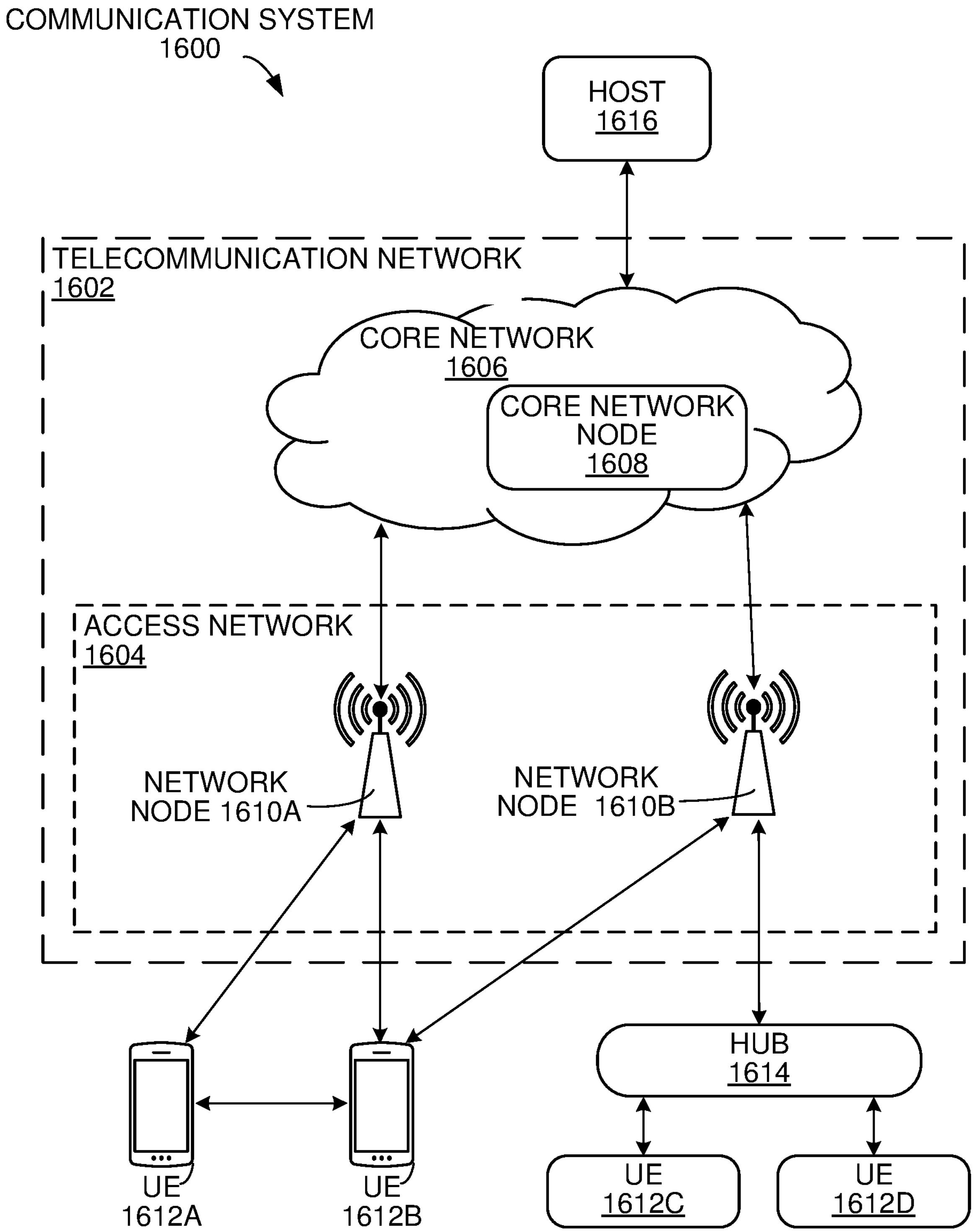

COMMUNICATION SYSTEM
1600
HOST
1616
TELECOMMUNICATION NETWORK
1602
CORE NETWORK
1606
CORE NETWORK
NODE
1608
ACCESS NETWORK
1604
NETWORK
NODE 1610A
NETWORK
NODE 1610B
UE
1612A
UE
1612B
HUB
1614
UE
1612C
UE
1612D

FIG. 16

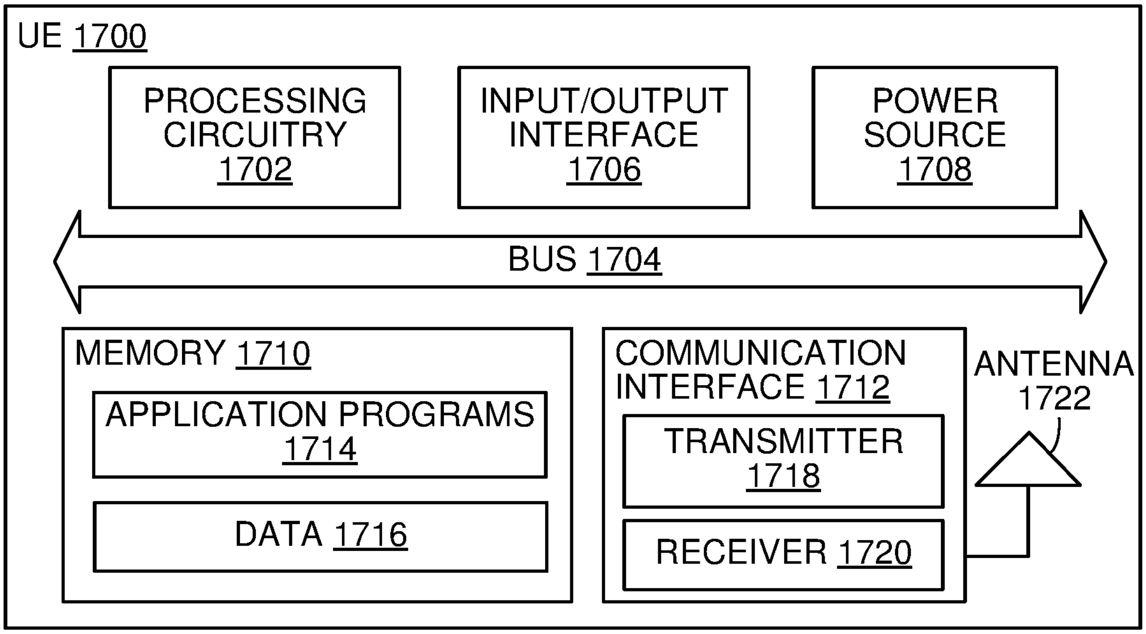

UE 1700
PROCESSING CIRCUITRY 1702
INPUT/OUTPUT INTERFACE 1706
POWER SOURCE 1708
BUS 1704
MEMORY 1710
APPLICATION PROGRAMS 1714
DATA 1716
COMMUNICATION INTERFACE 1712
TRANSMITTER 1718
RECEIVER 1720
ANTENNA 1722

FIG. 17

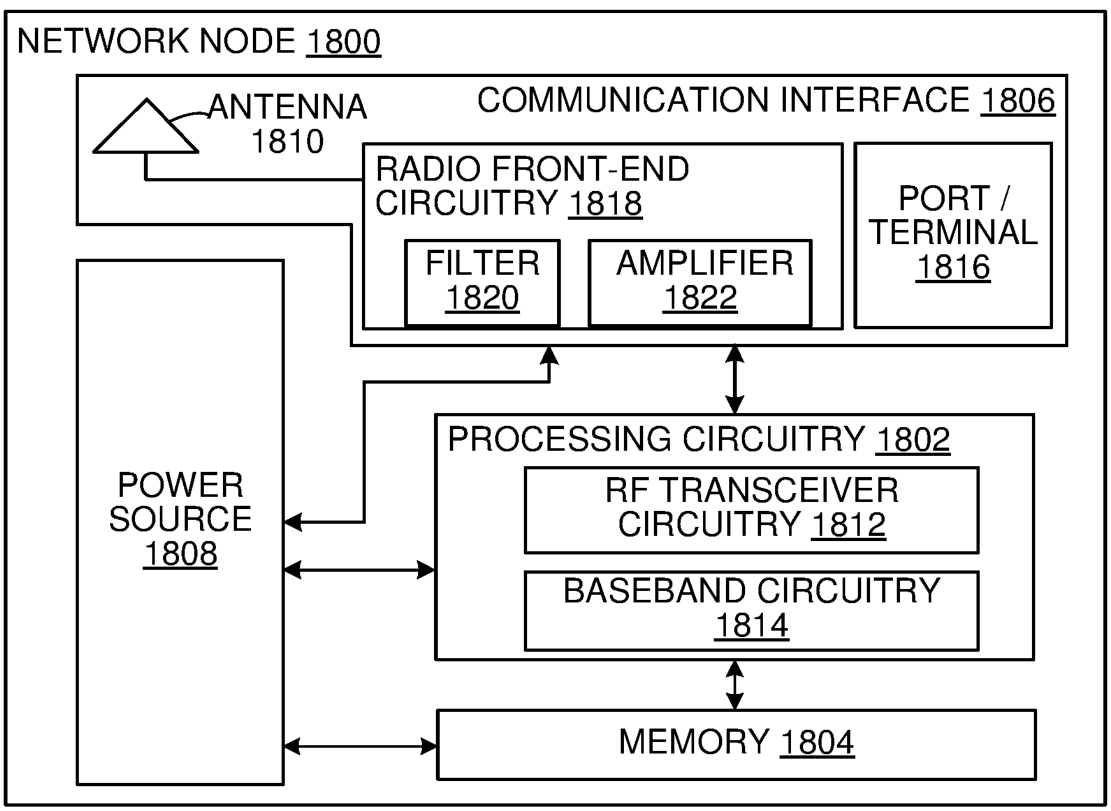

NETWORK NODE 1800
COMMUNICATION INTERFACE 1806
ANTENNA 1810
RADIO FRONT-END CIRCUITRY 1818
FILTER 1820
AMPLIFIER 1822
PORT / TERMINAL 1816
POWER SOURCE 1808
PROCESSING CIRCUITRY 1802
RF TRANSCEIVER CIRCUITRY 1812
BASEBAND CIRCUITRY 1814
MEMORY 1804

FIG. 18

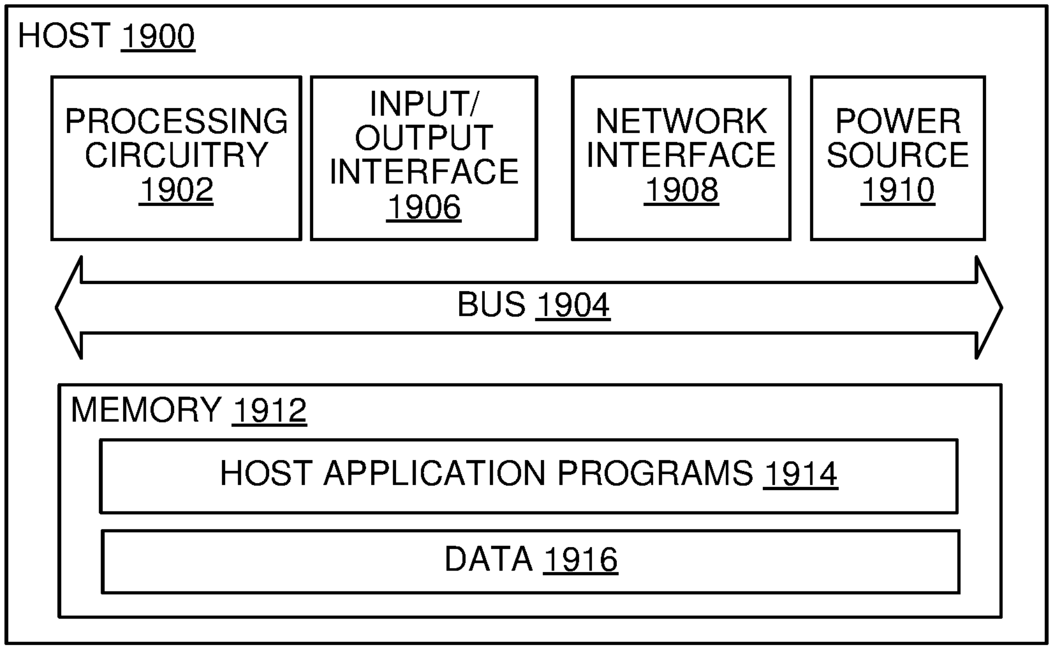

HOST 1900
PROCESSING CIRCUITRY 1902
INPUT/ OUTPUT INTERFACE 1906
NETWORK INTERFACE 1908
POWER SOURCE 1910
BUS 1904
MEMORY 1912
HOST APPLICATION PROGRAMS 1914
DATA 1916

