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(54) **METHOD AND APPARATUS FOR CROSS-LAYER, IN-BAND MONITORING OF TUNNELS BY INSERTION OF TELEMETRY DATA INTO A PACKET**

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H04L 12/46 (2006.01)

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See application file for complete search history.

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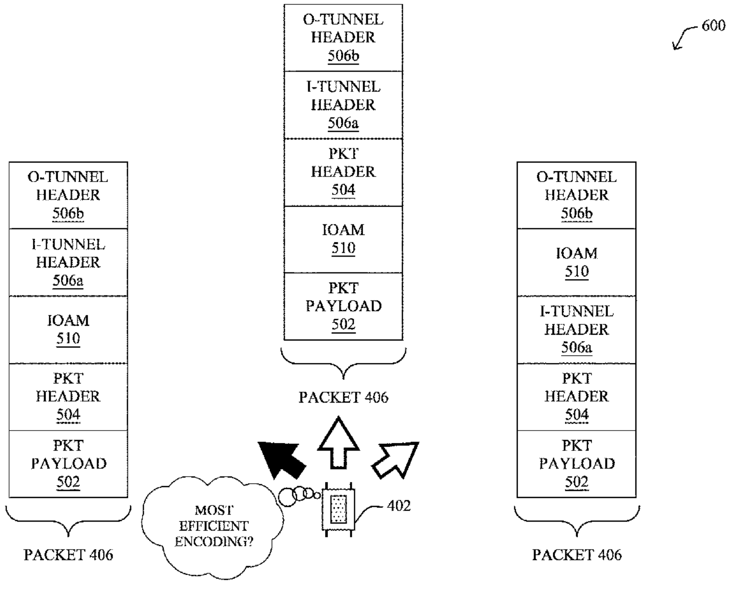
(57) **ABSTRACT**

In one embodiment, a network device along a path in a network receives a schedule that controls when the networking device is to insert telemetry data into data traffic passing through the networking device. The networking device generates the telemetry data for insertion into the data traffic passing through the networking device. The networking device inserts, according to the schedule, the telemetry data into a particular packet of the data traffic passing through the networking device. The networking device sends the particular packet to a next hop along the path in the network.

16 Claims, 9 Drawing Sheets



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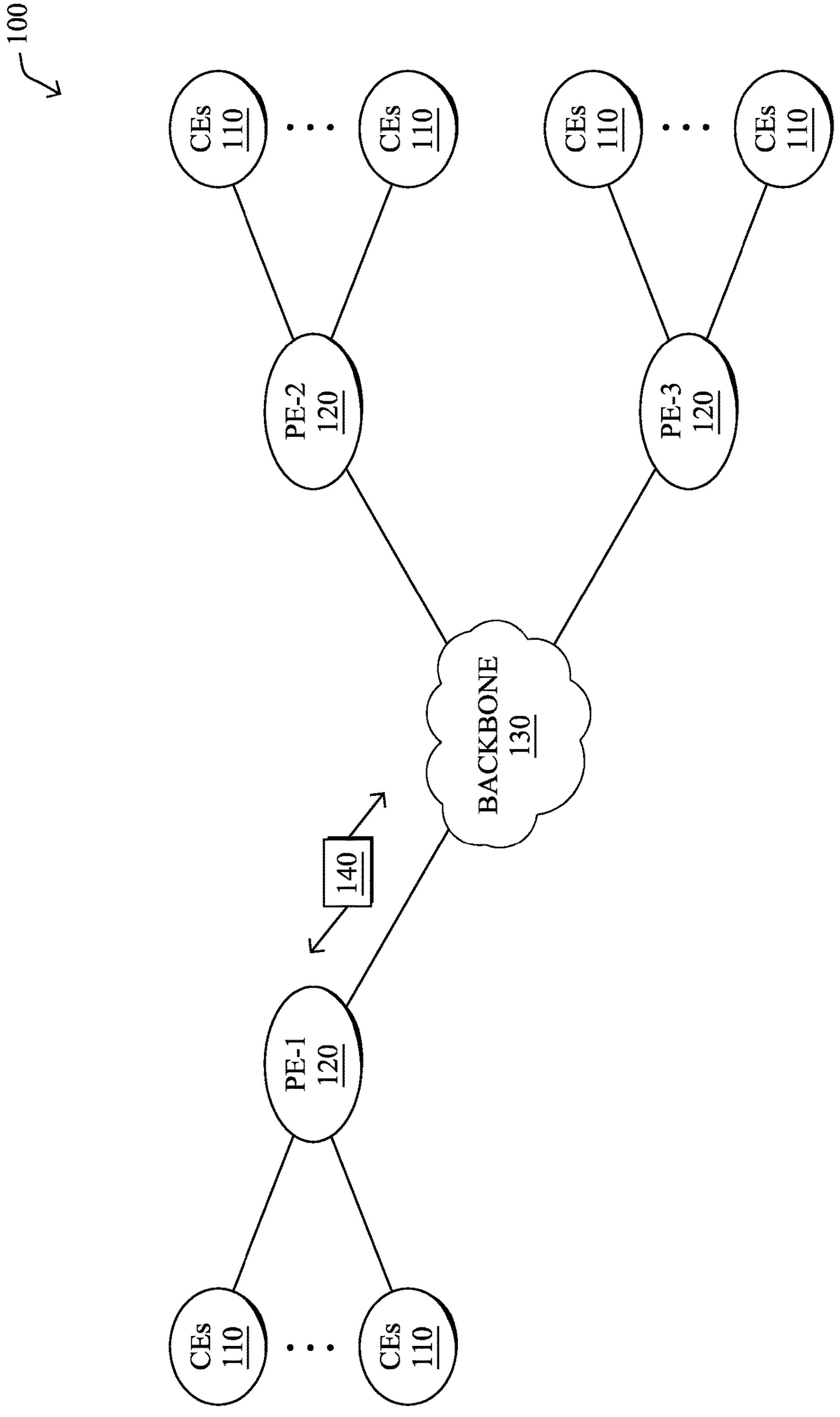
100
CEs 110
CEs 110
CEs 110
CEs 110
PE-2 120
PE-3 120
BACKBONE 130
140
PE-1 120
CEs 110
CEs 110

FIG. 1A

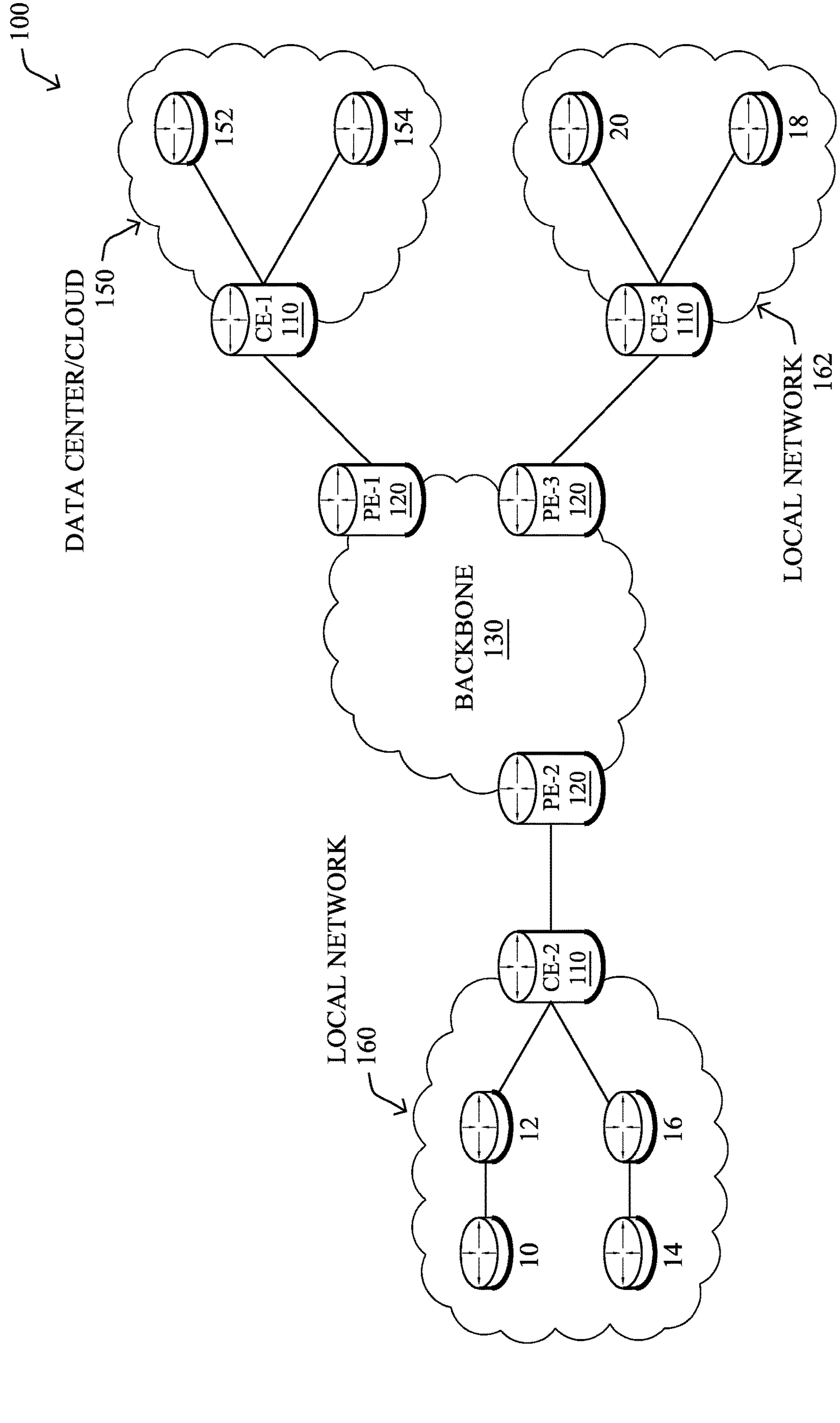
100
DATA CENTER/CLOUD
150
152
154
CE-1
110
PE-1
120
PE-3
120
BACKBONE
130
PE-2
120
CE-2
110
CE-3
110
20
18
LOCAL NETWORK
162
LOCAL NETWORK
160
12
16
10
14

