US012395419B2

(12) **United States Patent**
Mullis

(10) **Patent No.: US 12,395,419 B2**
(45) **Date of Patent: Aug. 19, 2025**

(54) **PROGRAMMABLE NETWORK DETECTION OF NETWORK LOOPS**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 479 days.

(21) Appl. No.: **18/161,165**

(22) Filed: **Jan. 30, 2023**

(65) **Prior Publication Data**

US 2023/0344743 A1 Oct. 26, 2023

Related U.S. Application Data

(60) Provisional application No. 63/334,755, filed on Apr. 26, 2022.

(51) **Int. Cl.**

H04L 12/00	(2006.01)
H04L 43/50	(2022.01)
H04L 45/18	(2022.01)

(52) **U.S. Cl.**
CPC ***H04L 43/50*** (2013.01); ***H04L 45/18*** (2013.01)

(58) **Field of Classification Search**
CPC H04L 43/50; H04L 45/18; H04L 41/0816; H04L 41/40; H04L 41/0873; H04L 41/122
USPC 370/242
See application file for complete search history.

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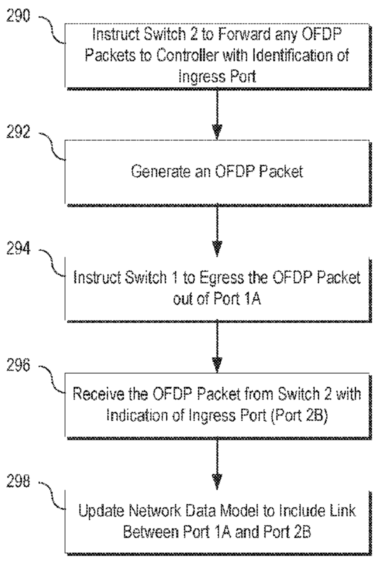
(57) **ABSTRACT**

A device may include a loop detection subsystem to place a network flow on a first switch to forward any received open flow discovery protocol (OFDP) packets to the software-defined network (SDN) controller. The device may cause the first switch to egress a query OFDP packet out of a first port of the first switch. The device may detect that the first port on the first switch is attached to a network loop based on the same query OFDP packet being ingressed by the first port of the first switch. The device may implement a remedial action in response to the detected network loop.

21 Claims, 11 Drawing Sheets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Instruct Switch 2 to Forward any OFDP Packets to Controller with Identification of Ingress Port
292
Generate an OFDP Packet
294
Instruct Switch 1 to Egress the OFDP Packet out of Port 1A
296
Receive the OFDP Packet from Switch 2 with Indication of Ingress Port (Port 2B)
298
Update Network Data Model to Include Link Between Port 1A and Port 2B