FIG. 19

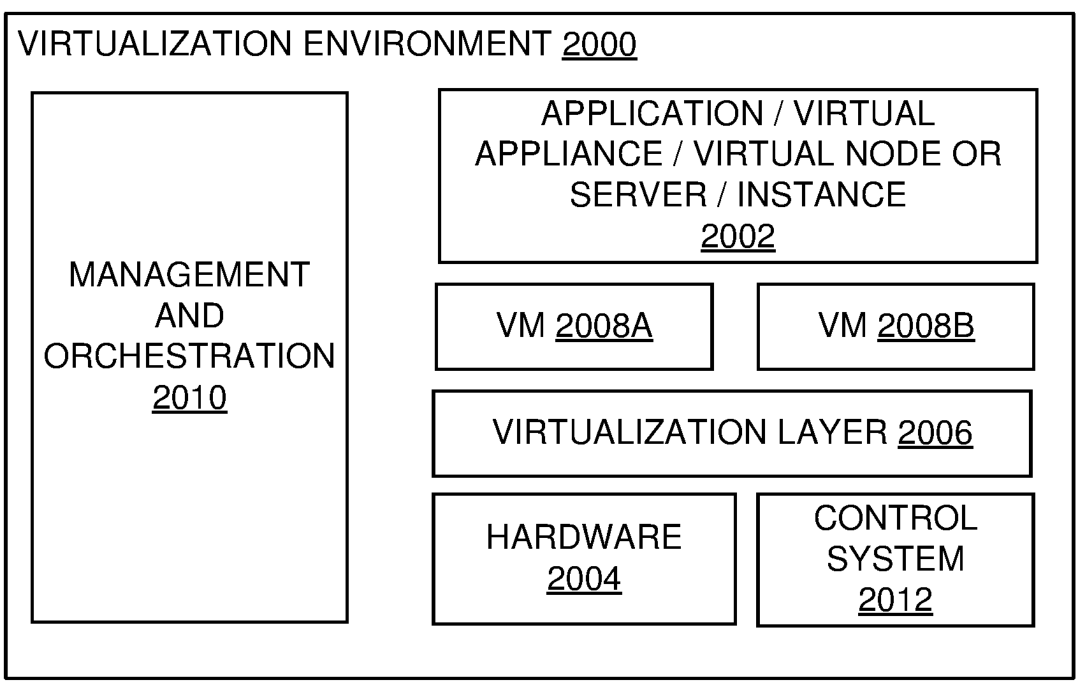

VIRTUALIZATION ENVIRONMENT 2000
MANAGEMENT AND ORCHESTRATION 2010
APPLICATION / VIRTUAL APPLIANCE / VIRTUAL NODE OR SERVER / INSTANCE 2002
VM 2008A
VM 2008B
VIRTUALIZATION LAYER 2006
HARDWARE 2004
CONTROL SYSTEM 2012

FIG. 20

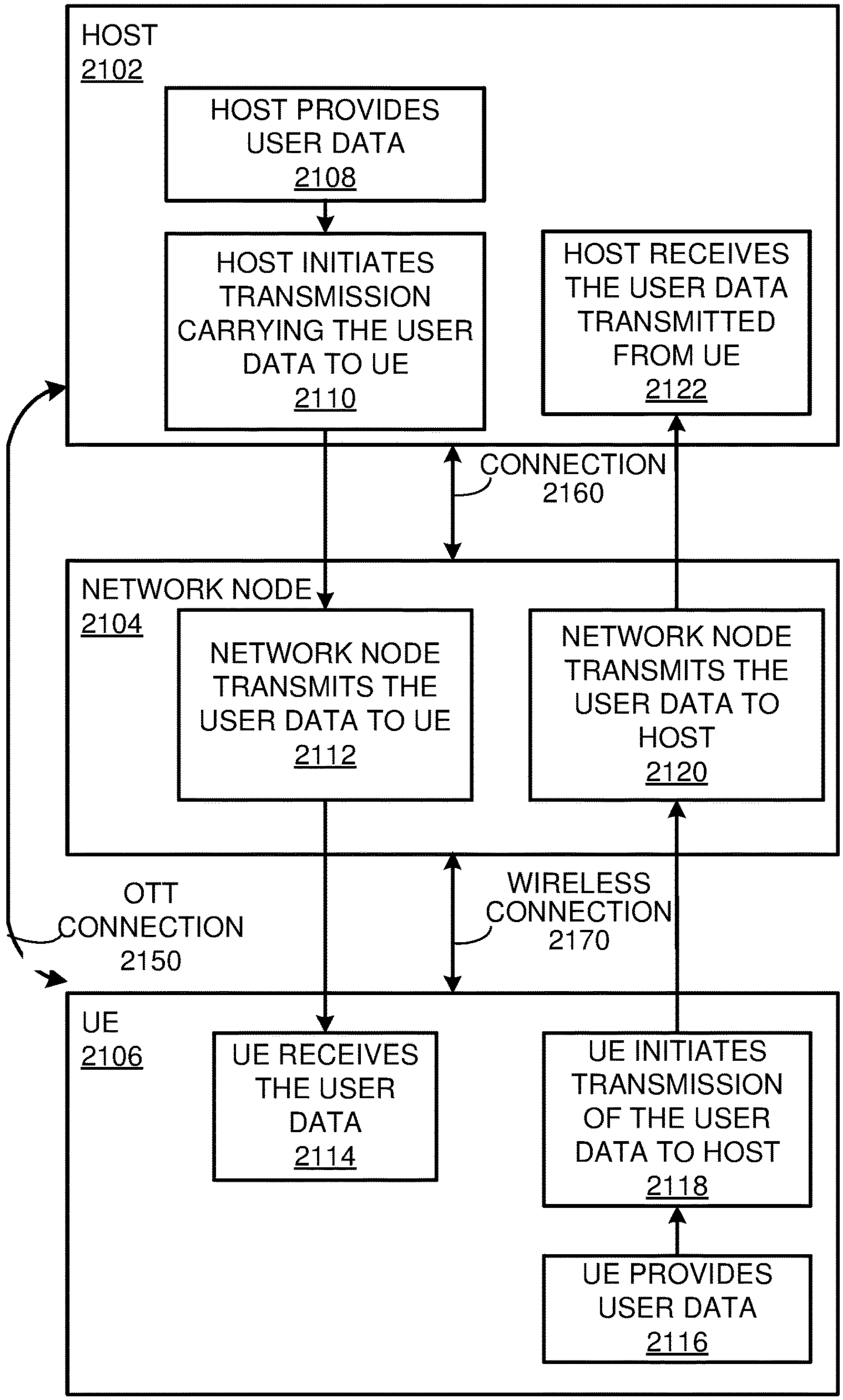

HOST
2102
HOST PROVIDES USER DATA
2108
HOST INITIATES TRANSMISSION CARRYING THE USER DATA TO UE
2110
HOST RECEIVES THE USER DATA TRANSMITTED FROM UE
2122
CONNECTION
2160
NETWORK NODE
2104
NETWORK NODE TRANSMITS THE USER DATA TO UE
2112
NETWORK NODE TRANSMITS THE USER DATA TO HOST
2120
OTT CONNECTION
2150
WIRELESS CONNECTION
2170
UE
2106
UE RECEIVES THE USER DATA
2114
UE INITIATES TRANSMISSION OF THE USER DATA TO HOST
2118
UE PROVIDES USER DATA
2116

FIG. 21

CALIBRATION OVER ASYMMETRIC LINKS

TECHNICAL FIELD

[0001] The present disclosure is related to wireless communication systems and more particularly to automatic precise time protocol ("PTP") calibration over asymmetric links.

BACKGROUND

[0002] FIG. **1** illustrates an example of a new radio ("NR") network (e.g., a 5th Generation ("5G") network) including a 5G core ("5GC") network **130**, network node **120** (e.g., 5G base station ("gNB")), and a communication device **110** (also referred to as user equipment ("UE")). In some examples, the network node **120** is communicatively coupled with the communication device **110** and/or the core network **130** via a wired connection (e.g., optical fiber).

[0003] Optical communication can support 5G and future 6th Generation ("6G") mobile networks, which can require a high precision of synchronization for fronthaul and backhaul traffic of radio access network ("RAN") transport networks. Support for precise time protocol ("PTP") is a standard requirement for any Fronthaul network in particular when dealing with 4th Generation ("4G") and 5G time division duplex ("TDD") since the network nodes can require very precise synchronization (e.g., up to nanosecond precision).

[0004] Wavelength division multiplexing ("WDM") technology can be used to carry traffic over fiber infrastructure with scarce availability of fibers.

[0005] Timing protocols rely on symmetric communication systems. In some examples, when delivering time information via timing protocols it can be important to estimate the time it takes for a timing message to be delivered from a synchronization master to a synchronization receiver. A round trip time ("RTT") can be calculated and divided by 2 to get the one-way delay. However, any asymmetry between optical fibers can add errors to this estimation.

SUMMARY

[0006] According to some embodiments, a method of operating a first transceiver communicatively coupled to a second transceiver by a first cable and a second cable is provided. The method includes transmitting a first message to the second transceiver at a first time, T_1, via the first cable. The method further includes receiving a second message from the second transceiver via the second cable. The second message includes an indication of a second time, T_2, and an indication of a third time, T_3, associated with when a pulse associated with the second message was transmitted by the second transceiver. The method further includes receiving the pulse associated with the second message from the second transceiver at a fourth time, T_4, via the first cable. The method further includes determining a first delay associated with the first cable based on the T_1, the T_2, the T_3, and the T_4.

[0007] According to other embodiments, a method of operating a first transceiver communicatively coupled to a second transceiver by a first cable and a second cable is provided. The method includes transmitting a first message and an associated first pulse to the second transceiver at a first time, T_1, via the first cable. The method further includes receiving an indication of a second time, T_2, associated with when the first pulse was detected by the second transceiver. The method further includes transmitting a third message and an associated second pulse to the second transceiver at a third time, T_3, via the second cable. The method further includes receiving an indication of a fourth time, T_4, associated with when the second pulse was detected by the second transceiver. The method further includes determining a difference between a first delay associated with the first cable and a second delay associated with the second cable based on the T_1, the T_2, the T_3, and the T_4.

[0008] According to other embodiments, a method of operating a first transceiver communicatively coupled to a second transceiver by a first cable and a second cable is provided. The method includes receiving a first message from the second transceiver via the first cable. The first message includes an indication of a first time, T_1, associated with when the first message was transmitted by the second transceiver. The method further includes determining a second time, T_2, at which the first pulse was detected. The method further includes transmitting a second message to the second transceiver via the second cable at a third time, T_3, the second message including an indication of the T_2 and the T_3. The method further includes transmitting a second pulse to the second transceiver via the first cable at the T_3.

[0009] According to other embodiments, a method of operating a first transceiver communicatively coupled to a second transceiver by a first cable and a second cable is provided. The method includes receiving a first pulse from the second transceiver via the first cable. The first pulse can include an indication of a first time, T_1, associated with when the first pulse was transmitted by the second transceiver. The method can further include determining a second time, T_2, at which the first pulse was detected. The method can further include receiving a second pulse from the second transceiver via the second cable. The second pulse including an indication of a third time, T_3, associated with when the second pulse was transmitted by the second transceiver. The method can further include determining a fourth time, T_4, at which the second pulse was detected. The method can further include determining a difference between a first delay associated with the first cable and a second delay associated with the second cable based on the T_1, the T_2, the T_3, and the T_4.

[0010] According to other embodiments, a first transceiver, a computer program, a computer program product, or a non-transitory computer readable medium is provided to perform one of the methods above.

[0011] Certain embodiments may provide one or more of the following technical advantages. In some embodiments, differential delay impairment can be monitored without impacting traffic and without adding any additional instrument for delay measurement. In some examples, the innovations can be added as part of a transceiver design without major cost penalties and allow for the auto-calibration of 25 GHz and beyond links with PTP support for mobile network applications.