FIG. 1B

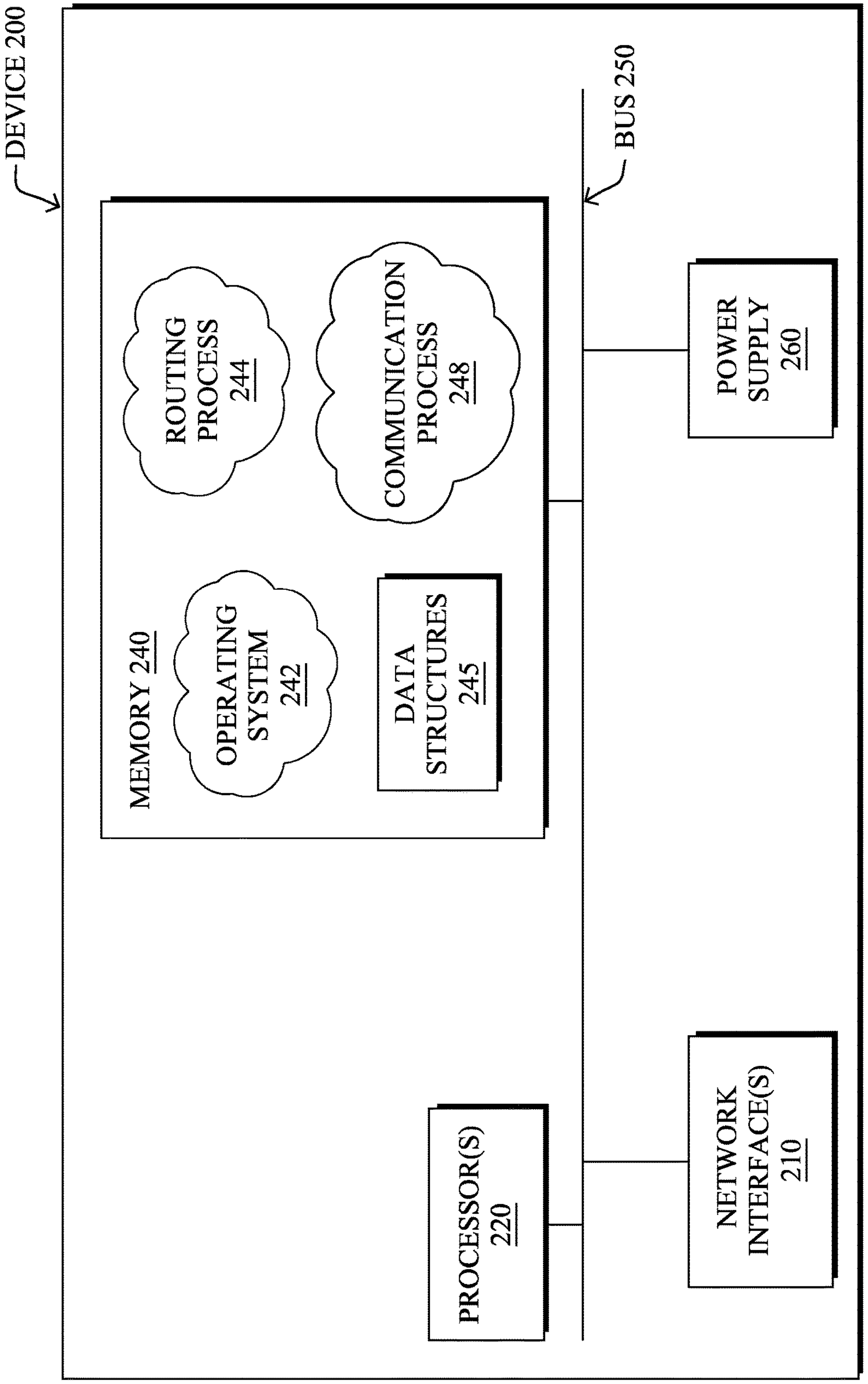
DEVICE 200
BUS 250
MEMORY 240
OPERATING SYSTEM 242
DATA STRUCTURES 245
ROUTING PROCESS 244
COMMUNICATION PROCESS 248
POWER SUPPLY 260
PROCESSOR(S) 220
NETWORK INTERFACE(S) 210

FIG. 2

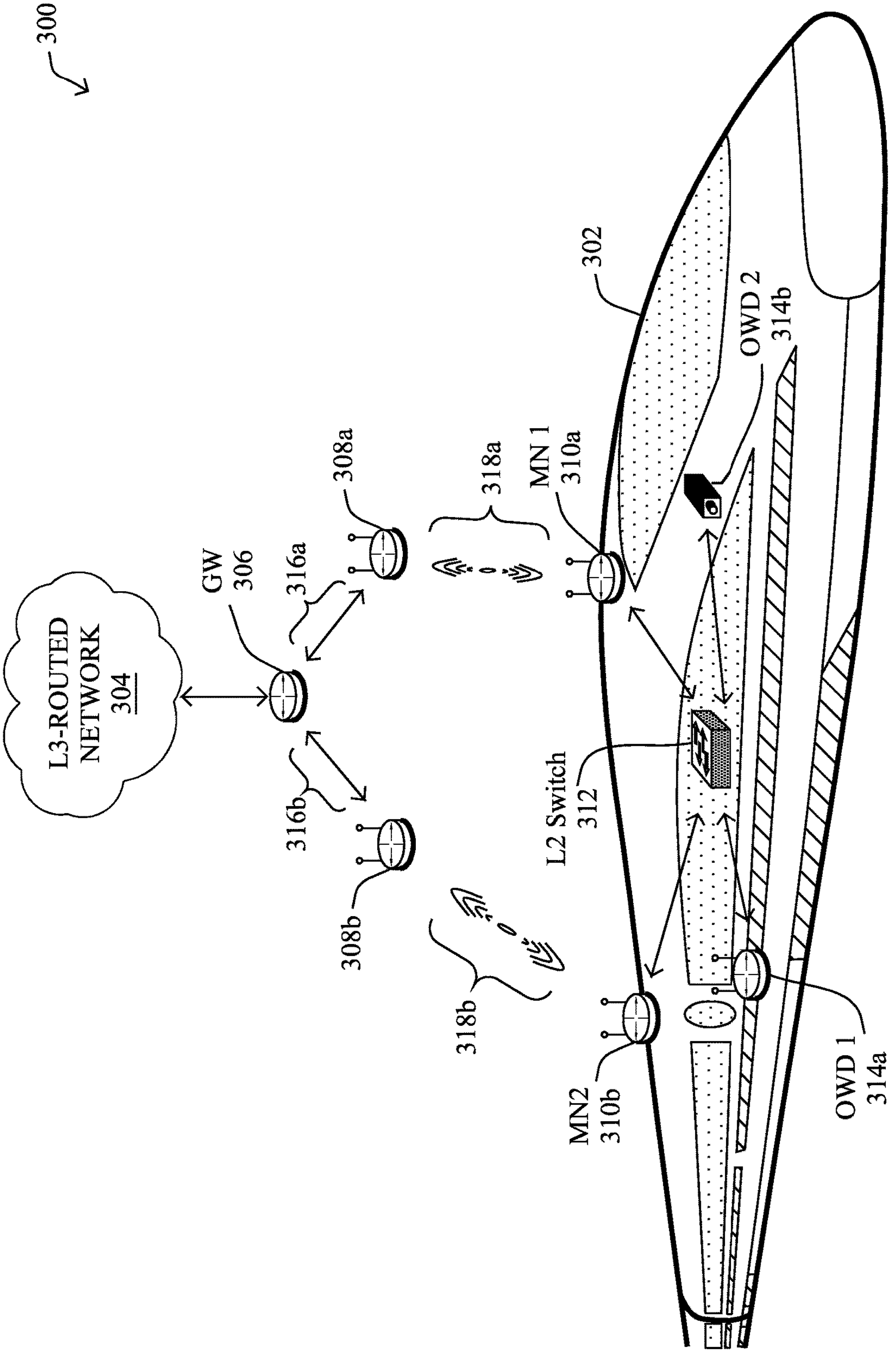
300
L3-ROUTED NETWORK 304
GW 306
316a
308a
316b
308b
318a
318b
MN 1 310a
MN2 310b
302
OWD 2 314b
L2 Switch 312
OWD 1 314a