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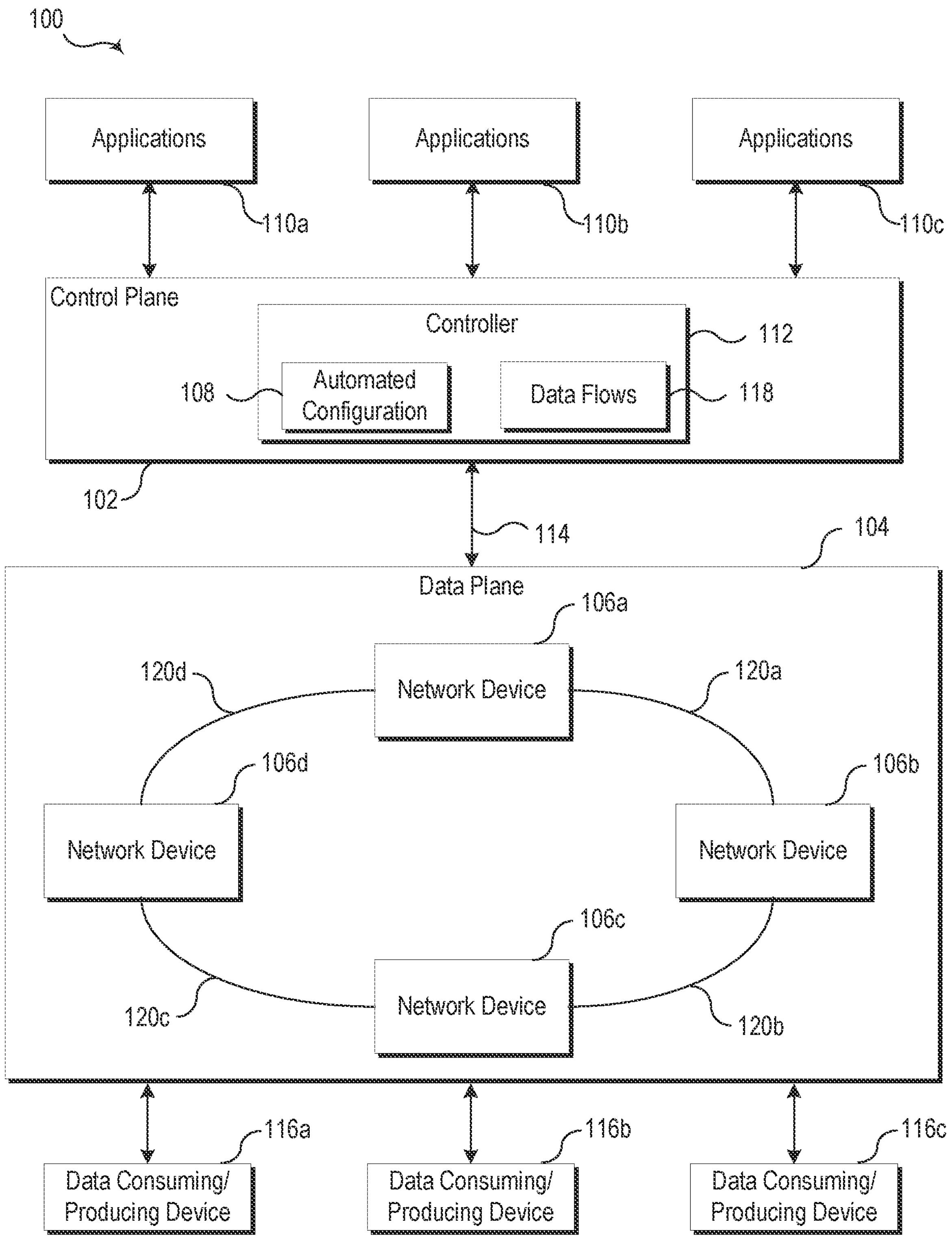
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Applications
Applications
Applications
110a
110b
110c
Control Plane
Controller
112
108
Automated Configuration
Data Flows
118
102
114
104
Data Plane
106a
Network Device
120d
120a
106d
106b
Network Device
Network Device
106c
Network Device
120c
120b
116a
116b
116c
Data Consuming/ Producing Device
Data Consuming/ Producing Device
Data Consuming/ Producing Device

FIG. 1

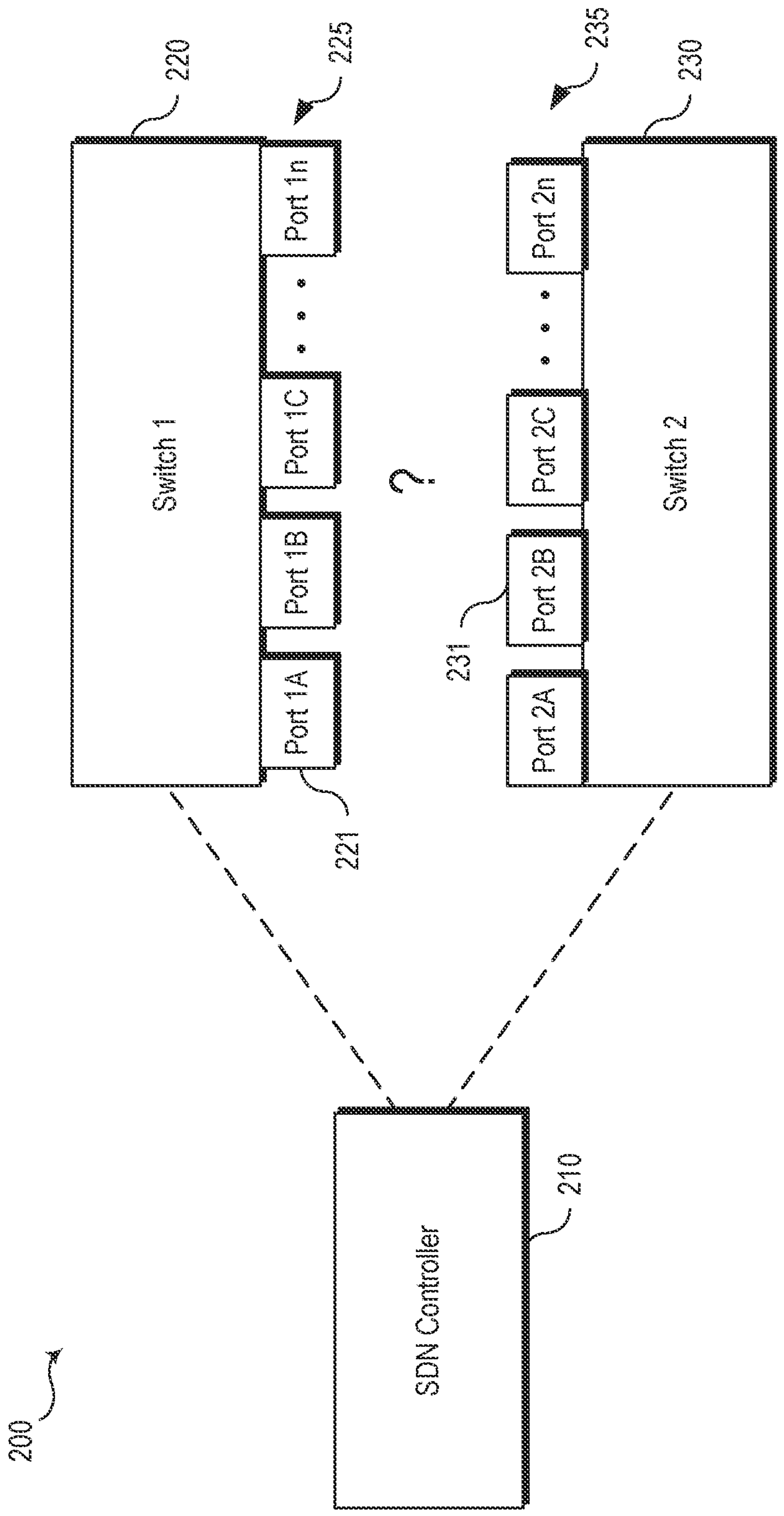
200
SDN Controller
210
Switch 1
220
Port 1A
221
Port 1B
Port 1C
Port 1n
225
?
235
Port 2A
231
Port 2B
Port 2C
Port 2n
Switch 2
230