[0012] In additional or alternative embodiments, each transceiver can calculate the end-to-end differential delay due to the different crossed fibers. A sync pulse can be propagated within the same spectrum used for PTP and payload traffic and can traverse the same optical path. In some examples, the usage of sync pulses without impacting

PTP protocols is backwards compatible with prior-art technology and may not require any change to standardized PTP protocols.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] The accompanying drawings, which are included to provide a further understanding of the disclosure and are incorporated in and constitute a part of this application, illustrate certain non-limiting embodiments of inventive concepts. In the drawings:

[0014] FIG. **1** is a schematic diagram illustrating an example of a 5^{th} generation ("5G") network;

[0015] FIG. **2** is a block diagram illustrating an example of a first transceiver communicatively coupled to a second transceiver in accordance with some embodiments;

[0016] FIG. **3** is a schematic diagram illustrating an example of a first transceiver communicatively coupled to a second transceiver via asymmetric paths in accordance with some embodiments;

[0017] FIGS. **4-5** are schematic diagrams illustrating examples of signal flows between the first transceiver and second transceiver of FIG. **3** to determine the asymmetry in accordance with some embodiments;

[0018] FIG. **6** is a block diagram illustrating an example of superimposing a frequency pulse onto an amplitude modulated signal using a phase optical modulator in accordance with some embodiments;

[0019] FIGS. **7-8** are diagrams illustrating an example of superimposing a pulse onto an amplitude modulated signal using a chirp generated by a directly modulated laser in accordance with some embodiments;

[0020] FIG. **9** is a diagram illustrating an example of a pulse superimposed onto an amplitude modulated signal in accordance with some embodiments;

[0021] FIG. **10** is a block diagram illustrating an example of a pulse being separated from an amplitude modulated signal at a transceiver in accordance with some embodiments;

[0022] FIG. **11** is a block diagram illustrating an example of splitters/circulators being used by the first transceiver and the second transceiver of FIG. **3** in accordance with some embodiments;

[0023] FIGS. **12-15** are flow charts illustrating examples of operations performed by a first transceiver to determine asymmetry between a communication path between the first transceiver and a second transceiver in accordance with some embodiments;

[0024] FIG. **16** is a block diagram of a communication system in accordance with some embodiments;

[0025] FIG. **17** is a block diagram of a user equipment in accordance with some embodiments;

[0026] FIG. **18** is a block diagram of a network node in accordance with some embodiments;

[0027] FIG. **19** is a block diagram of a host computer communicating with a user equipment in accordance with some embodiments;

[0028] FIG. **20** is a block diagram of a virtualization environment in accordance with some embodiments; and

[0029] FIG. **21** is a block diagram of a host computer communicating via a base station with a user equipment over a partially wireless connection in accordance with some embodiments in accordance with some embodiments.

DETAILED DESCRIPTION

[0030] Some of the embodiments contemplated herein will now be described more fully with reference to the accompanying drawings. Embodiments are provided by way of example to convey the scope of the subject matter to those skilled in the art, in which examples of embodiments of inventive concepts are shown. Inventive concepts may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of present inventive concepts to those skilled in the art. It should also be noted that these embodiments are not mutually exclusive. Components from one embodiment may be tacitly assumed to be present/used in another embodiment.

[0031] FIG. **2** illustrates an example of a first transceiver **210** communicatively coupled to a second transceiver **220** via a channel **230**. Each of the first transceiver **210** and the second transceiver can be included in the core network **130**, network node **120**, or communication device **110** of FIG. **1** (as well as the UE **1700** of FIG. **17** or network node **1800** of FIG. **18**). The channel **230** can be a wireless channel or a wired channel (e.g., via copper wires or optical fibers). The transmitter **210** includes processing circuitry **212** and memory **214**. The memory **214** can include instructions stored therein that are executable by the processing circuitry **212** to cause the first transceiver **210** to perform operations including communicating with the second transceiver **220**. In some examples, the operations further include determining an asymmetry between communication paths between the first transceiver **210** and the second transceiver **220**. The receiver **220** includes processing circuitry **222** and memory **224**. The memory **224** can include instructions stored therein that are executable by the processing circuitry **222** to cause the receiver **220** to perform operations including communicating with the second transceiver **220**. In some examples, the operations further include determining an asymmetry between communication paths between the first transceiver **210** and the second transceiver **220**.

[0032] FIG. **3** illustrates an example of communication between a first transceiver (here a local transceiver) and a second transceiver (here a remote transceiver) over a pair of cables (here a first fiber and a second fiber). In this example, a sync pulse is inserted over an optical channel, without affecting the receiver operations and without requiring any change to existing timing protocol messages. In this example, the sync pulse is transmitted over the first fiber. Note that the optical sync pulse, described in more detail below, is not the same as the PTP sync message.

[0033] The sync pulse is associated with a timing message (e.g., a message carrying or associated with a specific timestamp T_{L1} generated by the Clock of the local transceiver). For example, the association of the sync pulse and timing message comprises that the optical sync pulse is transmitted at the same time as the timing message (e.g. timing protocol message). Any timing protocol (e.g., precision time protocol ("PTP")) can be used for this measurement. For example, the timing protocol (e.g. PTP) provides for a two-way average delay experienced by the timing messages. In some cases, the two-way delay measurement uses both the first and second optical fiber, e.g. the timing protocol uses a timing message from the local transceiver to the remote transceiver on the first optical fiber and a further timing message from the remote transceiver to the local transceiver on the second optical fiber. As such, the timing protocol provides an average of the delays of the two transmission directions.

[0034] The detection of the sync pulse at the remote transceiver determines a timestamp (T_{R2}) from the remote clock. In some examples, the timestamp (T_{R2}) from the remote clock alternatively corresponds to the detection of the timing message at the remote transceiver.

[0035] In some examples, a second optical sync pulse is sent on the same fiber from the remote transceiver to the local transceiver at a time T_{R3}, i.e. the first fiber. In some examples, the second optical sync pulse is associated with a timing message (e.g. also transmitted at a time T_{R3}). In some examples, the timing message is sent on the second fiber (from the remote transceiver to the local transceiver). The sync pulse is received by the local transceiver at a time T_{L4}. In some examples, the timing message transmitted from the remote transceiver to the local transceiver carries timing information, e.g. the value of the timestamp T_{R2} and/or timestamp T_{R3}. The timing message carrying the information may be in an initial timing message, e.g. transmitted at the same time as the timing message (e.g. time T_{R3}) or may be in a later message from the timing protocol, e.g. a PTP follow-up message. References to a message may refer to a single message used for both timing (e.g. determining T_{R4}) and carrying timing information (e.g. timestamp T_{R3}). Alternatively, a reference to a message may refer to two separate messages, e.g. a timing message (e.g. a sync message determining T_{R4}) and a follow-up message carrying timing information (e.g. timestamp T_{R3}).

[0036] The delay/length of the first fiber can be evaluated, e.g. by the local transceiver, as:

$$D_1 = [(T_{L4} - T_{L1}) - (T_{R3} - T_{R2})]/2$$

[0037] A similar process can be implemented on the second fiber, allowing an estimate of the delay/length of the second fiber, D_2. To be determined as:

$$D_2 = [(T'_{L4} - T'_{L1}) - (T'_{R3} - T'_{R2})]/2$$

[0038] In this example, T'_{L1} is a time at which the sync pulse is transmitted from the local transceiver to the remote transceiver via the second fiber. T'_{R2} is the time that the pulse is detected by the remote transceiver. T'_{R3} is the time the remote transceiver transmits a second optical sync pulse back to the local transceiver via the second fiber. T'_{L4} is the time at which the local transceiver detects the pulse sent from the remote transceiver along the second fiber.

[0039] The delay/length of the first fiber and the second fiber can be used to find an asymmetry (A) between the communication paths based on:

$$A = D_2 - D_1$$

[0040] The logical sequence of the signals (pulses) sent over the fibers is shown in FIG. **4**. First, the pair of pulses, labelled as 1 and 2, are transmitted on a first optical fiber (with related timestamps T_{L1}, T_{R2}, T_{R3}, and T_{L4}). Optionally, also a further pair of pulses **3** and **4** (with related timestamps T'_{R1}, T'_{L2}, T'_{L3}, and T'_{R4}). These are examples, and different directions and measurements of timestamps may be used.

[0041] In any example, the asymmetry impacting the timing protocol (e.g. PTP) may be due to one or more of: Fiber propagation asymmetry, DSP Processing time, and Remote Clock Offset. The measurement of the optical sync pulse(s) can determine one or more of these asymmetry factors.

[0042] Other possible mathematical expressions are possible. In some embodiments, having the systems synchronized allows for asymmetry to be determined by the remote transceiver (e.g., without the remote transceiver transmitting return pulses). Instead, the local transceiver transmits a pulse from the local transceiver to the remote transceiver on a first fiber with a related timestamps T_{L1} (instant at the time of transmission from the local clock) and on a second fiber with a related timestamp T'_{L1} (instant at the time of transmission from the local clock). The remote transceiver can determine T_{R2} (when the pulse is received via the first fiber) and T'_{R2} (when the pulse is received via the second fiber).

[0043] FIG. **4** shows the complete method with the sync pulses sent in either direction over the same fiber, calculating the actual Fiber Propagation delay without the asymmetric DSP Processing and the Remote Clock Offset.

[0044] The logical sequence of the signals (pulses) sent over the fibers is shown in FIG. **5**. FIG. **5** shows a simplified method where the two end points (transceivers) are already tuned to the same frequency (synchronized) so the optical sync pulses can be used over a single fiber.

[0045] In this example, the method comprises sending a first pulse (labelled as Pulse **1**, with related timestamps T_{L1} and T_{R2}), and then a second pulse, labelled as Pulse **2**, with related timestamps T'_{L1} and T'_{R2}).

[0046] The asymmetry can be calculated as follows:

$$A = (T'_{R2} - T_{R2}) - (T'_{L1} - T_{L1})$$

[0047] Using this method, each transceiver can calculate the differential delay to be compensated due to the different crossed fibers.

[0048] In a further example, a time delay of a single optical pulse is used to determine an asymmetry and/or delay between the local transceiver and remote transceiver. For example, the timing of a single optical pulse provides the time delay in one direction, e.g. from the remote transceiver to the local transceiver. The single optical pulse may be transmitted with an associated timing message, e.g. transmitted at the same time as the timing message. The time measured by the optical pulse can be used in a calculation with the average two-way time obtained from the two-way timing protocol (e.g. PTP) to determine the delay in each direction. For example, the delay on the optical fiber not used for the optical pulse equals the total delay due to the optical fibers from the two-way timing measurement minus the delay measured by the optical pulse. is the Thus, the asymmetry can be calculated. Delays due to processing delays can be assumed to be equal at each transceiver or measured in another way.

[0049] In some examples, a time reference can be sent by superimposing a frequency pulse (e.g., a sudden variation of the optical carrier frequency) to the transmitted intensity-modulated (e.g., OOK or PAM4) optical signal. This has an advantage of not penalizing the received signal, since the photodiode used to receive in a direct detection system is only sensitive to the input signal amplitude and not to its phase.

[0050] FIGS. **6-7** illustrate two different ways to superimpose a frequency pulse (or, in general, a frequency modulation) to an amplitude modulated signal.

[0051] FIG. **6** illustrates an example of superimposing a frequency pulse by applying it using a phase optical modulator, independent of the amplitude modulator used for the data. The frequency, f, is the derivative of the phase, Φ, f=½π·dΦ/dt, the pulse can be integrated before being modulated. In some examples, the phase and amplitude modulator can be monolithically integrated on the same photonic integrated circuit ("PIC") (e.g., a silicon photonic circuit). In other examples, the phase modulator and the amplitude modulator can be implemented separately.

[0052] By directly applying the pulse to the phase modulator, two spikes of frequency of opposite sign in correspondence to the pulse edge are obtained, which can be used to detect the time stamp on the ramp-up and ramp-down of the integrated pulse.

[0053] FIGS. **7-8** illustrates an example of superimposing a frequency pulse without an additional phase modulator and relies instead on a chirp generated by a directly modulated laser. In some embodiments, a high bias current, far from the lasing threshold, is applied to the laser and a current pulse is superimposed by means of a laser driver.

[0054] The pulse amplitude can be small, to keep small the corresponding output power variation (e.g., within an extinction ratio, r, of 1 dB), which would disturb the data signal. With a high bias current even small amplitude variations give significant power variations.

[0055] The frequency variation due to the chirp is given by the equation below:

$$f(t) = \frac{\alpha}{4\pi}\left(\frac{1}{P(t)}\frac{dP(t)}{dt} + kP(t)\right)$$

[0056] The first term, referred to as a transient chirp, is associated to the variations of the optical power. The second term is proportional to the optical power and is referred to as an adiabatic chirp.