FIG. 3

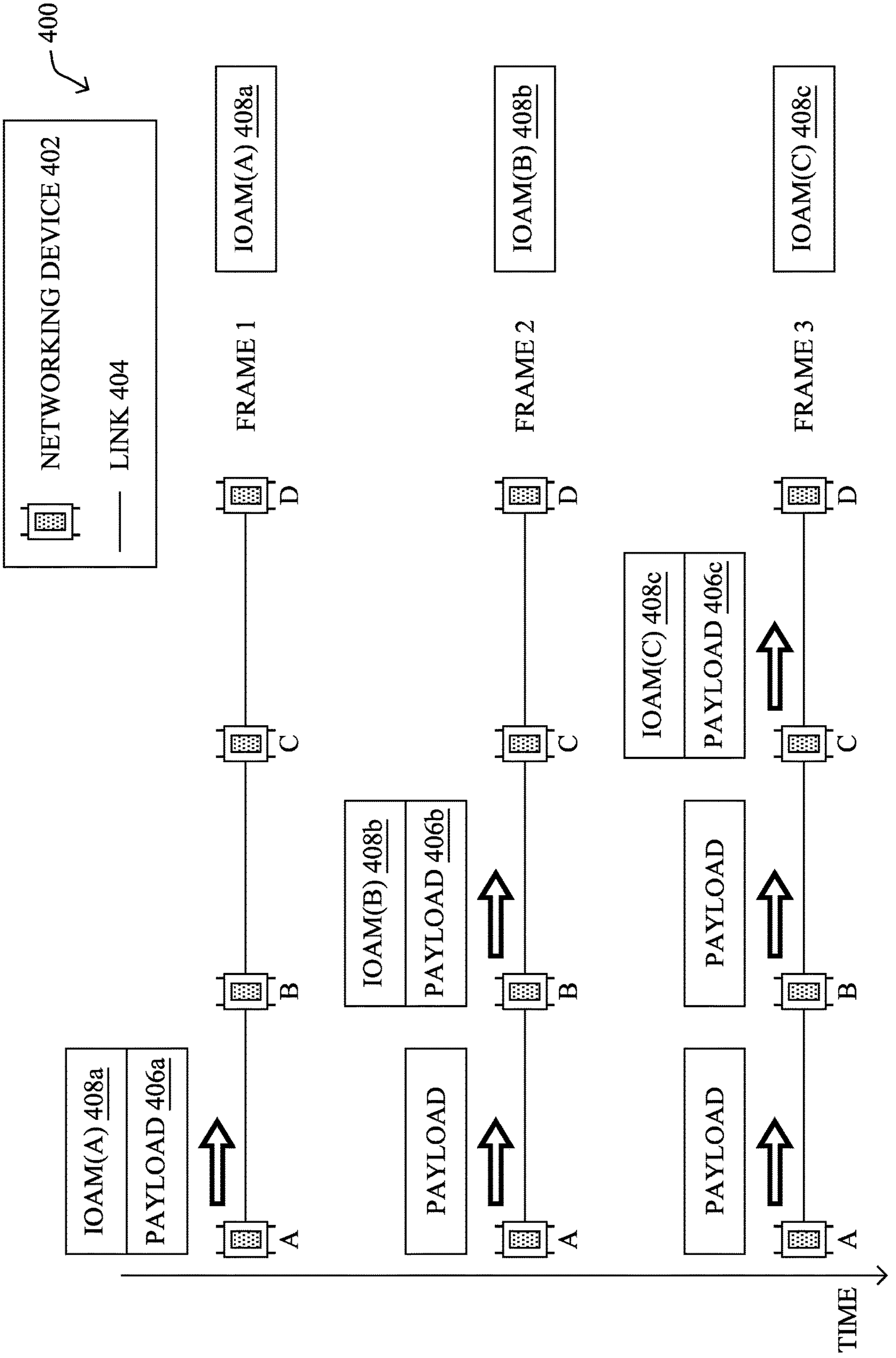
400
NETWORKING DEVICE 402
LINK 404
IOAM(A) 408a
PAYLOAD 406a
A
B
C
D
FRAME 1
IOAM(A) 408a
PAYLOAD
IOAM(B) 408b
PAYLOAD 406b
A
B
C
D
FRAME 2
IOAM(B) 408b
PAYLOAD
PAYLOAD
IOAM(C) 408c
PAYLOAD 406c
A
B
C
D
FRAME 3
IOAM(C) 408c
TIME

FIG. 4

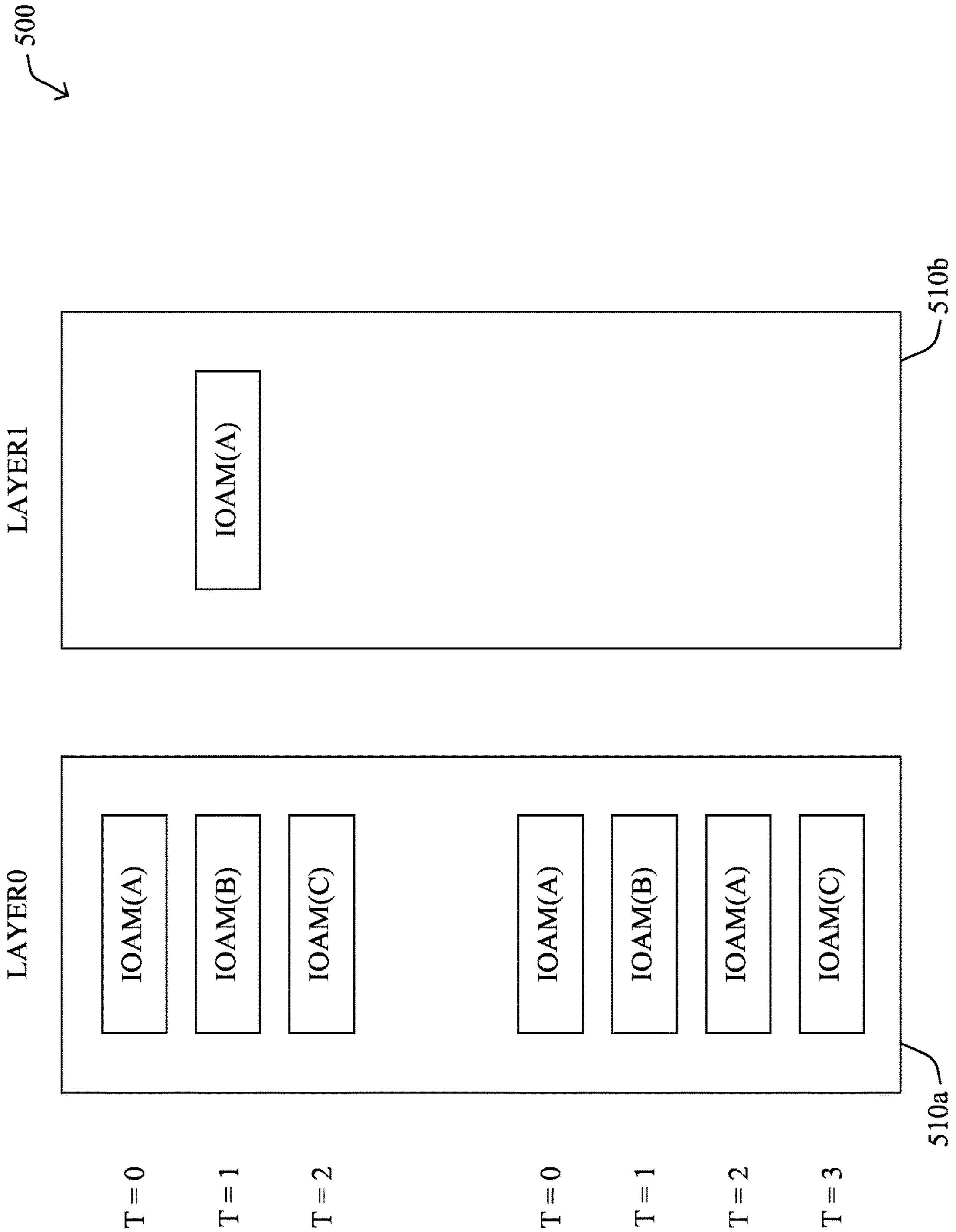
500
LAYER0
LAYER1
510a
510b
T = 0
T = 1
T = 2
T = 0
T = 1
T = 2
T = 3
IOAM(A)
IOAM(B)
IOAM(C)
IOAM(A)
IOAM(B)
IOAM(A)
IOAM(C)
IOAM(A)

FIG. 5A

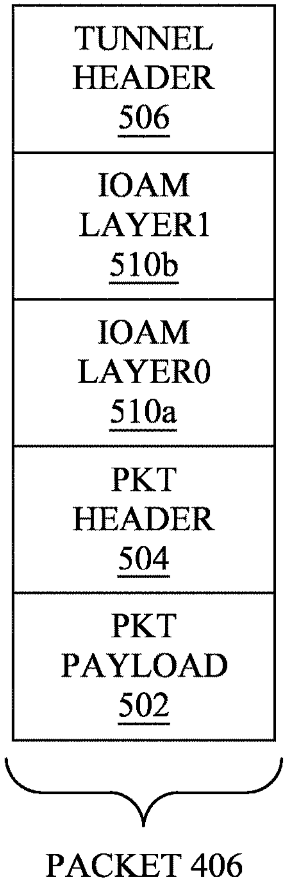
TUNNEL HEADER 506
IOAM LAYER1 510b
IOAM LAYER0 510a
PKT HEADER 504
PKT PAYLOAD 502
PACKET 406

FIG. 5B

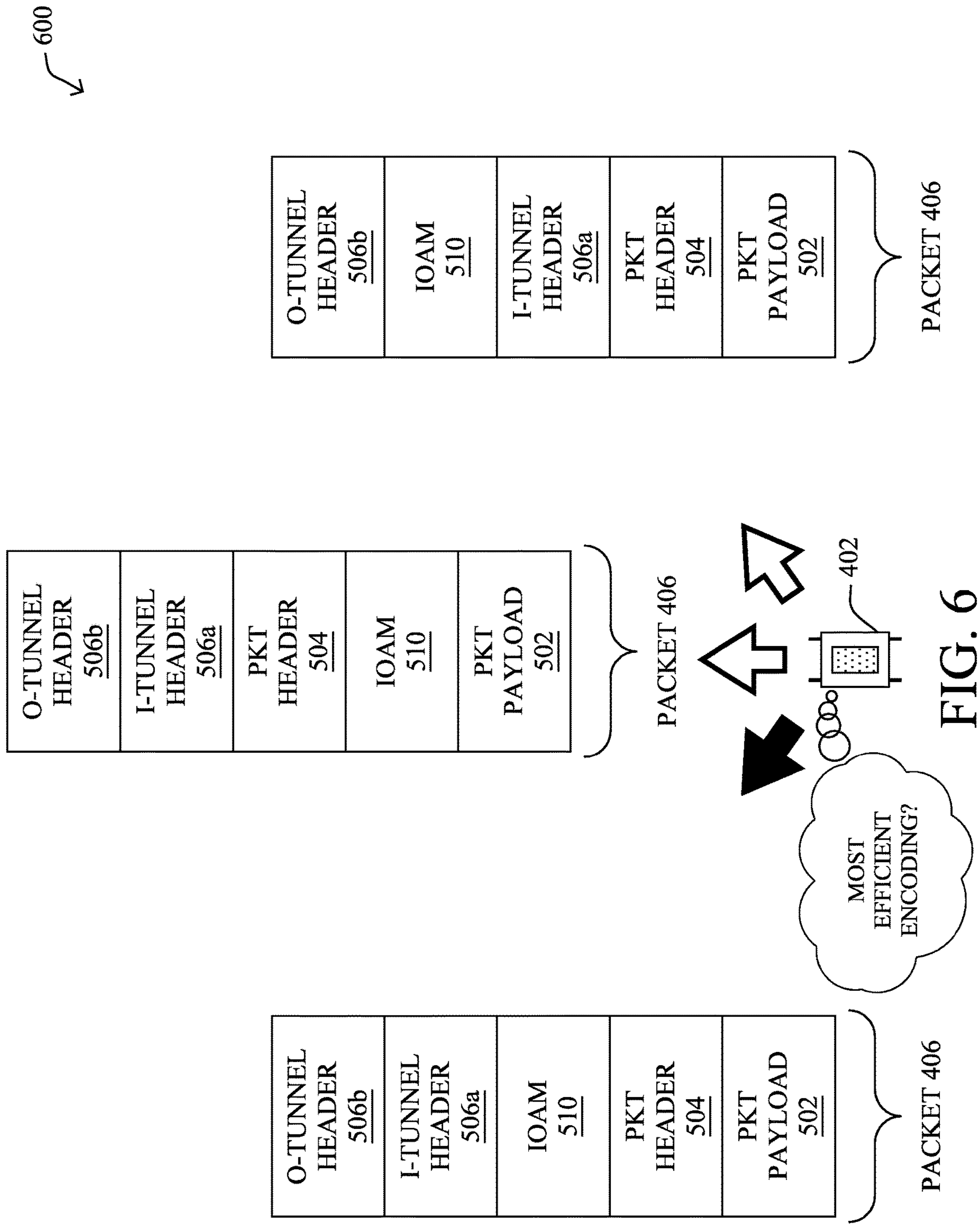
600
O-TUNNEL HEADER 506b
IOAM 510
I-TUNNEL HEADER 506a
PKT HEADER 504
PKT PAYLOAD 502
PACKET 406
O-TUNNEL HEADER 506b
I-TUNNEL HEADER 506a
PKT HEADER 504
IOAM 510
PKT PAYLOAD 502
PACKET 406
402
MOST EFFICIENT ENCODING?
O-TUNNEL HEADER 506b
I-TUNNEL HEADER 506a
IOAM 510
PKT HEADER 504
PKT PAYLOAD 502
PACKET 406

FIG. 6

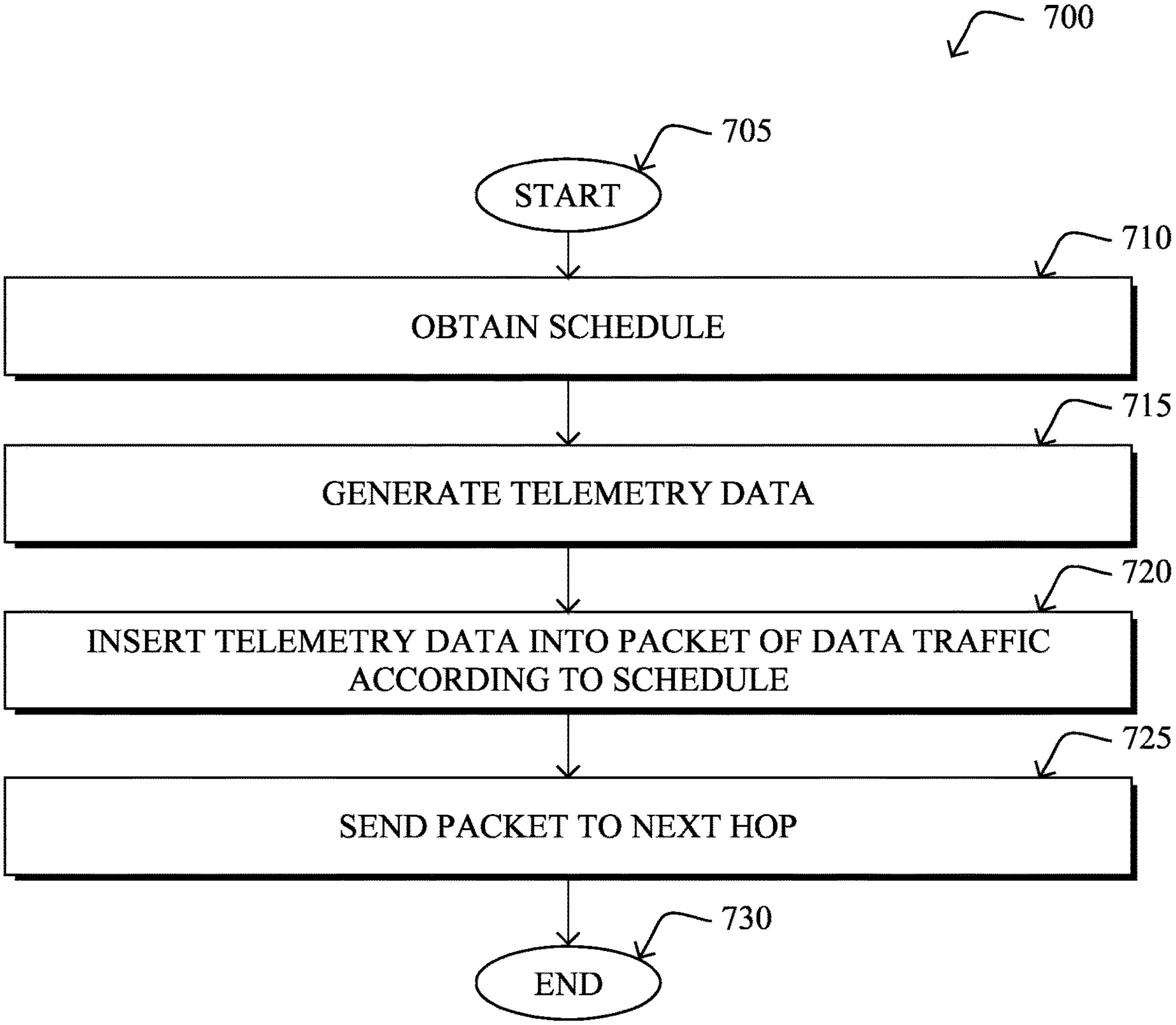
700
705
START
710
OBTAIN SCHEDULE
715
GENERATE TELEMETRY DATA
720
INSERT TELEMETRY DATA INTO PACKET OF DATA TRAFFIC ACCORDING TO SCHEDULE
725
SEND PACKET TO NEXT HOP
730
END

FIG. 7

METHOD AND APPARATUS FOR CROSS-LAYER, IN-BAND MONITORING OF TUNNELS BY INSERTION OF TELEMETRY DATA INTO A PACKET

TECHNICAL FIELD

The present disclosure relates generally to computer networks, and, more particularly, to the cross-layer, in-band monitoring of tunnels.

BACKGROUND

Cellular network coverage has made Internet connectivity increasingly ubiquitous. This has led to an ever-increasing demand for bandwidth, to accommodate traffic such as multimedia content and communications (e.g., bandwidth-intensive high definition video streaming or real time video calls, etc.). For instance, passengers of public transportation now expect on-board, high-speed connectivity, which implies a reliable wireless ground-to-vehicle communication. Accordingly, wireless mesh networks are now being deployed, to provide connectivity to such fast-moving nodes.

Monitoring a network, such as a wireless mesh network, requires the collection of telemetry data from various parts of the network. However, doing so is not a zero-cost operation and consumes resources that could otherwise be devoted to data traffic in the network. In other words, it is often unfeasible for every networking device in a network to stream every possible form of telemetry data in real time, for purposes of assessing the health of the network.