[0057] The first term can be dominant when the laser is biased close to the threshold and the power difference between the low and high levels of the transmitted pulses is high, as happens in regular OOK transmissions. The adiabatic chirp dominates instead in these working conditions (high output power and small power variation) so that:

$$f(t) \approx \frac{\alpha k P(t)}{4\pi}$$

[0058] The high and low levels of the pulse, P_1 and P_0 respectively, obey to the following equations:

$$P_{bias} = (P_1 + P_0)/2 \text{ and } r = P_1/P_0,$$

where P_{bias} and r are the average output power and the extinction ratio, respectively. Using these equations, we obtain the frequency deviation Df associated to the pulse:

$$Df \approx \frac{\alpha k(P_1 - P_0)}{4\pi} = \frac{\alpha k}{2\pi} P_{bias} \frac{r(r-1)}{r+1}$$

[0059] Considering a=2.8, k=11.4 GHz/mW, P_{bias}=3 mW Error! Reference source not found., r=1 dB (i.e. 1.26 in linear units), Df=2 GHZ. The laser can be designed such that higher frequency deviations can be obtained.

[0060] At the receiver the photodiode cannot detect the signal frequency. FIGS. **9-10** illustrate that a frequency modulated signal can be converted into an amplitude modulated signal using filter detuned with respect to the optical carrier.

[0061] Since the optical carrier is centered on the slope of the filter, any change of its frequency leads to an amplitude variation.

[0062] Even if the received signal is tapped for detecting the frequency pulse, it introduces negligible insertion loss on the main signal path. The insertion loss is instead significant on the path used for the frequency pulse detection, due to the splitting ratio and the filter insertion loss. This is not an issue since the receiver only needs to detect the presence of the pulse and does not have demanding performance requirements for digital detection. The direct detect receiver on the tap line has a bandwidth much lower than the signal bandwidth (e.g., 2 GHz for a 25 Gbit/s signal) so that most of the signal spectrum is filtered out and the one in the receiver narrow bandwidth can be considered as tolerable additive white noise.

[0063] The transmission of the pulse co-directional with the traffic can be implemented seamlessly while different embodiments can be adopted for the contra-directional propagation.

[0064] FIG. **11** illustrates an example of a splitter/circulator implemented at each of the local transceiver and remote transceiver in order to inject the modulated pulse to the remote site and a photodiode detector. In some examples, these additions can also provide reflection monitoring and local loop monitoring.

[0065] In the description that follows, while the first transceiver may be any of communication device **110**, network node **120**, first transceiver **210**, second transceiver **220**, wireless device **1612**A-B, wired or wireless devices UE **1612**C-D, UE **1700**, Hub **1614**, network node **1610**A-B, core network node **1608**, network node **1800**, virtualization hardware **2004**, virtual machines **2008**A, **2008**B, network node **2104**, or UE **2106**, the first transceiver **210** shall be used to describe the functionality of the operations of the first transceiver. Operations of the first transceiver **210** (implemented using the structure of the block diagram of FIG. **2**) will now be discussed with reference to the flow charts of FIGS. **12-15** according to some embodiments of inventive concepts. For example, modules may be stored in memory **214** of FIG. **2**, and these modules may provide instructions so that when the instructions of a module are executed by respective first transceiver processing circuitry **212**, processing circuitry **212** performs respective operations of the flow charts.

[0066] FIG. **12** illustrates an example of operations performed by a first transceiver communicatively coupled to a second transceiver by a first cable and a second cable.

[0067] At block **1210**, processing circuitry **212** transmits a first message to the second transceiver at a first time, T_1, via the first cable. In some embodiments, transmitting the first message includes transmitting the first message and an associated first pulse at the T_1 via the first cable. In some examples transmitting the first message and the associated first pulse includes: (1) generating an amplitude modulated signal including data associated with the first message using an amplitude modulator; (2) generating a transmit signal by superimposing the first pulse on the amplitude modulated signal using a phase optical modulator independent of the amplitude modulator; and (3) transmitting the transmit signal.

[0068] In additional or alternative embodiments, transmitting the first message and the associated first pulse includes: (1) applying the first pulse and a bias current that is above a laser threshold to a laser driver; (2) generating an optical signal by a laser using the laser driver; (3) generating a transmit signal by amplitude modulating the optical signal based on data associated with the first message; and (4) transmitting the transmit signal.

[0069] At block **1220**, processing circuitry **212** receiving a second message from the second transceiver via the second cable. The second message can include an indication of a second time, T_2, and an indication of a third time, T_3, associated with when a pulse (sometimes referred to as a second pulse) that is associated with the second message was transmitted by the second transceiver. In some examples, the second time T_2 is a time associated with when the first message was detected by the second transceiver. In additional or alternative examples, the second time T_2 is a time associated with when the first optical pulse (associated with the first message) was detected by the second transceiver.

[0070] At block **1230**, processing circuitry **212** receives a second pulse from the second transceiver at a fourth time, T_4, via the first cable.

[0071] At block **1240**, processing circuitry **212** determines a first delay associated with the first cable based on the T_1, the T_2, the T_3, and the T_4. In some embodiments, determining the first delay associated with the first cable includes determining the first delay, D_1, based on $D_1=[(T_4-T_1)-(T_3-T_2)]/2$.

[0072] At block **1250**, processing circuitry **212** transmits a third message to the second transceiver at a fifth time, T_5, via the second cable. In some embodiments, the third message (and, in some examples, the associated third pulse) are transmitted in a process similar to the first message (and the first pulse) in block **1210**.

[0073] At block **1260**, processing circuitry **212** receives a fourth message from the second transceiver via the first cable. The fourth message can include an indication of a sixth time, T_6, and an indication of a seventh time, T_7, associated with when a fourth pulse that is associated with the fourth message was transmitted by the second transceiver.

[0074] At block **1270**, processing circuitry **212** receives the fourth pulse associated with the fourth message from the second transceiver at an eighth time, T'_{L4}, via the second cable.

[0075] At block **1280**, processing circuitry **212** determines a second delay associated with the second cable based on the T_5, the T_6, the T_7, and the T_8. In some embodiments, determining the second delay associated with the second cable includes determining the second delay, D_2, based on $D_2=[(T_8-T_5)-(T_7-T_6)]/2$.

[0076] At block **1290**, processing circuitry **212** determines a difference between the first delay and the second delay. In some embodiments, determining the difference between the first delay and the second delay includes determining an asymmetry between at least one of: a first length of the first cable and a second length of the second cable; a first digital signal processing ("DSP") time of the first transceiver and a second DSP time of the second transceiver; and a first application-specific integrated circuitry ("ASIC") processing time on the first transceiver and a second ASIC processing time of the second transceiver.

[0077] At block **1295**, processing circuitry **212** communicates with the second transceiver based on the difference between the first delay and the second delay. In some embodiments, the messages (e.g., the first message and the second message) are each precise time protocol ("PTP") messages that include timestamps indicating when they were transmitted.

[0078] In additional or alternative embodiments, the first cable is a first optical fiber having a first length and the second cable is a second optical fiber having a second length. In some examples the first length is different than the second length.

[0079] Various operations of FIG. **12** may be optional. In some embodiments, blocks **1250**, **1260**, **1270**, **1280**, **1290**, and **1295** are optional.

[0080] FIG. **13** illustrates an example of additional or alternative operations performed by a first transceiver communicatively coupled to a second transceiver by a first cable and a second cable.

[0081] At block **1310**, processing circuitry **212** receives a first message and an associated first pulse from the second transceiver via the first cable. The first message can include an indication of a first time, T_1, associated with when the first message was transmitted by the second transceiver.

[0082] At block **1320**, processing circuitry **212** determines a second time, T_2, at which the first pulse was detected.

[0083] At block **1330**, processing circuitry **212** transmits a second message to the second transceiver via the second cable at a third time, T_3. The second message can include an indication of the T_2 and the T_3. In some embodiments, transmitting the second message and the associated second pulse includes: (1) generating an amplitude modulated signal including data associated with the second message using an amplitude modulator; (2) generating a transmit signal by superimposing the second pulse on the amplitude modulated signal using a phase optical modulator independent of the amplitude modulator; and (3) transmitting the transmit signal.

[0084] In additional or alternative embodiments, transmitting the second message and the associated second pulse includes: (1) applying the second pulse and a bias current that is above a laser threshold to a laser driver; (2) generating an optical signal by a laser using the laser driver; (3)

generating a transmit signal by amplitude modulating the optical signal based on data associated with the second message; and (4) transmitting the transmit signal.

[0085] At block **1340**, processing circuitry **212** transmits a second pulse to the second transceiver via the first cable at the T_3.

[0086] In some embodiments, receiving the first message and the associated first pulse includes receiving the first message and the associated first pulse at a first port of a circulator. Transmitting the second message and the second pulse includes passing a transmit signal including the second message and the associated second pulse through a splitter, the splitter passing the second message to the second transceiver via the second cable and passing the second pulse to a third port of the circulator.

[0087] At block **1350**, processing circuitry **212** receives a third message and an associated third pulse from the second transceiver via the second cable. The third message can include an indication of a fifth time, T_5, associated with when the third message was transmitted by the second transceiver.

[0088] At block **1360**, processing circuitry **212** determines a sixth time, T_6, at which the third pulse was detected.

[0089] At block **1370**, processing circuitry **212** transmits a fourth message to the second transceiver via the first cable at a seventh time, T_7, the fourth message including an indication of the T_6 and the T_7. In some embodiments, the fourth message and the associated fourth pulse are transmitted in a process similar to the second message and the second pulse in block **1330**.

[0090] At block **1380**, processing circuitry **212** transmits a fourth pulse to the second transceiver via the second cable at the T_7.

[0091] At block **1390**, processing circuitry **212** determines a difference between a first delay associated with the first cable and a second delay associated with the second cable. In some embodiments, determining the difference between the first delay and the second delay includes determining an asymmetry between at least one of: a first length of the first cable and a second length of the second cable; a first digital signal processing, DSP, time of the first transceiver and a second DSP time of the second transceiver; and a first application-specific integrated circuitry, ASIC, processing time on the first transceiver and a second ASIC processing time of the second transceiver.

[0092] At block **1395**, processing circuitry **212** communicates with the second transceiver based on the difference between the first delay and the second delay.

[0093] In some embodiments, the messages (e.g., the first message and the second message) are each precise time protocol ("PTP") messages that include timestamps indicating when they were transmitted.

[0094] In additional or alternative embodiments, the first cable is a first optical fiber having a first length and the second cable is a second optical fiber having a second length. In some examples the first length is different than the second length.

[0095] Various operations of FIG. **13** may be optional. In some embodiments, blocks **1350**, **1360**, **1370**, **1380**, **1390**, and **1395** are optional.

[0096] FIG. **14** illustrates an example of additional or alternative operations performed by a first transceiver communicatively coupled to a second transceiver by a first cable and a second cable.

[0097] At block **1410**, processing circuitry **212** synchronizes the first transceiver and the second transceiver.

[0098] At block **1420**, processing circuitry **212** transmits a first message and an associated first pulse to the second transceiver at a first time, T_1, via the first cable.

[0099] At block **1430**, processing circuitry **212** receives an indication of a second time, T_2, associated with when the first pulse was detected by the second transceiver.

[0100] At block **1440**, processing circuitry **212** transmits a second message and an associated second pulse to the second transceiver at a third time, T_3, via the second cable.

[0101] At block **1450**, processing circuitry **212** receives an indication of a fourth time, T_4, associated with when the second pulse was detected by the second transceiver.

[0102] At block **1460**, processing circuitry **212** determines a difference between a first delay associated with the first cable and a second delay associated with the second cable based on the T_1, the T_2, the T_3, and the T_4. In some embodiments, determining the difference, A, between the first delay and the second delay comprises determining $A=(T_4-T_2)-(T_3-T_1)$.

[0103] In additional or alternative embodiments, determining the difference between the first delay and the second delay includes determining an asymmetry between at least one of: a first length of the first cable and a second length of the second cable; a first digital signal processing, DSP, time of the first transceiver and a second DSP time of the second transceiver; and a first application-specific integrated circuitry, ASIC, processing time on the first transceiver and a second ASIC processing time of the second transceiver.

[0104] In some embodiments, the messages (e.g., the first message and the second message) are each precise time protocol ("PTP") messages that include timestamps indicating when they were transmitted.

[0105] In additional or alternative embodiments, the first cable is a first optical fiber having a first length and the second cable is a second optical fiber having a second length. In some examples the first length is different than the second length.

[0106] Various operations of FIG. **14** may be optional. In some embodiments, block **1410** is optional.