BRIEF DESCRIPTION OF THE DRAWINGS

The embodiments herein may be better understood by referring to the following description in conjunction with the accompanying drawings in which like reference numerals indicate identically or functionally similar elements, of which:

FIGS. **1**A-**1**B illustrate an example communication network;

FIG. **2** illustrates an example network device/node;

FIG. **3** illustrates an example of a mobile system communicating wirelessly;

FIG. **4** illustrates an example of the scheduling of telemetry data to be inserted into data traffic by networking devices along a path;

FIGS. **5**A-**5**B illustrate examples of different layers of a packet into which telemetry data may be inserted;

FIG. **6** illustrates an example of a networking device selecting a location to insert telemetry data into a packet; and

FIG. **7** illustrates an example simplified procedure for the cross-layer, in-band monitoring of tunnels.

DESCRIPTION OF EXAMPLE EMBODIMENTS

Overview

According to one or more embodiments of the disclosure, a network device along a path in a network receives a schedule that controls when the networking device is to insert telemetry data into data traffic passing through the networking device. The networking device generates the telemetry data for insertion into the data traffic passing through the networking device. The networking device inserts, according to the schedule, the telemetry data into a particular packet of the data traffic passing through the networking device. The networking device sends the particular packet to a next hop along the path in the network.

DESCRIPTION

A computer network is a geographically distributed collection of nodes interconnected by communication links and segments for transporting data between end nodes, such as personal computers and workstations, or other devices, such as sensors, etc. Many types of networks are available, with the types ranging from local area networks (LANs) to wide area networks (WANs). LANs typically connect the nodes over dedicated private communications links located in the same general physical location, such as a building or campus. WANs, on the other hand, typically connect geographically dispersed nodes over long-distance communications links, such as common carrier telephone lines, optical lightpaths, synchronous optical networks (SONET), or synchronous digital hierarchy (SDH) links, or Powerline Communications (PLC) such as IEEE 61334, IEEE P1901.2, and others. The Internet is an example of a WAN that connects disparate networks throughout the world, providing global communication between nodes on various networks. The nodes typically communicate over the network by exchanging discrete frames or packets of data according to predefined protocols, such as the Transmission Control Protocol/Internet Protocol (TCP/IP). In this context, a protocol consists of a set of rules defining how the nodes interact with each other. Computer networks may be further interconnected by an intermediate network node, such as a router, to extend the effective "size" of each network.

Smart object networks, such as sensor networks, in particular, are a specific type of network having spatially distributed autonomous devices such as sensors, actuators, etc., that cooperatively monitor physical or environmental conditions at different locations, such as, e.g., energy/power consumption, resource consumption (e.g., water/gas/etc. for advanced metering infrastructure or "AMI" applications) temperature, pressure, vibration, sound, radiation, motion, pollutants, etc. Other types of smart objects include actuators, e.g., responsible for turning on/off an engine or perform any other actions. Sensor networks, a type of smart object network, are typically shared-media networks, such as wireless or PLC networks. That is, in addition to one or more sensors, each sensor device (node) in a sensor network may generally be equipped with a radio transceiver or other communication port such as PLC, a microcontroller, and an energy source, such as a battery. Often, smart object networks are considered field area networks (FANs), neighborhood area networks (NANs), personal area networks (PANs), etc. Generally, size and cost constraints on smart object nodes (e.g., sensors) result in corresponding constraints on resources such as energy, memory, computational speed and bandwidth.

FIG. **1**A is a schematic block diagram of an example computer network **100** illustratively comprising nodes/devices, such as a plurality of routers/devices interconnected by links or networks, as shown. For example, customer edge (CE) routers **110** may be interconnected with provider edge (PE) routers **120** (e.g., PE-**1**, PE-**2**, and PE-**3**) in order to communicate across a core network, such as an illustrative network backbone **130**. For example, routers **110**, **120** may be interconnected by the public Internet, a multiprotocol label switching (MPLS) virtual private network (VPN), or the like. Data packets **140** (e.g., traffic/messages) may be exchanged among the nodes/devices of the computer network **100** over links using predefined network communication protocols such as the Transmission Control Protocol/Internet Protocol (TCP/IP), User Datagram Protocol (UDP), Asynchronous Transfer Mode (ATM) protocol, Frame Relay protocol, or any other suitable protocol. Those skilled in the art will understand that any number of nodes, devices, links, etc. may be used in the computer network, and that the view shown herein is for simplicity.

In some implementations, a router or a set of routers may be connected to a private network (e.g., dedicated leased lines, an optical network, etc.) or a virtual private network (VPN), such as an MPLS VPN thanks to a carrier network, via one or more links exhibiting very different network and service level agreement characteristics. For the sake of illustration, a given customer site may fall under any of the following categories:

1.) Site Type A: a site connected to the network (e.g., via a private or VPN link) using a single CE router and a single link, with potentially a backup link (e.g., a 3G/4G/5G/LTE backup connection). For example, a particular CE router **110** shown in network **100** may support a given customer site, potentially also with a backup link, such as a wireless connection.

2.) Site Type B: a site connected to the network by the CE router via two primary links (e.g., from different Service Providers), with potentially a backup link (e.g., a 3G/4G/5G/LTE connection). A site of type B may itself be of different types:

2a.) Site Type B1: a site connected to the network using two MPLS VPN links (e.g., from different Service Providers), with potentially a backup link (e.g., a 3G/4G/5G/LTE connection).

2b.) Site Type B2: a site connected to the network using one MPLS VPN link and one link connected to the public Internet, with potentially a backup link (e.g., a 3G/4G/5G/LTE connection). For example, a particular customer site may be connected to network **100** via PE-**3** and via a separate Internet connection, potentially also with a wireless backup link.

2c.) Site Type B3: a site connected to the network using two links connected to the public Internet, with potentially a backup link (e.g., a 3G/4G/5G/LTE connection).

Notably, MPLS VPN links are usually tied to a committed service level agreement, whereas Internet links may either have no service level agreement at all or a loose service level agreement (e.g., a “Gold Package” Internet service connection that guarantees a certain level of performance to a customer site).

3.) Site Type C: a site of type B (e.g., types B1, B2 or B3) but with more than one CE router (e.g., a first CE router connected to one link while a second CE router is connected to the other link), and potentially a backup link (e.g., a wireless 3G/4G/5G/LTE backup link). For example, a particular customer site may include a first CE router **110** connected to PE-**2** and a second CE router **110** connected to PE-**3**.

FIG. **1**B illustrates an example of network **100** in greater detail, according to various embodiments. As shown, network backbone **130** may provide connectivity between devices located in different geographical areas and/or different types of local networks. For example, network **100** may comprise local/branch networks **160**, **162** that include devices/nodes **10-16** and devices/nodes **18-20**, respectively, as well as a data center/cloud environment **150** that includes servers **152-154**. Notably, local networks **160-162** and data center/cloud environment **150** may be located in different geographic locations.

Servers **152-154** may include, in various embodiments, a network management server (NMS), a dynamic host configuration protocol (DHCP) server, a constrained application protocol (CoAP) server, an outage management system (OMS), an application policy infrastructure controller (APIC), an application server, etc. As would be appreciated, network **100** may include any number of local networks, data centers, cloud environments, devices/nodes, servers, etc.

In some embodiments, the techniques herein may be applied to other network topologies and configurations. For example, the techniques herein may be applied to peering points with high-speed links, data centers, etc.

According to various embodiments, a software-defined WAN (SD-WAN) may be used in network **100** to connect local network **160**, local network **162**, and data center/cloud environment **150**. In general, an SD-WAN uses a software defined networking (SDN)-based approach to instantiate tunnels on top of the physical network and control routing decisions, accordingly. For example, as noted above, one tunnel may connect router CE-**2** at the edge of local network **160** to router CE-**1** at the edge of data center/cloud environment **150** over an MPLS or Internet-based service provider network in backbone **130**. Similarly, a second tunnel may also connect these routers over a 4G/5G/LTE cellular service provider network. SD-WAN techniques allow the WAN functions to be virtualized, essentially forming a virtual connection between local network **160** and data center/cloud environment **150** on top of the various underlying connections. Another feature of SD-WAN is centralized management by a supervisory service that can monitor and adjust the various connections, as needed.

FIG. **2** is a schematic block diagram of an example node/device **200** that may be used with one or more embodiments described herein. As shown, device **200** may comprise one or more communication interfaces **210** (e.g., wired, wireless, etc.), at least one processor **220**, and a memory **240** interconnected/coupled by a system bus **250**, as well as a power supply **260** (e.g., battery, plug-in, etc.).

Communication interface(s) **210** include the mechanical, electrical, and signaling circuitry for communicating data over a communication link. To this end, communication interface(s) **210** may be configured to transmit and/or receive data using a variety of different communication protocols, such as TCP/IP, UDP, Ethernet, etc. Note that the device **200** may have multiple different types of communication interface(s) **210**, e.g., wireless and wired/physical connections, and that the view herein is merely for illustration.

The memory **240** comprises a plurality of storage locations that are addressable by the processor(s) **220** and the communication interface(s) **210** for storing software programs and data structures associated with the embodiments described herein. The processor **220** may comprise necessary elements or logic adapted to execute the software programs and manipulate the data structures **245**. An operating system **242**, portions of which are typically resident in memory **240** and executed by the processor(s), functionally organizes the node by, inter alia, invoking network operations in support of software processors and/or services executing on the device. These software processors and/or services may comprise a routing process **244** and/or a communication process **248**.