[0107] FIG. **15** illustrates an example of additional or alternative operations performed by a first transceiver communicatively coupled to a second transceiver by a first cable and a second cable.

[0108] At block **1510**, processing circuitry **212** synchronizes the first transceiver and the second transceiver.

[0109] At block **1520**, processing circuitry **212** receives a first pulse from the second transceiver via the first cable. The first pulse can include an indication of a first time, T_1, associated with when the first pulse was transmitted by the second transceiver.

[0110] At block **1530**, processing circuitry **212** determines a second time, T_2, at which the first pulse was detected.

[0111] At block **1540**, processing circuitry **212** receives a second pulse from the second transceiver via the second cable. The second pulse can include an indication of a third time, T_3, associated with when the second pulse was transmitted by the second transceiver.

[0112] At block **1550**, processing circuitry **212** determines a fourth time, T_4, at which the second pulse was detected.

[0113] At block **1560**, processing circuitry determines a difference between a first delay associated with the first cable and a second delay associated with the second cable based on the T_1, the T_2, the T_3, and the T_4. In some embodiments, determining the difference, A, between the first delay and the second delay includes determining $A=(T_4-T_2)-(T_3-T_1)$.

[0114] Various operations of FIG. **15** may be optional. In some embodiments, block **1510** is optional.

[0115] FIG. **16** shows an example of a communication system **1600** in accordance with some embodiments.

[0116] In the example, the communication system **1600** includes a telecommunication network **1602** that includes an access network **1604**, such as a radio access network (RAN), and a core network **1606**, which includes one or more core network nodes **1608**. The access network **1604** includes one or more access network nodes, such as network nodes **1610***a* and **1610***b* (one or more of which may be generally referred to as network nodes **1610**), or any other similar 3^{rd} Generation Partnership Project (3GPP) access node or non-3GPP access point. Moreover, as will be appreciated by those of skill in the art, the network nodes **1610** are not necessarily limited to an implementation in which a radio portion and a baseband portion are supplied and integrated by a single vendor. Thus, it will be understood that the network nodes **1610** may include disaggregated implementations or portions thereof. For example, in some embodiments, the telecommunication network **1602** includes one or more Open-RAN (ORAN) network nodes. An ORAN network node is a node in the telecommunication network **1602** that supports an ORAN specification (e.g., a specification published by the O-RAN Alliance, or any similar organization) and may operate alone or together with other nodes to implement one or more functionalities of any node in the telecommunication network **1602**, including one or more network nodes **1610** and/or core network nodes **1608**.

[0117] Examples of an ORAN network node include an open radio unit (O-RU), an open distributed unit (O-DU), an open central unit (O-CU), including an O-CU control plane (O-CU-CP) or an O-CU user plane (O-CU-UP), a RAN intelligent controller (near-real time or non-real time) hosting software or software plug-ins, such as a near-real time RAN control application (e.g., xApp) or a non-real time RAN automation application (e.g., rApp), or any combination thereof (the adjective "open" designating support of an ORAN specification). The network node may support a specification by, for example, supporting an interface defined by the ORAN specification, such as an A1, F1, W1, E1, E2, X2, Xn interface, an open fronthaul user plane interface, or an open fronthaul management plane interface. Intents and content-aware notifications described herein may be communicated from a 3GPP network node or an ORAN network node over 3GPP-defined interfaces (e.g., N2, N3) and/or ORAN Alliance-defined interfaces (e.g., A1, O1). Moreover, an ORAN network node may be a logical node in a physical node. Furthermore, an ORAN network node may be implemented in a virtualization environment (described further below) in which one or more network functions are virtualized. For example, the virtualization environment may include an O-Cloud computing platform orchestrated by a Service Management and Orchestration Framework via an O-2 interface defined by the O-RAN Alliance. The network nodes **1610** facilitate direct or indirect connection of user equipment (UE), such as by connecting wireless devices **1612***a*, **1612***b*, **1612***c*, and **1612***d* (one or more of which may be generally referred to as UEs **1612**) to the core network **1606** over one or more wireless connections. The network nodes **1610** facilitate direct or indirect connection of user equipment (UE), such as by connecting UEs **1612***a*, **1612***b*, **1612***c*, and **1612***d* (one or more of which may be generally referred to as UEs **1612**) to the core network **1606** over one or more wireless connections.

[0118] Example wireless communications over a wireless connection include transmitting and/or receiving wireless signals using electromagnetic waves, radio waves, infrared waves, and/or other types of signals suitable for conveying information without the use of wires, cables, or other material conductors. Moreover, in different embodiments, the communication system **1600** may include any number of wired or wireless networks, network nodes, UEs, and/or any other components or systems that may facilitate or participate in the communication of data and/or signals whether via wired or wireless connections. The communication system **1600** may include and/or interface with any type of communication, telecommunication, data, cellular, radio network, and/or other similar type of system.

[0119] The UEs **1612** may be any of a wide variety of communication devices, including wireless devices arranged, configured, and/or operable to communicate wirelessly with the network nodes **1610** and other communication devices. Similarly, the network nodes **1610** are arranged, capable, configured, and/or operable to communicate directly or indirectly with the UEs **1612** and/or with other network nodes or equipment in the telecommunication network **1602** to enable and/or provide network access, such as wireless network access, and/or to perform other functions, such as administration in the telecommunication network **1602**.

[0120] In the depicted example, the core network **1606** connects the network nodes **1610** to one or more hosts, such as host **1616**. These connections may be direct or indirect via one or more intermediary networks or devices. In other examples, network nodes may be directly coupled to hosts. The core network **1606** includes one more core network nodes (e.g., core network node **1608**) that are structured with hardware and software components. Features of these components may be substantially similar to those described with respect to the UEs, network nodes, and/or hosts, such that the descriptions thereof are generally applicable to the corresponding components of the core network node **1608**. Example core network nodes include functions of one or more of a Mobile Switching Center (MSC), Mobility Management Entity (MME), Home Subscriber Server (HSS), Access and Mobility Management Function (AMF), Session Management Function (SMF), Authentication Server Function (AUSF), Subscription Identifier De-concealing function (SIDF), Unified Data Management (UDM), Security Edge Protection Proxy (SEPP), Network Exposure Function (NEF), and/or a User Plane Function (UPF).

[0121] The host **1616** may be under the ownership or control of a service provider other than an operator or provider of the access network **1604** and/or the telecommunication network **1602**, and may be operated by the service provider or on behalf of the service provider. The host **1616** may host a variety of applications to provide one or more service. Examples of such applications include live and pre-recorded audio/video content, data collection services such as retrieving and compiling data on various ambient conditions detected by a plurality of UEs, analytics functionality, social media, functions for controlling or otherwise interacting with remote devices, functions for an alarm and surveillance center, or any other such function performed by a server.

[0122] As a whole, the communication system **1600** of FIG. **16** enables connectivity between the UEs, network nodes, and hosts. In that sense, the communication system may be configured to operate according to predefined rules or procedures, such as specific standards that include, but are not limited to: Global System for Mobile Communications (GSM); Universal Mobile Telecommunications System (UMTS); Long Term Evolution (LTE), and/or other suitable 2G, 3G, 4G, 5G standards, or any applicable future generation standard (e.g., 6G); wireless local area network (WLAN) standards, such as the Institute of Electrical and Electronics Engineers (IEEE) 802.11 standards (WiFi); and/or any other appropriate wireless communication standard, such as the Worldwide Interoperability for Microwave Access (WiMax), Bluetooth, Z-Wave, Near Field Communication (NFC) ZigBee, LiFi, and/or any low-power wide-area network (LPWAN) standards such as LoRa and Sigfox.

[0123] In some examples, the telecommunication network **1602** is a cellular network that implements 3GPP standardized features. Accordingly, the telecommunications network **1602** may support network slicing to provide different logical networks to different devices that are connected to the telecommunication network **1602**. For example, the telecommunications network **1602** may provide Ultra Reliable Low Latency Communication (URLLC) services to some UEs, while providing Enhanced Mobile Broadband (eMBB) services to other UEs, and/or Massive Machine Type Communication (mMTC)/Massive IoT services to yet further UEs.

[0124] In some examples, the UEs **1612** are configured to transmit and/or receive information without direct human interaction. For instance, a UE may be designed to transmit information to the access network **1604** on a predetermined schedule, when triggered by an internal or external event, or in response to requests from the access network **1604**. Additionally, a UE may be configured for operating in single- or multi-RAT or multi-standard mode. For example, a UE may operate with any one or combination of Wi-Fi, NR (New Radio) and LTE, i.e. being configured for multi-radio dual connectivity (MR-DC), such as E-UTRAN (Evolved-UMTS Terrestrial Radio Access Network) New Radio—Dual Connectivity (EN-DC).

[0125] In the example, the hub **1614** communicates with the access network **1604** to facilitate indirect communication between one or more UEs (e.g., UE **1612***c* and/or **1612***d*) and network nodes (e.g., network node **1610***b*). In some examples, the hub **1614** may be a controller, router, content source and analytics, or any of the other communication devices described herein regarding UEs. For example, the hub **1614** may be a broadband router enabling access to the core network **1606** for the UEs. As another example, the hub **1614** may be a controller that sends commands or instructions to one or more actuators in the UEs. Commands or instructions may be received from the UEs, network nodes **1610**, or by executable code, script, process, or other instructions in the hub **1614**. As another example, the hub **1614** may be a data collector that acts as temporary storage for UE data and, in some embodiments, may perform analysis or other processing of the data. As another example, the hub **1614** may be a content source. For example, for a UE that is a VR headset, display, loudspeaker or other media delivery device, the hub **1614** may retrieve VR assets, video, audio, or other media or data related to sensory information via a network node, which the hub **1614** then provides to the UE either directly, after performing local processing, and/or after adding additional local content. In still another example, the hub **1614** acts as a proxy server or orchestrator for the UEs, in particular in if one or more of the UEs are low energy IoT devices.

[0126] The hub **1614** may have a constant/persistent or intermittent connection to the network node **1610***b*. The hub **1614** may also allow for a different communication scheme and/or schedule between the hub **1614** and UEs (e.g., UE **1612***c* and/or **1612***d*), and between the hub **1614** and the core network **1606**. In other examples, the hub **1614** is connected to the core network **1606** and/or one or more UEs via a wired connection. Moreover, the hub **1614** may be configured to connect to an M2M service provider over the access network **1604** and/or to another UE over a direct connection. In some scenarios, UEs may establish a wireless connection with the network nodes **1610** while still connected via the hub **1614** via a wired or wireless connection. In some embodiments, the hub **1614** may be a dedicated hub—that is, a hub whose primary function is to route communications to/from the UEs from/to the network node **1610***b*. In other embodiments, the hub **1614** may be a non-dedicated hub—that is, a device which is capable of operating to route communications between the UEs and network node **1610***b*, but which is additionally capable of operating as a communication start and/or end point for certain data channels.

[0127] FIG. **17** shows a UE **1700** in accordance with some embodiments. As used herein, a UE refers to a device capable, configured, arranged and/or operable to communicate wirelessly with network nodes and/or other UEs. Examples of a UE include, but are not limited to, a smart phone, mobile phone, cell phone, voice over IP (VOIP) phone, wireless local loop phone, desktop computer, personal digital assistant (PDA), wireless cameras, gaming console or device, music storage device, playback appliance, wearable terminal device, wireless endpoint, mobile station, tablet, laptop, laptop-embedded equipment (LEE), laptop-mounted equipment (LME), smart device, wireless customer-premise equipment (CPE), vehicle-mounted or vehicle embedded/integrated wireless device, etc. Other examples include any UE identified by the 3rd Generation Partnership Project (3GPP), including a narrow band internet of things (NB-IoT) UE, a machine type communication (MTC) UE, and/or an enhanced MTC (eMTC) UE.

[0128] A UE may support device-to-device (D_2D) communication, for example by implementing a 3GPP standard for sidelink communication, Dedicated Short-Range Communication (DSRC), vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), or vehicle-to-everything (V2X). In other examples, a UE may not necessarily have a user in the sense of a human user who owns and/or operates the relevant device. Instead, a UE may represent a device that is intended for sale to, or operation by, a human user but which may not, or which may not initially, be associated with a specific human user (e.g., a smart sprinkler controller). Alternatively, a UE may represent a device that is not intended for sale to, or operation by, an end user but which may be associated with or operated for the benefit of a user (e.g., a smart power meter).

[0129] The UE **1700** includes processing circuitry **1702** that is operatively coupled via a bus **1704** to an input/output interface **1706**, a power source **1708**, a memory **1710**, a communication interface **1712**, and/or any other component, or any combination thereof. Certain UEs may utilize all or a subset of the components shown in FIG. **17**. The level of integration between the components may vary from one UE to another UE. Further, certain UEs may contain multiple instances of a component, such as multiple processors, memories, transceivers, transmitters, receivers, etc.

[0130] The processing circuitry **1702** is configured to process instructions and data and may be configured to implement any sequential state machine operative to execute instructions stored as machine-readable computer programs in the memory **1710**. The processing circuitry **1702** may be implemented as one or more hardware-implemented state machines (e.g., in discrete logic, field-programmable gate arrays (FPGAs), application specific integrated circuits (ASICs), etc.); programmable logic together with appropriate firmware; one or more stored computer programs, general-purpose processors, such as a microprocessor or digital signal processor (DSP), together with appropriate software; or any combination of the above. For example, the processing circuitry **1702** may include multiple central processing units (CPUs).

[0131] In the example, the input/output interface **1706** may be configured to provide an interface or interfaces to an input device, output device, or one or more input and/or output devices. Examples of an output device include a speaker, a sound card, a video card, a display, a monitor, a printer, an actuator, an emitter, a smartcard, another output device, or any combination thereof. An input device may allow a user to capture information into the UE **1700**. Examples of an input device include a touch-sensitive or presence-sensitive display, a camera (e.g., a digital camera, a digital video camera, a web camera, etc.), a microphone, a sensor, a mouse, a trackball, a directional pad, a trackpad, a scroll wheel, a smartcard, and the like. The presence-sensitive display may include a capacitive or resistive touch sensor to sense input from a user. A sensor may be, for instance, an accelerometer, a gyroscope, a tilt sensor, a force sensor, a magnetometer, an optical sensor, a proximity sensor, a biometric sensor, etc., or any combination thereof. An output device may use the same type of interface port as an input device. For example, a Universal Serial Bus (USB) port may be used to provide an input device and an output device.

[0132] In some embodiments, the power source **1708** is structured as a battery or battery pack. Other types of power sources, such as an external power source (e.g., an electricity outlet), photovoltaic device, or power cell, may be used. The power source **1708** may further include power circuitry for delivering power from the power source **1708** itself, and/or an external power source, to the various parts of the UE **1700** via input circuitry or an interface such as an electrical power cable. Delivering power may be, for example, for charging of the power source **1708**. Power circuitry may perform any formatting, converting, or other modification to the power from the power source **1708** to make the power suitable for the respective components of the UE **1700** to which power is supplied.

[0133] The memory **1710** may be or be configured to include memory such as random access memory (RAM), read-only memory (ROM), programmable read-only memory (PROM), erasable programmable read-only memory (EPROM), electrically erasable programmable read-only memory (EEPROM), magnetic disks, optical disks, hard disks, removable cartridges, flash drives, and so forth. In one example, the memory **1710** includes one or more application programs **1714**, such as an operating system, web browser application, a widget, gadget engine, or other application, and corresponding data **1716**. The memory **1710** may store, for use by the UE **1700**, any of a variety of various operating systems or combinations of operating systems.

[0134] The memory **1710** may be configured to include a number of physical drive units, such as redundant array of independent disks (RAID), flash memory, USB flash drive, external hard disk drive, thumb drive, pen drive, key drive, high-density digital versatile disc (HD-DVD) optical disc drive, internal hard disk drive, Blu-Ray optical disc drive, holographic digital data storage (HDDS) optical disc drive, external mini-dual in-line memory module (DIMM), synchronous dynamic random access memory (SDRAM), external micro-DIMM SDRAM, smartcard memory such as tamper resistant module in the form of a universal integrated circuit card (UICC) including one or more subscriber identity modules (SIMs), such as a USIM and/or ISIM, other memory, or any combination thereof. The UICC may for example be an embedded UICC (eUICC), integrated UICC (iUICC) or a removable UICC commonly known as 'SIM card.' The memory **1710** may allow the UE **1700** to access instructions, application programs and the like, stored on transitory or non-transitory memory media, to off-load data, or to upload data. An article of manufacture, such as one utilizing a communication system may be tangibly embodied as or in the memory **1710**, which may be or comprise a device-readable storage medium.

[0135] The processing circuitry **1702** may be configured to communicate with an access network or other network using the communication interface **1712**. The communication interface **1712** may comprise one or more communication subsystems and may include or be communicatively coupled to an antenna **1722**. The communication interface **1712** may include one or more transceivers used to communicate, such as by communicating with one or more remote transceivers of another device capable of wireless communication (e.g., another UE or a network node in an access network). Each transceiver may include a transmitter **1718** and/or a receiver **1720** appropriate to provide network communications (e.g., optical, electrical, frequency allocations, and so forth). Moreover, the transmitter **1718** and receiver **1720** may be coupled to one or more antennas (e.g., antenna **1722**) and may share circuit components, software or firmware, or alternatively be implemented separately.

[0136] In the illustrated embodiment, communication functions of the communication interface **1712** may include cellular communication, Wi-Fi communication, LPWAN communication, data communication, voice communication, multimedia communication, short-range communications such as Bluetooth, near-field communication, location-based communication such as the use of the global positioning system (GPS) to determine a location, another like communication function, or any combination thereof. Communications may be implemented in according to one or more communication protocols and/or standards, such as IEEE 802.11, Code Division Multiplexing Access (CDMA), Wideband Code Division Multiple Access (WCDMA), GSM, LTE, New Radio (NR), UMTS, WiMax, Ethernet, transmission control protocol/internet protocol (TCP/IP), synchronous optical networking (SONET), Asynchronous Transfer Mode (ATM), QUIC, Hypertext Transfer Protocol (HTTP), and so forth.

[0137] Regardless of the type of sensor, a UE may provide an output of data captured by its sensors, through its communication interface **1712**, via a wireless connection to a network node. Data captured by sensors of a UE can be communicated through a wireless connection to a network node via another UE. The output may be periodic (e.g., once every 15 minutes if it reports the sensed temperature), random (e.g., to even out the load from reporting from several sensors), in response to a triggering event (e.g., when moisture is detected an alert is sent), in response to a request (e.g., a user initiated request), or a continuous stream (e.g., a live video feed of a patient).

[0138] As another example, a UE comprises an actuator, a motor, or a switch, related to a communication interface configured to receive wireless input from a network node via a wireless connection. In response to the received wireless input the states of the actuator, the motor, or the switch may change. For example, the UE may comprise a motor that adjusts the control surfaces or rotors of a drone in flight according to the received input or to a robotic arm performing a medical procedure according to the received input.

[0139] A UE, when in the form of an Internet of Things (IoT) device, may be a device for use in one or more application domains, these domains comprising, but not limited to, city wearable technology, extended industrial application and healthcare. Non-limiting examples of such an IoT device are a device which is or which is embedded in: a connected refrigerator or freezer, a TV, a connected lighting device, an electricity meter, a robot vacuum cleaner, a voice controlled smart speaker, a home security camera, a motion detector, a thermostat, a smoke detector, a door/window sensor, a flood/moisture sensor, an electrical door lock, a connected doorbell, an air conditioning system like a heat pump, an autonomous vehicle, a surveillance system, a weather monitoring device, a vehicle parking monitoring device, an electric vehicle charging station, a smart watch, a fitness tracker, a head-mounted display for Augmented Reality (AR) or Virtual Reality (VR), a wearable for tactile augmentation or sensory enhancement, a water sprinkler, an animal- or item-tracking device, a sensor for monitoring a plant or animal, an industrial robot, an Unmanned Aerial Vehicle (UAV), and any kind of medical device, like a heart rate monitor or a remote controlled surgical robot. A UE in the form of an IoT device comprises circuitry and/or software in dependence of the intended application of the IoT device in addition to other components as described in relation to the UE **1700** shown in FIG. **17**.

[0140] As yet another specific example, in an IoT scenario, a UE may represent a machine or other device that performs monitoring and/or measurements, and transmits the results of such monitoring and/or measurements to another UE and/or a network node. The UE may in this case be an M2M device, which may in a 3GPP context be referred to as an MTC device. As one particular example, the UE may implement the 3GPP NB-IoT standard. In other scenarios, a UE may represent a vehicle, such as a car, a bus, a truck, a ship and an airplane, or other equipment that is capable of monitoring and/or reporting on its operational status or other functions associated with its operation.

[0141] In practice, any number of UEs may be used together with respect to a single use case. For example, a first UE might be or be integrated in a drone and provide the drone's speed information (obtained through a speed sensor) to a second UE that is a remote controller operating the drone. When the user makes changes from the remote controller, the first UE may adjust the throttle on the drone (e.g. by controlling an actuator) to increase or decrease the drone's speed. The first and/or the second UE can also include more than one of the functionalities described above. For example, a UE might comprise the sensor and the actuator, and handle communication of data for both the speed sensor and the actuators.

[0142] FIG. **18** shows a network node **1800** in accordance with some embodiments. As used herein, network node refers to equipment capable, configured, arranged and/or operable to communicate directly or indirectly with a UE and/or with other network nodes or equipment, in a telecommunication network. Examples of network nodes include, but are not limited to, access points (APs) (e.g., radio access points), base stations (BSs) (e.g., radio base stations, Node Bs, evolved Node Bs (eNBs), NR NodeBs (gNBs)), O-RAN nodes, or components of an O-RAN node (e.g., intelligent controller, O-RU, O-DU, O-CU).

[0143] Base stations may be categorized based on the amount of coverage they provide (or, stated differently, their transmit power level) and so, depending on the provided amount of coverage, may be referred to as femto base stations, pico base stations, micro base stations, or macro base stations. A base station may be a relay node or a relay donor node controlling a relay. A network node may also include one or more (or all) parts of a distributed radio base station such as centralized digital units and/or remote radio units (RRUs), sometimes referred to as Remote Radio Heads (RRHs). Such remote radio units may or may not be integrated with an antenna as an antenna integrated radio. Parts of a distributed radio base station may also be referred to as nodes in a distributed antenna system (DAS).

[0144] Other examples of network nodes include multiple transmission point (multi-TRP) 5G access nodes, multi-standard radio (MSR) equipment such as MSR BSs, network controllers such as radio network controllers (RNCs) or base station controllers (BSCs), base transceiver stations (BTSs), transmission points, transmission nodes, multi-cell/multicast coordination entities (MCEs), Operation and Maintenance (O&M) nodes, Operations Support System (OSS) nodes, Self-Organizing Network (SON) nodes, positioning nodes (e.g., Evolved Serving Mobile Location Centers (E-SMLCs)), and/or Minimization of Drive Tests (MDTs).

[0145] The network node **1800** includes a processing circuitry **1802**, a memory **1804**, a communication interface **1806**, and a power source **1808**. The network node **1800** may be composed of multiple physically separate components (e.g., a NodeB component and a RNC component, or a BTS component and a BSC component, etc.), which may each have their own respective components. In certain scenarios in which the network node **1800** comprises multiple separate components (e.g., BTS and BSC components), one or more of the separate components may be shared among several network nodes. For example, a single RNC may control multiple NodeBs. In such a scenario, each unique NodeB and RNC pair, may in some instances be considered a single separate network node. In some embodiments, the network node **1800** may be configured to support multiple radio access technologies (RATs). In such embodiments, some components may be duplicated (e.g., separate memory **1804**

for different RATs) and some components may be reused (e.g., a same antenna **1810** may be shared by different RATs). The network node **1800** may also include multiple sets of the various illustrated components for different wireless technologies integrated into network node **1800**, for example GSM, WCDMA, LTE, NR, WiFi, Zigbee, Z-wave, LoRaWAN, Radio Frequency Identification (RFID) or Bluetooth wireless technologies. These wireless technologies may be integrated into the same or different chip or set of chips and other components within network node **1800**.

[0146] The processing circuitry **1802** may comprise a combination of one or more of a microprocessor, controller, microcontroller, central processing unit, digital signal processor, application-specific integrated circuit, field programmable gate array, or any other suitable computing device, resource, or combination of hardware, software and/or encoded logic operable to provide, either alone or in conjunction with other network node **1800** components, such as the memory **1804**, to provide network node **1800** functionality.

[0147] In some embodiments, the processing circuitry **1802** includes a system on a chip (SOC). In some embodiments, the processing circuitry **1802** includes one or more of radio frequency (RF) transceiver circuitry **1812** and baseband processing circuitry **1814**. In some embodiments, the radio frequency (RF) transceiver circuitry **1812** and the baseband processing circuitry **1814** may be on separate chips (or sets of chips), boards, or units, such as radio units and digital units. In alternative embodiments, part or all of RF transceiver circuitry **1812** and baseband processing circuitry **1814** may be on the same chip or set of chips, boards, or units.