It will be apparent to those skilled in the art that other processor and memory types, including various computer-readable media, may be used to store and execute program instructions pertaining to the techniques described herein.

Also, while the description illustrates various processes, it is expressly contemplated that various processes may be embodied as modules configured to operate in accordance with the techniques herein (e.g., according to the functionality of a similar process). Further, while processes may be shown and/or described separately, those skilled in the art will appreciate that processes may be routines or modules within other processes.

Routing process **244** includes instructions executable by processor **220** to perform functions provided by one or more routing protocols, such as proactive or reactive routing protocols as will be understood by those skilled in the art. These functions may, on capable devices, be configured to manage a routing/forwarding table (a data structure **245**) including, e.g., data used to make routing/forwarding decisions. In particular, in proactive routing, connectivity is discovered and known prior to computing routes to any destination in the network, e.g., link state routing such as Open Shortest Path First (OSPF), or Intermediate-System-to-Intermediate-System (ISIS), or Optimized Link State Routing (OLSR). Reactive routing, on the other hand, discovers neighbors (i.e., does not have an a priori knowledge of network topology), and in response to a needed route to a destination, sends a route request into the network to determine which neighboring node may be used to reach the desired destination. Example reactive routing protocols may comprise Ad-hoc On-demand Distance Vector (AODV), Dynamic Source Routing (DSR), 6LoWPAN Ad Hoc On-Demand Distance Vector Routing (LOAD), DYnamic MANET On-demand Routing (DYMO), etc. Notably, on devices not capable or configured to store routing entries, routing process **244** may consist solely of providing mechanisms necessary for source routing techniques. That is, for source routing, other devices in the network can tell the less capable devices exactly where to send the packets, and the less capable devices simply forward the packets as directed.

In general, communication process **248** includes instructions executable by processor **220** to perform functions related to a mobile system roaming from one wireless access point to another. To this end, communication process **248** may operate in conjunction with routing process **244**, in some instances, to establish and maintain one or more LSPs between a mobile system and the backend infrastructure. An example protocol that uses label-switched paths is the Multiprotocol Label Switching (MPLS) protocol. In general, MPLS operates by appending an MPLS header to a packet that includes a label 'stack.' The label(s) in the stack are inserted by a label edge router (LER) based on the forwarding equivalence class (FEC) of the packet. Paths are also managed via the Label Distribution Protocol (LDP) or Resource Reservation Protocol-Traffic Engineering (RSVP-TE). Another protocol that communication process **248** may utilize is the Control and Provisioning of Wireless Access Points (CAPWAP) protocol.

FIG. **3** illustrates an example **300** of a mobile system communicating wirelessly, according to various embodiments. As shown, the mobile system **302** may generally take the form of any mobile object or set of objects equipped with its own internal network and configured to communicate wirelessly with a backhauling system during motion. For instance, mobile system **302** may take the form of a train, bus, airplane or other flying vehicle, ferry, automobile, mine cart, crane, truck, another form of vehicle that may be used for transportation or shipping, a vehicle that may be found in a worksite, mining location, industrial site, factory, etc., a robot, or the like. In further cases, mobile system **302** may be a fully-autonomous, or partially-autonomous, vehicle or other system that moves with little or no direct human control.

Onboard mobile system **302** may be various networking devices that support the mobile domain of mobile system **302**. In some embodiments, as shown, there may be a Layer-2 (L2) switch **312** onboard mobile system **302** that is connected to any number of onboard devices **314** within the mobile domain of mobile system **302**. For instance, onboard device **314***a* may take the form of an onboard Wi-Fi™ access point that provides connectivity to any number of user devices (e.g., mobile phones, computers, etc.) of passengers being transported by mobile system **302**. Conversely, onboard device **314***b* may take the form of a security camera that is also connected to L2 switch **312**. In various embodiments, some or all of the onboard devices **314** may be onboard wired devices (OWDs), meaning that they communicate with L2 switch **312** via wired connections, such as an Ethernet network or the like.

According to various embodiments, the mobile domain of mobile system **302** may also include a plurality of mobile nodes **310**, denoted "MN" in the Figures for simplicity. For instance, as shown, mobile system **302** may include a first MN **310***a* and a second MN **310***b*. Each MN **310** may generally include: 1.) a wireless interface to exchange data with wireless access points of the backhaul network and 2.) a local interface to exchange data with the local network of mobile system **302**. For instance, MN **310***a* and MN **310***b* may each have a wired connection to L2 switch **312**.

As would be appreciated, MN **310***a* and MN **310***b* may be located on mobile system **302** at a distance from one another, so as to provide spatial diversity to the potential wireless connection points utilized by mobile system **302**. For example, MN **310***a* may be located near the front of mobile system **302** (e.g., the head-end of a train), while MN **310***b* may be located farther towards the rear of mobile system **302** than that of MN **310***a*. Thus, even if a particular MN **310** does not have a reliable wireless connection to the backhaul system, another MN **310** of mobile system **302** may (e.g., if the train is going around a curve in the track, etc.). In some instances, MNs **310** may also offer frequency diversity, as well, such as by operating on different frequencies, at least part of the time. As a result, even if one frequency is experiencing interference, the other frequency could be used to form a wireless connection between mobile system **302** and the backhaul system.

Located along the path of travel of mobile system **302** (e.g., a railroad track, a road, a waterway, a runway, etc.) may be any number of wireless access points/base stations **308**. For instance, as shown, there may be trackside access points (APs)/base stations **308***a*-**308***b* shown. Note that while these wireless access points are referred to herein as 'trackside,' their locations can be varied depending on the deployment scenario (e.g., roadside, etc.).

During operation, base stations **308***a*-**308***b* may form wireless connections with MN **310***a* and/or MN **310***b*, to provide wireless connectivity to mobile system **302** as it travels. To this end, each base station **308** may include at least 1.) a wireless interface to communicate with a MN **310** and 2.) an interface to communicate with a gateway, denoted "GW" **306** in the Figures for simplicity. Typically, the connections between base stations **308***a*-**308***b* and GW **306** are wired connections that use a suitable wired communication protocol, such as Ethernet.

GW **306** represents the other end of the backhauling system and provides Layer-3 (L3) routing functions. To do so, GW **306** may include at least one interface connected to

L3-routed network **304**, as well as any number of interfaces to communicate with base stations **308**. For instance, L3-routed network **304** may take the form of the Internet, in many instances, although the techniques herein may be extended to any number of different types of external networks, as desired.

Traditionally, a backhaul system supporting mobile domains/systems relies on the use of multiple tunnels, to convey traffic between the L3 gateway and the mobile domain/system. For instance, as shown, assume that MN **310***a* has formed a wireless connection **318***a* with base station **308***a*. Such a connection may be formed using a suitable transmission protocol, such as the Prodigy protocol by Fluidmesh™ (now Cisco Systems™) or another wireless protocol that supports extremely fast handoffs. Consequently, MN **310***a* may establish a first tunnel over wireless connection **318***a*. GW **306** and base station **308***a* may form a second tunnel via their connection **316***a*, likewise. Thus, when base station **308***a* sends traffic that it receives from MN **310***a* towards GW **306**, it may encapsulate the traffic and tunneled via the first tunnel, which base station **308***a* then encapsulates for transport via the second tunnel to GW **306**. A similar approach may be taken with respect to wireless connection **318***b* between MN **310***b* and base station **308***b*, as well as connection **316***b* between base station **308***b* and GW **306**.

In alternative embodiments, a single L2 tunnel may be established between each base station **308** and GW **306**. This tunnel will carry L2 traffic between GW **306** and the MN **310** to which the base station **308** is connected. For instance, a first L2 tunnel may be formed between GW **306** and base station **308***a* over which traffic conveyed between base station **308***a* and MN **310***a* may be transported, assuming that wireless connection **318***a* exists. Similarly, another GW **306** and base station **308***b* may form a second L2 tunnel over which traffic conveyed between base station **308***b* and MN **310***b* may be transported, assuming that wireless connection **318***a* exists.

Typically, only a single wireless link is active at any given time between a mobile system, such as mobile system **302**, and any given base station **308**. For instance, assume that MN **310***a* is wirelessly connected to base station **308***a*. In such a case, any other MN **310** on mobile system **302** (e.g., MN **310***b*, etc.) may be in an idle state at that time. In other words, one of the mobile nodes (e.g., MN **310***a*) may be designated as the primary, while the other is designated as the secondary (e.g., MN **310***b*) and remains idle. As mobile system **302** roams, the primary node may begin passing its traffic to the secondary node, to begin leveraging its own connection to the fixed infrastructure. In turn, the roles of the two nodes may be switched, thereby making MN **310***a* the secondary node and MN **310***b* the primary node.

As noted above, backhaul connectivity in many wireless mesh networks in fixed deployments for fast-moving clients/nodes rely on some form of tunneling, such as through the use of MPLS, CAPWAP, EoGRE, or the like. In many of these cases, tunneling is hierarchical in that tunnels are carried within tunnels, in order to preserve segmentation across different domains and abstract network characteristics. To do so, a packet may be encapsulated any number of times with different tunnel headers, during its transit to its destination (e.g., the network gateway, etc.).

One of the challenges with respect to the above approach relates to the collection of telemetry data along the paths/tunnels of the network. Indeed, it is often difficult, if not impossible, to obtain a full picture of all of the important, key performance indicators (KPIs) on all of the different network nodes/devices for purposes of the following:

selecting the best networking devices for path instantiation

highlighting potential issues

troubleshooting

acting upon failure to perform restoration

To perform the above, there needs to be a telemetry collection mechanism in the network capable of capturing and reporting on information such as the health of a deployment in terms of node/device health, link health, traffic statistics, or the like.

Cross-Layer In-Band Monitoring of Tunnels

The techniques herein introduce various mechanisms for the collection of telemetry data in an intelligent manner across a network path over which any number of tunnels may extend. In some aspects, the techniques herein provide for the collection of the telemetry data using an in-band/in-situ approach, whereby the telemetry data is inserted into data traffic conveyed over the path. In another aspect, the techniques herein introduce scheduling mechanisms for the telemetry reporting that can help to reduce overhead on the path and conserve bandwidth. In a further aspect, the techniques herein also introduce dynamic mechanisms that allow a networking device to select where the telemetry data is to be inserted into a particular packet, so as to select the most efficient encoding available.

Illustratively, the techniques described herein may be performed by hardware, software, and/or firmware, such as in accordance with the communication process **248**, which may include computer executable instructions executed by the processor **220** (or independent processor of interfaces **210**) to perform functions relating to the techniques described herein, potentially in conjunction with routing process **244**.

Specifically, in various embodiments, a network device along a path in a network receives a schedule that controls when the networking device is to insert telemetry data into data traffic passing through the networking device. The networking device generates the telemetry data for insertion into the data traffic passing through the networking device. The networking device inserts, according to the schedule, the telemetry data into a particular packet of the data traffic passing through the networking device. The networking device sends the particular packet to a next hop along the path in the network.

Operationally, the techniques herein propose extending in-situ operations, administration, and management (iOAM) approaches to network paths over which multiple tunnels may span and in an intelligent manner. In general, iOAM, also sometimes referred to as "in-band" OAM, entails piggybacking data in the data plane for purposes of reporting OAM data. As would be appreciated, network operations are often classified as being part of a control plane or a data plane. Typically, the control plane is responsible for signaling and controlling how paths in the network are established and used. In contrast, the data plane is used to transmit data packets (e.g., those conveying data to/from a user device, etc.) over those paths established by the control plane.

By way of example, say a user submits certain information to a website. During transmission of those packets, a processing networking device may insert certain OAM data into those packets, such as the ingress and egress identifiers for the interfaces over which the packets are received and sent. In doing so, a downstream device is able to extract this information from the data packets. Without such a mechanism, the ingress and egress identifiers would otherwise need to be sent to the downstream device via their own packets.

In networks that rely on tunneling, such as certain wireless backhaul networks, insertion and extraction of iOAM data becomes somewhat complicated, as the data packets flowing along the tunnel(s) are also encapsulated. This raises the question: where should any iOAM data be inserted into a packet? In addition, as would be appreciated, each networking device along a path inserting iOAM data into each data packet traversing that device could very will impinge on the operation of the network. This is because doing so could consume additional resources (e.g., bandwidth, memory, etc.) and reduce the performance of the path/tunnel, such as by taking longer to process each packet.

According to various embodiments, certain aspects of the techniques herein propose implementing iOAM scheduling on the networking devices along a path/tunnel in the network. More specifically, in order to efficiently use the bandwidth and other resources of the path, the techniques herein propose relaxing the requirement that telemetry data be inserted into the data traffic at each node, at any given point in time and/or for any given packet. Rather, nodes insert telemetry information when it's their turn to "speak."

By way of example, consider FIG. **4** which shows a network path **400** over the course of time. As shown, path **400** may include any number of networking devices **402** interconnected by links **404** (e.g., wireless links, wired links, etc.). For instance, networking devices **402** may take the form of wireless nodes, wireless access points/base stations, switches, routers, gateways, any of the devices described previously, or the like. For simplicity, path **400** is shown to include four networking devices **402**, denoted devices A-D. However, the techniques herein are limited as such and could be used for paths including any number of interconnected networking devices.

In some embodiments, any or all of devices A-D may obtain a reporting schedule that controls when it is to insert telemetry data into data traffic passing through the networking device. For instance, such a schedule may be provided to a given networking device **402** along path **400** by a supervisory device or service (e.g., the network gateway, a network controller, etc.), computed by the networking device itself, or even from another networking device along path **400**, in some instances.

In one embodiment, the reporting schedule of a networking device **402** may be based in part on the topology of the network or, more specifically, path **400**. More specifically, each of devices A-D may be aware of at least a portion of the topology of the network, such as the number of hops present along path **400**. Here, the idea is that each node keeps track of the number of packets/frames (N) on the same tunnel. In turn, in some embodiments, when N % n_hops==k and the device is in k^{th} position in the path, then it is that device's turn to provide iOAM information/telemetry data via the data traffic (e.g., traffic sent over the data plane of the network). This approach keeps a very short overhead on the frame by spreading the reported telemetry data across multiple frames.

More specifically, devices A-D may each generate any or all of the following telemetry data:

Node health information, such as available/consumed CPU, memory, etc.

Node interface queuing information, such as queue status information, traffic statistics, estimated delays, or the like.

These are critical pieces of information to determine what are the best nodes to use for a handover in the case of roaming and for path instauration whenever a new connection is established.

Once generated, a networking device **402** may use its topology knowledge, as well as the number of frames/packets of the data traffic, to determine when it is its turn to insert its telemetry data into a particular frame/packet, in accordance with its schedule. For instance, as shown, device A may insert telemetry/iOAM data **408***a* into a first frame **406***a*, based on the location of device A along the path, as well as a count associated with frame **406***a*. Similarly, device B may insert iOAM data **408***b* into a second frame **406***b* and device C may insert iOAM data **408***c* into a third frame **406***c*. In doing so, the iOAM data **408** may be spread across multiple frames, reducing the overhead on networking devices **402**.

In some embodiments, the schedules of networking devices **402** may be fixed, according to their priority. For instance, the following sequence indicates a potential scheduled ordering to this reporting: A, B, A, C, A, B, A, C, etc. However, in further embodiments, the reporting sequence may also be dynamic through the use of one or more scheduling rules.

In one embodiment, each reporting networking device **402** may be assigned a credit/bandwidth that controls the maximum number of iOAM opportunities and/or telemetry data that it can send in any given epoch of N frames/packets. Such a policy rule may ensure that any given networking device **402** only reports up to a maximum amount of telemetry data every threshold number of data packets. Thus, in some instances, a deficit round robin (DRR)-like scheduling approach or even a more refined approach, can be used for the scheduling, while still keeping the iOAM bandwidth overhead under control.

In further embodiments, the schedules of networking devices **402** may also take into account the level of urgency/criticality of the telemetry data being reported. In one embodiment, for instance, the scheduling may allow for "URGENT" bits of information to be inserted by any networking device **402**, if their information is very critical, potentially with different 'credit' requirements, as well.

To prevent iOAM information stacking, different iOAM layers may be utilized for any given packet. For instance, FIG. **5**A illustrates an example **500** of a first iOAM layer **510***a* and a second iOAM layer **510***b* that may be utilized. Over any given time period (e.g., times T=0 to T=3), first iOAM layer **510***a* may be used by the networking devices to report their telemetry/iOAM data that has a base or default degree of criticality. Use of the second iOAM layer **510***b*, however, may be reserved for the reporting only of critical telemetry data, such as certain events.

In other words, scheduling can be determined for each layer, and have different decisions for each iOAM layer, in some embodiments. For instance, as shown, networking device A may insert its normal telemetry data into a frame/packet at time T=0, but then also insert critical telemetry data into a subsequent frame/packet at time T=1, even though this deviates from its baseline reporting schedule. Of course, while bifurcated iOAM layers are show in FIG. **5**A, this is for exemplary purposes only, and further embodiments provide for additional layers to be used for additional categories of criticality (e.g., NORMAL criticality, MEDIUM criticality, HIGH criticality, etc.).

FIG. **5**B illustrates an example frame/packet **406** having different iOAM layers into which telemetry data may be inserted by one or more networking devices along a path via which frame/packet **406** is conveyed. As shown, frame/packet **406** may include a payload **502** via which user and/or application data may be sent. Frame/packet **406** may also include a packet header **504**. In various embodiments, packet **406** may also be encapsulated using one or more tunnel headers **506**, as it is communicated via a path/tunnel. Indeed, if tunnel-in-tunnel encapsulation is used in the network, frame/packet **406** may have multiple tunnel headers **506**.

As shown, telemetry data may be inserted by a networking device processing packet **406** into either of two iOAM layers **510***a*-**510***b*, such as according to the criticality of the reported telemetry data. Here, iOAM layers **510***a*-**510***b* may be implemented as one or more headers inserted into packet **406**. The data fields of that header are then used to carry the telemetry data from the networking device. This allows any subsequent receiver of packet **406** to extract and process the telemetry data.

According to various embodiments, the techniques herein also provide for the efficient encoding of any telemetry/iOAM data within a packet by a networking device. A key observation herein is that when multiple encapsulations are present, it does not really matter at what encapsulation level the iOAM telemetry is inserted. In other words, whenever one encapsulation layer is requiring telemetry, this is a transitive property that can be applied to the whole frame and, therefore, the telemetry data can be encapsulated in any header. However, it has also been noted that each protocol has different ways of encoding iOAM data according to standard. Thus, in some embodiments, the networking device inserting telemetry data into a frame/packet may select a particular location (e.g., encapsulation layer) in the packet that offers the best encoding efficiency metrics associated with those encapsulation layers.