[0148] The memory **1804** may comprise any form of volatile or non-volatile computer-readable memory including, without limitation, persistent storage, solid-state memory, remotely mounted memory, magnetic media, optical media, random access memory (RAM), read-only memory (ROM), mass storage media (for example, a hard disk), removable storage media (for example, a flash drive, a Compact Disk (CD) or a Digital Video Disk (DVD)), and/or any other volatile or non-volatile, non-transitory device-readable and/or computer-executable memory devices that store information, data, and/or instructions that may be used by the processing circuitry **1802**. The memory **1804** may store any suitable instructions, data, or information, including a computer program, software, an application including one or more of logic, rules, code, tables, and/or other instructions capable of being executed by the processing circuitry **1802** and utilized by the network node **1800**. The memory **1804** may be used to store any calculations made by the processing circuitry **1802** and/or any data received via the communication interface **1806**. In some embodiments, the processing circuitry **1802** and memory **1804** is integrated.

[0149] The communication interface **1806** is used in wired or wireless communication of signaling and/or data between a network node, access network, and/or UE. As illustrated, the communication interface **1806** comprises port(s)/terminal(s) **1816** to send and receive data, for example to and from a network over a wired connection. The communication interface **1806** also includes radio front-end circuitry **1818** that may be coupled to, or in certain embodiments a part of, the antenna **1810**. Radio front-end circuitry **1818** comprises filters **1820** and amplifiers **1822**. The radio front-end circuitry **1818** may be connected to an antenna **1810** and processing circuitry **1802**. The radio front-end circuitry may be configured to condition signals communicated between antenna **1810** and processing circuitry **1802**. The radio front-end circuitry **1818** may receive digital data that is to be sent out to other network nodes or UEs via a wireless connection. The radio front-end circuitry **1818** may convert the digital data into a radio signal having the appropriate channel and bandwidth parameters using a combination of filters **1820** and/or amplifiers **1822**. The radio signal may then be transmitted via the antenna **1810**. Similarly, when receiving data, the antenna **1810** may collect radio signals which are then converted into digital data by the radio front-end circuitry **1818**. The digital data may be passed to the processing circuitry **1802**. In other embodiments, the communication interface may comprise different components and/or different combinations of components.

[0150] In certain alternative embodiments, the network node **1800** does not include separate radio front-end circuitry **1818**, instead, the processing circuitry **1802** includes radio front-end circuitry and is connected to the antenna **1810**. Similarly, in some embodiments, all or some of the RF transceiver circuitry **1812** is part of the communication interface **1806**. In still other embodiments, the communication interface **1806** includes one or more ports or terminals **1816**, the radio front-end circuitry **1818**, and the RF transceiver circuitry **1812**, as part of a radio unit (not shown), and the communication interface **1806** communicates with the baseband processing circuitry **1814**, which is part of a digital unit (not shown).

[0151] The antenna **1810** may include one or more antennas, or antenna arrays, configured to send and/or receive wireless signals. The antenna **1810** may be coupled to the radio front-end circuitry **1818** and may be any type of antenna capable of transmitting and receiving data and/or signals wirelessly. In certain embodiments, the antenna **1810** is separate from the network node **1800** and connectable to the network node **1800** through an interface or port.

[0152] The antenna **1810**, communication interface **1806**, and/or the processing circuitry **1802** may be configured to perform any receiving operations and/or certain obtaining operations described herein as being performed by the network node. Any information, data and/or signals may be received from a UE, another network node and/or any other network equipment. Similarly, the antenna **1810**, the communication interface **1806**, and/or the processing circuitry **1802** may be configured to perform any transmitting operations described herein as being performed by the network node. Any information, data and/or signals may be transmitted to a UE, another network node and/or any other network equipment.

[0153] The power source **1808** provides power to the various components of network node **1800** in a form suitable for the respective components (e.g., at a voltage and current level needed for each respective component). The power source **1808** may further comprise, or be coupled to, power management circuitry to supply the components of the network node **1800** with power for performing the functionality described herein. For example, the network node **1800** may be connectable to an external power source (e.g., the power grid, an electricity outlet) via an input circuitry or interface such as an electrical cable, whereby the external power source supplies power to power circuitry of the power source **1808**. As a further example, the power source **1808**

may comprise a source of power in the form of a battery or battery pack which is connected to, or integrated in, power circuitry. The battery may provide backup power should the external power source fail.

[0154] Embodiments of the network node **1800** may include additional components beyond those shown in FIG. **18** for providing certain aspects of the network node's functionality, including any of the functionality described herein and/or any functionality necessary to support the subject matter described herein. For example, the network node **1800** may include user interface equipment to allow input of information into the network node **1800** and to allow output of information from the network node **1800**. This may allow a user to perform diagnostic, maintenance, repair, and other administrative functions for the network node **1800**.

[0155] FIG. **19** is a block diagram of a host **1900**, which may be an embodiment of the host **1616** of FIG. **16**, in accordance with various aspects described herein. As used herein, the host **1900** may be or comprise various combinations hardware and/or software, including a standalone server, a blade server, a cloud-implemented server, a distributed server, a virtual machine, container, or processing resources in a server farm. The host **1900** may provide one or more services to one or more UEs.

[0156] The host **1900** includes processing circuitry **1902** that is operatively coupled via a bus **1904** to an input/output interface **1906**, a network interface **1908**, a power source **1910**, and a memory **1912**. Other components may be included in other embodiments. Features of these components may be substantially similar to those described with respect to the devices of previous figures, such as FIGS. **17** and **18**, such that the descriptions thereof are generally applicable to the corresponding components of host **1900**.

[0157] The memory **1912** may include one or more computer programs including one or more host application programs **1914** and data **1916**, which may include user data, e.g., data generated by a UE for the host **1900** or data generated by the host **1900** for a UE. Embodiments of the host **1900** may utilize only a subset or all of the components shown. The host application programs **1914** may be implemented in a container-based architecture and may provide support for video codecs (e.g., Versatile Video Coding (VVC), High Efficiency Video Coding (HEVC), Advanced Video Coding (AVC), MPEG, VP9) and audio codecs (e.g., FLAC, Advanced Audio Coding (AAC), MPEG, G.711), including transcoding for multiple different classes, types, or implementations of UEs (e.g., handsets, desktop computers, wearable display systems, heads-up display systems). The host application programs **1914** may also provide for user authentication and licensing checks and may periodically report health, routes, and content availability to a central node, such as a device in or on the edge of a core network. Accordingly, the host **1900** may select and/or indicate a different host for over-the-top services for a UE. The host application programs **1914** may support various protocols, such as the HTTP Live Streaming (HLS) protocol, Real-Time Messaging Protocol (RTMP), Real-Time Streaming Protocol (RTSP), Dynamic Adaptive Streaming over HTTP (MPEG-DASH), etc.

[0158] FIG. **20** is a block diagram illustrating a virtualization environment **2000** in which functions implemented by some embodiments may be virtualized. In the present context, virtualizing means creating virtual versions of apparatuses or devices which may include virtualizing hardware platforms, storage devices and networking resources. As used herein, virtualization can be applied to any device described herein, or components thereof, and relates to an implementation in which at least a portion of the functionality is implemented as one or more virtual components. Some or all of the functions described herein may be implemented as virtual components executed by one or more virtual machines (VMs) implemented in one or more virtual environments **2000** hosted by one or more of hardware nodes, such as a hardware computing device that operates as a network node, UE, core network node, or host. Further, in embodiments in which the virtual node does not require radio connectivity (e.g., a core network node or host), then the node may be entirely virtualized. In some embodiments, the virtualization environment **2000** includes components defined by the O-RAN Alliance, such as an O-Cloud environment orchestrated by a Service Management and Orchestration Framework via an O-2 interface.

[0159] Applications **2002** (which may alternatively be called software instances, virtual appliances, network functions, virtual nodes, virtual network functions, etc.) are run in the virtualization environment Q400 to implement some of the features, functions, and/or benefits of some of the embodiments disclosed herein.

[0160] Hardware **2004** includes processing circuitry, memory that stores software and/or instructions executable by hardware processing circuitry, and/or other hardware devices as described herein, such as a network interface, input/output interface, and so forth. Software may be executed by the processing circuitry to instantiate one or more virtualization layers **2006** (also referred to as hypervisors or virtual machine monitors (VMMs)), provide VMs **2008***a* and **2008***b* (one or more of which may be generally referred to as VMs **2008**), and/or perform any of the functions, features and/or benefits described in relation with some embodiments described herein. The virtualization layer **2006** may present a virtual operating platform that appears like networking hardware to the VMs **2008**.

[0161] The VMs **2008** comprise virtual processing, virtual memory, virtual networking or interface and virtual storage, and may be run by a corresponding virtualization layer **2006**. Different embodiments of the instance of a virtual appliance **2002** may be implemented on one or more of VMs **2008**, and the implementations may be made in different ways. Virtualization of the hardware is in some contexts referred to as network function virtualization (NFV). NFV may be used to consolidate many network equipment types onto industry standard high volume server hardware, physical switches, and physical storage, which can be located in data centers, and customer premise equipment.

[0162] In the context of NFV, a VM **2008** may be a software implementation of a physical machine that runs programs as if they were executing on a physical, non-virtualized machine. Each of the VMs **2008**, and that part of hardware **2004** that executes that VM, be it hardware dedicated to that VM and/or hardware shared by that VM with others of the VMs, forms separate virtual network elements. Still in the context of NFV, a virtual network function is responsible for handling specific network functions that run in one or more VMs **2008** on top of the hardware **2004** and corresponds to the application **2002**.

[0163] Hardware **2004** may be implemented in a standalone network node with generic or specific components.

Hardware **2004** may implement some functions via virtualization. Alternatively, hardware **2004** may be part of a larger cluster of hardware (e.g. such as in a data center or CPE) where many hardware nodes work together and are managed via management and orchestration **2010**, which, among others, oversees lifecycle management of applications **2002**. In some embodiments, hardware **2004** is coupled to one or more radio units that each include one or more transmitters and one or more receivers that may be coupled to one or more antennas. Radio units may communicate directly with other hardware nodes via one or more appropriate network interfaces and may be used in combination with the virtual components to provide a virtual node with radio capabilities, such as a radio access node or a base station. In some embodiments, some signaling can be provided with the use of a control system **2012** which may alternatively be used for communication between hardware nodes and radio units.

[0164] FIG. **21** shows a communication diagram of a host **2102** communicating via a network node **2104** with a UE **2106** over a partially wireless connection in accordance with some embodiments. Example implementations, in accordance with various embodiments, of the UE (such as a UE **1612***a* of FIG. **16** and/or UE **1700** of FIG. **17**), network node (such as network node **1610***a* of FIG. **16** and/or network node **1800** of FIG. **18**), and host (such as host **1616** of FIG. **16** and/or host **1900** of FIG. **19**) discussed in the preceding paragraphs will now be described with reference to FIG. **21**.

[0165] Like host **1900**, embodiments of host **2102** include hardware, such as a communication interface, processing circuitry, and memory. The host **2102** also includes software, which is stored in or accessible by the host **2102** and executable by the processing circuitry. The software includes a host application that may be operable to provide a service to a remote user, such as the UE **2106** connecting via an over-the-top (OTT) connection **2150** extending between the UE **2106** and host **2102**. In providing the service to the remote user, a host application may provide user data which is transmitted using the OTT connection **2150**.

[0166] The network node **2104** includes hardware enabling it to communicate with the host **2102** and UE **2106**. The connection **2160** may be direct or pass through a core network (like core network **1606** of FIG. **16**) and/or one or more other intermediate networks, such as one or more public, private, or hosted networks. For example, an intermediate network may be a backbone network or the Internet.

[0167] The UE **2106** includes hardware and software, which is stored in or accessible by UE **2106** and executable by the UE's processing circuitry. The software includes a client application, such as a web browser or operator-specific "app" that may be operable to provide a service to a human or non-human user via UE **2106** with the support of the host **2102**. In the host **2102**, an executing host application may communicate with the executing client application via the OTT connection **2150** terminating at the UE **2106** and host **2102**. In providing the service to the user, the UE's client application may receive request data from the host's host application and provide user data in response to the request data. The OTT connection **2150** may transfer both the request data and the user data. The UE's client application may interact with the user to generate the user data that it provides to the host application through the OTT connection **2150**.

[0168] The OTT connection **2150** may extend via a connection **2160** between the host **2102** and the network node **2104** and via a wireless connection **2170** between the network node **2104** and the UE **2106** to provide the connection between the host **2102** and the UE **2106**. The connection **2160** and wireless connection **2170**, over which the OTT connection **2150** may be provided, have been drawn abstractly to illustrate the communication between the host **2102** and the UE **2106** via the network node **2104**, without explicit reference to any intermediary devices and the precise routing of messages via these devices.

[0169] As an example of transmitting data via the OTT connection **2150**, in step **2108**, the host **2102** provides user data, which may be performed by executing a host application. In some embodiments, the user data is associated with a particular human user interacting with the UE **2106**. In other embodiments, the user data is associated with a UE **2106** that shares data with the host **2102** without explicit human interaction. In step **2110**, the host **2102** initiates a transmission carrying the user data towards the UE **2106**. The host **2102** may initiate the transmission responsive to a request transmitted by the UE **2106**. The request may be caused by human interaction with the UE **2106** or by operation of the client application executing on the UE **2106**. The transmission may pass via the network node **2104**, in accordance with the teachings of the embodiments described throughout this disclosure. Accordingly, in step **2112**, the network node **2104** transmits to the UE **2106** the user data that was carried in the transmission that the host **2102** initiated, in accordance with the teachings of the embodiments described throughout this disclosure. In step **2114**, the UE **2106** receives the user data carried in the transmission, which may be performed by a client application executed on the UE **2106** associated with the host application executed by the host **2102**.

[0170] In some examples, the UE **2106** executes a client application which provides user data to the host **2102**. The user data may be provided in reaction or response to the data received from the host **2102**. Accordingly, in step **2116**, the UE **2106** may provide user data, which may be performed by executing the client application. In providing the user data, the client application may further consider user input received from the user via an input/output interface of the UE **2106**. Regardless of the specific manner in which the user data was provided, the UE **2106** initiates, in step **2118**, transmission of the user data towards the host **2102** via the network node **2104**. In step **2120**, in accordance with the teachings of the embodiments described throughout this disclosure, the network node **2104** receives user data from the UE **2106** and initiates transmission of the received user data towards the host **2102**. In step **2122**, the host **2102** receives the user data carried in the transmission initiated by the UE **2106**.

[0171] One or more of the various embodiments improve the performance of OTT services provided to the UE **2106** using the OTT connection **2150**, in which the wireless connection **2170** forms the last segment. More precisely, the teachings of these embodiments may allow for differential delay impairment to be actively monitored without impacting traffic without adding any additional instrument for delay measurement.

[0172] In an example scenario, factory status information may be collected and analyzed by the host **2102**. As another example, the host **2102** may process audio and video data which may have been retrieved from a UE for use in creating maps. As another example, the host **2102** may collect and analyze real-time data to assist in controlling vehicle congestion (e.g., controlling traffic lights). As another example, the host **2102** may store surveillance video uploaded by a UE. As another example, the host **2102** may store or control access to media content such as video, audio, VR or AR which it can broadcast, multicast or unicast to UEs. As other examples, the host **2102** may be used for energy pricing, remote control of non-time critical electrical load to balance power generation needs, location services, presentation services (such as compiling diagrams etc. from data collected from remote devices), or any other function of collecting, retrieving, storing, analyzing and/or transmitting data.

[0173] In some examples, a measurement procedure may be provided for the purpose of monitoring data rate, latency and other factors on which the one or more embodiments improve. There may further be an optional network functionality for reconfiguring the OTT connection **2150** between the host **2102** and UE **2106**, in response to variations in the measurement results. The measurement procedure and/or the network functionality for reconfiguring the OTT connection may be implemented in software and hardware of the host **2102** and/or UE **2106**. In some embodiments, sensors (not shown) may be deployed in or in association with other devices through which the OTT connection **2150** passes; the sensors may participate in the measurement procedure by supplying values of the monitored quantities exemplified above, or supplying values of other physical quantities from which software may compute or estimate the monitored quantities. The reconfiguring of the OTT connection **2150** may include message format, retransmission settings, preferred routing etc.; the reconfiguring need not directly alter the operation of the network node **2104**. Such procedures and functionalities may be known and practiced in the art. In certain embodiments, measurements may involve proprietary UE signaling that facilitates measurements of throughput, propagation times, latency and the like, by the host **2102**. The measurements may be implemented in that software causes messages to be transmitted, in particular empty or 'dummy' messages, using the OTT connection **2150** while monitoring propagation times, errors, etc.

[0174] Although the computing devices described herein (e.g., UEs, network nodes, hosts) may include the illustrated combination of hardware components, other embodiments may comprise computing devices with different combinations of components. It is to be understood that these computing devices may comprise any suitable combination of hardware and/or software needed to perform the tasks, features, functions and methods disclosed herein. Determining, calculating, obtaining or similar operations described herein may be performed by processing circuitry, which may process information by, for example, converting the obtained information into other information, comparing the obtained information or converted information to information stored in the network node, and/or performing one or more operations based on the obtained information or converted information, and as a result of said processing making a determination. Moreover, while components are depicted as single boxes located within a larger box, or nested within multiple boxes, in practice, computing devices may comprise multiple different physical components that make up a single illustrated component, and functionality may be partitioned between separate components. For example, a communication interface may be configured to include any of the components described herein, and/or the functionality of the components may be partitioned between the processing circuitry and the communication interface. In another example, non-computationally intensive functions of any of such components may be implemented in software or firmware and computationally intensive functions may be implemented in hardware.

[0175] In certain embodiments, some or all of the functionality described herein may be provided by processing circuitry executing instructions stored on in memory, which in certain embodiments may be a computer program product in the form of a non-transitory computer-readable storage medium. In alternative embodiments, some or all of the functionality may be provided by the processing circuitry without executing instructions stored on a separate or discrete device-readable storage medium, such as in a hardwired manner. In any of those particular embodiments, whether executing instructions stored on a non-transitory computer-readable storage medium or not, the processing circuitry can be configured to perform the described functionality. The benefits provided by such functionality are not limited to the processing circuitry alone or to other components of the computing device, but are enjoyed by the computing device as a whole, and/or by end users and a wireless network generally.

The invention claimed is:

1. A method of operating a first transceiver communicatively coupled to a second transceiver by a first cable and a second cable, the method comprising:

transmitting a first message to the second transceiver at a first time, T_1, via the first cable;

receiving a second message from the second transceiver via the second cable, the second message including an indication of a second time, T_2,

receiving an optical pulse associated with the second message transmitted by the second transceiver; wherein the second message includes an indication of a third time, T_3, at which the optical pulse was transmitted;

wherein the receiving the optical pulse associated with the second message from the second transceiver is via the first cable and at a fourth time, T_4; and

determining a first delay associated with the first cable based on the determined values of T_1, the T_2, the T_3, and the T_4.

2. The method of claim **1**, wherein determining the first delay associated with the first cable comprises determining the first delay, D_1, based on

$$D_1 = [(T_4 - T_1) - (T_3 - T_2)]/2.$$

3. The method of claim **1**, wherein the T_2 is a time associated with when the first message was detected by the second transceiver.

4. The method of claim **1**, wherein the pulse is a second pulse,

wherein transmitting the first message comprises transmitting the first message and an associated first optical pulse to the second transceiver at the T_1 via the first cable, and wherein the T_2 is a time associated with when the first optical pulse was detected by the second transceiver.

5. The method of claim **4**, wherein transmitting the first message and the associated first optical pulse comprises:

generating an amplitude modulated signal including data associated with the first message using an amplitude modulator;

generating a transmit signal by superimposing the first optical pulse on the amplitude modulated signal using a phase optical modulator independent of the amplitude modulator; and

transmitting the transmit signal.

6. The method of claim **4**, wherein transmitting the first message and the associated first optical pulse comprises:

applying the first optical pulse and a bias current that is above a laser threshold to a laser driver;

generating an optical signal by a laser using the laser driver;

generating a transmit signal by amplitude modulating the optical signal based on data associated with the first message; and

transmitting the transmit signal.

7. The method of claim **1**, further comprising:

transmitting a third message to the second transceiver at a fifth time, T_5, via the second cable;

receiving a fourth message from the second transceiver via the first cable, the fourth message including an indication of a sixth time, T_6, and an indication of a seventh time, T_7, associated with when a fourth optical pulse that is associated with the fourth message was transmitted by the second transceiver;

receiving the fourth optical pulse associated with the fourth message from the second transceiver at an eighth time, T_8, via the second cable;

determining a second delay associated with the second cable based on the T_5, the T_6, the T_7, and the T_8; and

determining a difference between the first delay and the second delay.

8. The method of claim **7**, wherein determining the second delay associated with the second cable comprises determining the second delay, D_2, based on

$$D_2 = [(T_8 - T_5) - (T_7 - T_6)]/2.$$

9. The method of claim **7**, wherein the T_6 is a time associated with when the third message was detected by the second transceiver.

10. The method of claim **7**, wherein the optical pulse is a second pulse,

wherein transmitting the third message comprises transmitting the third message and an associated third optical pulse to the second transceiver at the T_5 via the second cable, and

wherein the T_6 is a time associated with when the third optical pulse was detected by the second transceiver.

11. The method of claim **7**, further comprising:

communicating with the second transceiver based on the difference between the first delay and the second delay.

12. The method of claim **7**, wherein determining the difference between the first delay and the second delay comprises determining an asymmetry between at least one of:

a first length of the first cable and a second length of the second cable;

a first digital signal processing, DSP, time of the first transceiver and a second DSP time of the second transceiver; and

a first application-specific integrated circuitry, ASIC, processing time on the first transceiver and a second ASIC processing time of the second transceiver.

13. The method of claim **1**, further comprising:

receiving a fifth message and an associated fifth pulse from the second transceiver via the first cable, the fifth message including an indication of a ninth time, T_9, associated with when the fifth message was transmitted by the second transceiver;

determining a tenth time, T_{10}, at which the fifth optical pulse was detected;

transmitting a sixth message to the second transceiver via the second cable at a eleventh time, T_{11}, the sixth message including an indication of the T_{10} and the T_{11};

transmitting a sixth optical pulse to the second transceiver via the first cable at the T_{11};

receiving a seventh message and an associated seventh pulse from the second transceiver via the second cable, the seventh message including an indication of a twelfth time, T_{12}, associated with when the seventh message was transmitted by the second transceiver;

determining a thirteenth time, T_{13}, at which the seventh optical pulse was detected;

transmitting an eighth message to the second transceiver via the first cable at a fourteenth time, T_{14}, the eighth message including an indication of the T_{13} and the T_{14}; and

transmitting an eighth pulse to the second transceiver via the second cable at the T_{14}.

14. The method of claim **1**, further comprising:

receiving a fifth message from the second transceiver via the first cable, the fifth message including an indication of a ninth time, T_9, associated with when the fifth message was transmitted by the second transceiver;

determining a tenth time, T_{10}, at which the fifth message was detected;

transmitting a sixth message to the second transceiver via the second cable at a eleventh time, T_{11}, the sixth message including an indication of the T_{10} and the T_{11};

transmitting a sixth optical pulse to the second transceiver via the first cable at the T_{11};

receiving a seventh message from the second transceiver via the second cable, the seventh message including an indication of a twelfth time, T_{12}, associated with when the seventh message was transmitted by the second transceiver;

determining a thirteenth time, T_{13}, at which the seventh message was detected;

transmitting an eighth message to the second transceiver via the first cable at a fourteenth time, T_{14}, the eighth message including an indication of the T_{13} and the T_{14}; and

transmitting an eighth pulse to the second transceiver via the second cable at the T_{14}.

15. The method of claim **14**, wherein receiving the fifth message and the associated fifth optical pulse comprises receiving the fifth message and the associated fifth pulse at a first port of a circulator, and wherein transmitting the sixth message and the sixth optical pulse comprises passing a transmit signal including the sixth message and the associated sixth optical pulse through a splitter, the splitter passing the sixth message to the second transceiver and passing the sixth optical pulse to a third port of the circulator.

16. The method of claim **1**, wherein the first message and the second message are each precise time protocol, PTP, messages, and

wherein the first message includes a first timestamp indicating the T_1.

17. The method of claim **1**, wherein the first cable is a first optical fiber having a first length, and

wherein the second cable is a second optical fiber having a second length.

18. The method of claim **17**, wherein the first length is different than the second length.

19-37. (canceled)

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