FIG. **6** illustrates an example **600** of a networking device selecting a location to insert telemetry data into a packet, according to various embodiments. As shown, assume that a networking device **402** receives a frame/packet **406** and is to insert telemetry/iOAM data into it, before sending it on to the next hop along the path. In this specific instance, frame/packet **406** may include two tunnel encapsulation headers: an internal tunnel (I-tunnel) header **506***a* and an outer-tunnel (O-tunnel) header **506***b*. Consequently, three possibilities exist with respect to where networking device **402** can insert its telemetry data:

Between packet header **504** and I-tunnel header **506***a;*

Between packet payload **502** and packet header **504**; or

Between I-tunnel header **506***a* and O-tunnel header **506***c*.

In various embodiments, networking device **402** may evaluate the three options, to select the one that offers the best encoding efficiency. For instance, networking device **402** may opt to insert iOAM layer/header **510** between packet header **504** and I-tunnel header **506***a*, if doing so offers the best encoding efficiency. To do so, in some embodiments, this evaluation may be computed offline and provided to networking device **402** in the form of a lookup-table for performance reasons.

In some embodiments, the efficient encoding mechanism introduced herein can also be used in conjunction with the scheduling and/or prioritization mechanisms described previously. For instance, while a singular iOAM layer/header **510** is shown in FIG. **6**, such a header may be bifurcated (or further divided) to support multiple reporting layers having different criticalities, as shown in FIG. **5**B. In addition, networking device **402** may only make its evaluations of the encoding efficiencies when it is to insert telemetry data into a given frame/packet, in accordance with its schedule.

FIG. **7** illustrates an example simplified procedure (e.g., a method) for the cross-layer, in-band monitoring of tunnels, in accordance with one or more embodiments described herein. For example, a non-generic, specifically configured device/apparatus (e.g., device **200**), located along a path in a network (e.g., a tunnel), may perform procedure **700** by executing stored instructions (e.g., communication process **248** and/or routing process **244**). Procedure **700** may start at step **705** and continues on to step **710** where, as described in greater detail above, the device may obtain a schedule that controls when the networking device is to insert telemetry data into data traffic passing through the networking device. In one embodiment, the schedule allows the networking device to insert the telemetry data into any packet of the data traffic, when the telemetry data is deemed urgent. In another embodiment, the schedule is based in part on a location of the networking device within a topology of the path. In a further embodiment, the schedule specifies a maximum amount of telemetry data that the networking device can insert into the data traffic every threshold number of packets. In yet another embodiment, the schedule allows the networking device to insert the telemetry data into packets of the data traffic at a particular cadence according to an ordering of those packets.

At step **715**, as detailed above, the device may generate the telemetry data for insertion into the data traffic passing through the networking device. In some embodiments, the telemetry data comprises health data for the networking device indicative of at least one of: memory consumption by the networking device or processor availability at the networking device. In further embodiments, the telemetry data comprises interface data for the networking device indicative of at least one of: a queueing status, an estimated interface delay, or traffic statistics for an interface of the networking device.

At step **720**, the device may insert, according to the schedule, the telemetry data into a particular packet of the data traffic passing through the networking device, as described in greater detail above. In some embodiments, the device may insert the telemetry data into the particular packet in part by selecting a particular encapsulation layer from among a plurality of encapsulation layers of the particular packet into which the telemetry data is to be inserted, based on encoding efficiency metrics associated with those encapsulation layers. For instance, the plurality of encapsulation layers may include an inner tunnel header and an outer tunnel header of the particular packet. In one embodiment, the particular encapsulation layer is selected further in part based on the schedule.

At step **725**, as detailed above, the device may send the particular packet to a next hop along the path in the network. Procedure **700** then ends at step **730**.

It should be noted that while certain steps within procedure **700** may be optional as described above, the steps shown in FIG. **7** are merely examples for illustration, and certain other steps may be included or excluded as desired. Further, while a particular order of the steps is shown, this ordering is merely illustrative, and any suitable arrangement of the steps may be utilized without departing from the scope of the embodiments herein.

While there have been shown and described illustrative embodiments that provide for the cross-layer, in-band monitoring of tunnels, it is to be understood that various other adaptations and modifications may be made within the spirit and scope of the embodiments herein. For example, while certain embodiments are described herein with respect to using certain wired and/or wireless protocols, other suitable protocols may be used, accordingly.

The foregoing description has been directed to specific embodiments. It will be apparent, however, that other variations and modifications may be made to the described embodiments, with the attainment of some or all of their advantages. For instance, it is expressly contemplated that the components and/or elements described herein can be implemented as software being stored on a tangible (non-transitory) computer-readable medium (e.g., disks/CDs/RAM/EEPROM/etc.) having program instructions executing on a computer, hardware, firmware, or a combination thereof. Accordingly, this description is to be taken only by way of example and not to otherwise limit the scope of the embodiments herein. Therefore, it is the object of the appended claims to cover all such variations and modifications as come within the true spirit and scope of the embodiments herein.

The invention claimed is:

1. A method comprising:

obtaining, by a networking device along a path in a network, a schedule that controls when the networking device is to insert telemetry data into data traffic passing through the networking device;

generating, by the networking device, the telemetry data for insertion into the data traffic passing through the networking device;

selecting, by the networking device, a particular encapsulation layer from among a plurality of different encapsulation layers of the data traffic into which the telemetry data is to be inserted based on encoding efficiency metrics associated with those encapsulation layers and the schedule that controls when the networking device is to insert the telemetry data;

inserting, by the networking device and according to the schedule, the telemetry data into the particular encapsulation layer of a particular packet of the data traffic passing through the networking device; and

sending, by the networking device, the particular packet to a next hop along the path in the network.

2. The method as in claim **1**, wherein the telemetry data comprises health data for the networking device indicative of at least one of: memory consumption by the networking device or processor availability at the networking device.

3. The method as in claim **1**, wherein the telemetry data comprises interface data for the networking device indicative of at least one of: a queueing status, an estimated interface delay, or traffic statistics for an interface of the networking device.

4. The method as in claim **1**, wherein the schedule allows the networking device to insert the telemetry data into any packet of the data traffic, when the telemetry data is deemed urgent.

5. The method as in claim **1**, wherein the plurality of different encapsulation layers comprises an inner tunnel header and an outer tunnel header of the particular packet.

6. The method as in claim **1**, wherein the schedule is based in part on a location of the networking device within a topology of the path.

7. The method as in claim **1**, wherein the schedule specifies a maximum amount of telemetry data that the networking device can insert into the data traffic every threshold number of packets.

8. The method as in claim **1**, wherein the schedule allows the networking device to insert the telemetry data into packets of the data traffic at a particular cadence according to an ordering of those packets.

9. An apparatus, comprising:

one or more network interfaces;

a processor coupled to the one or more network interfaces and configured to execute one or more processes; and

a memory configured to store a process that is executable by the processor, the process when executed configured to:

obtain a schedule that controls when the apparatus is to insert telemetry data into data traffic passing through the apparatus along a path in a network;

generate the telemetry data for insertion into the data traffic passing through the apparatus;

select a particular encapsulation layer from among a plurality of different encapsulation layers of the data traffic into which the telemetry data is to be inserted based on encoding efficiency metrics associated with those encapsulation layers and the schedule that controls when the apparatus is to insert the telemetry data;

insert, according to the schedule, the telemetry data into the particular encapsulation layer of a particular packet of the data traffic passing through the apparatus; and

send the particular packet to a next hop along the path in the network.

10. The apparatus as in claim **9**, wherein the telemetry data comprises health data for the apparatus indicative of at least one of: memory consumption by the apparatus or processor availability at the apparatus.

11. The apparatus as in claim **9**, wherein the telemetry data comprises interface data for the apparatus indicative of at least one of: a queueing status, an estimated interface delay, or traffic statistics for an interface of the apparatus.

12. The apparatus as in claim **9**, wherein the schedule allows the apparatus to insert the telemetry data into any packet of the data traffic, when the telemetry data is deemed urgent.

13. The apparatus as in claim **9**, wherein the plurality of different encapsulation layers comprises an inner tunnel header and an outer tunnel header of the particular packet.

14. The apparatus as in claim **9**, wherein the schedule is based in part on a location of the apparatus within a topology of the path.

15. The apparatus as in claim **9**, wherein the schedule allows the apparatus to insert the telemetry data into packets of the data traffic at a particular cadence according to an ordering of those packets.

16. A tangible, non-transitory, computer-readable medium storing program instructions that cause a networking device along a path in a network to execute a process comprising:

obtaining, by the networking device along the path in the network, a schedule that controls when the networking device is to insert telemetry data into data traffic passing through the networking device;

generating, by the networking device, the telemetry data for insertion into the data traffic passing through the networking device;

selecting, by the networking device, a particular encapsulation layer from among a plurality of different encapsulation layers of the data traffic into which the telemetry data is to be inserted based on encoding efficiency metrics associated with those encapsulation layers and the schedule that controls when the networking device is to insert the telemetry data;

inserting, by the networking device and according to the schedule, the telemetry data into the particular encapsulation layer of a particular packet of the data traffic passing through the networking device; and

sending, by the networking device, the particular packet to a next hop along the path in the network.

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