FIG. 2A

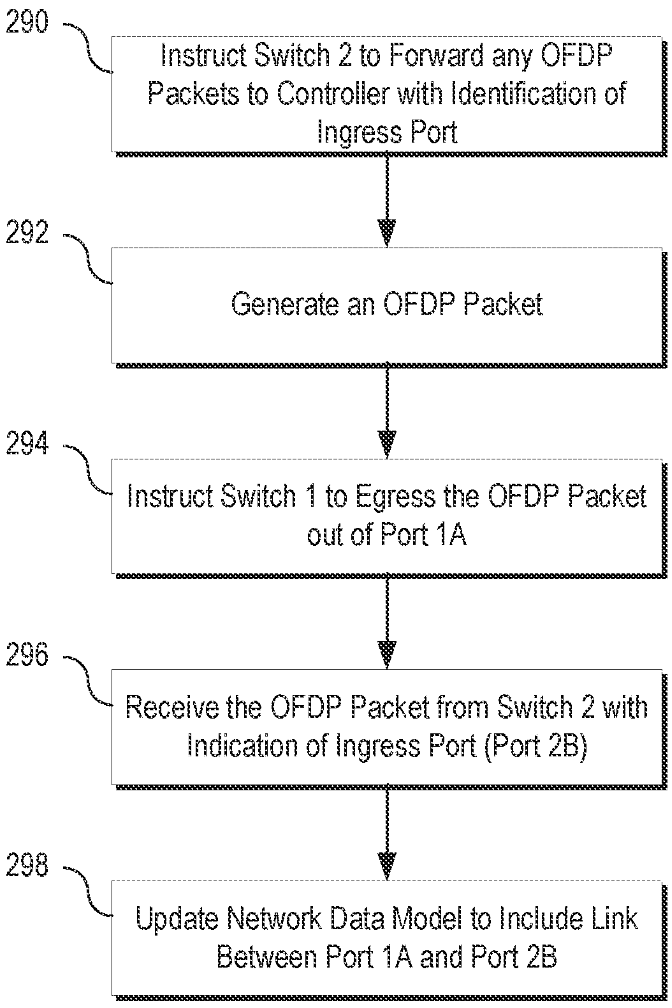
290
Instruct Switch 2 to Forward any OFDP Packets to Controller with Identification of Ingress Port
292
Generate an OFDP Packet
294
Instruct Switch 1 to Egress the OFDP Packet out of Port 1A
296
Receive the OFDP Packet from Switch 2 with Indication of Ingress Port (Port 2B)
298
Update Network Data Model to Include Link Between Port 1A and Port 2B

FIG. 2B

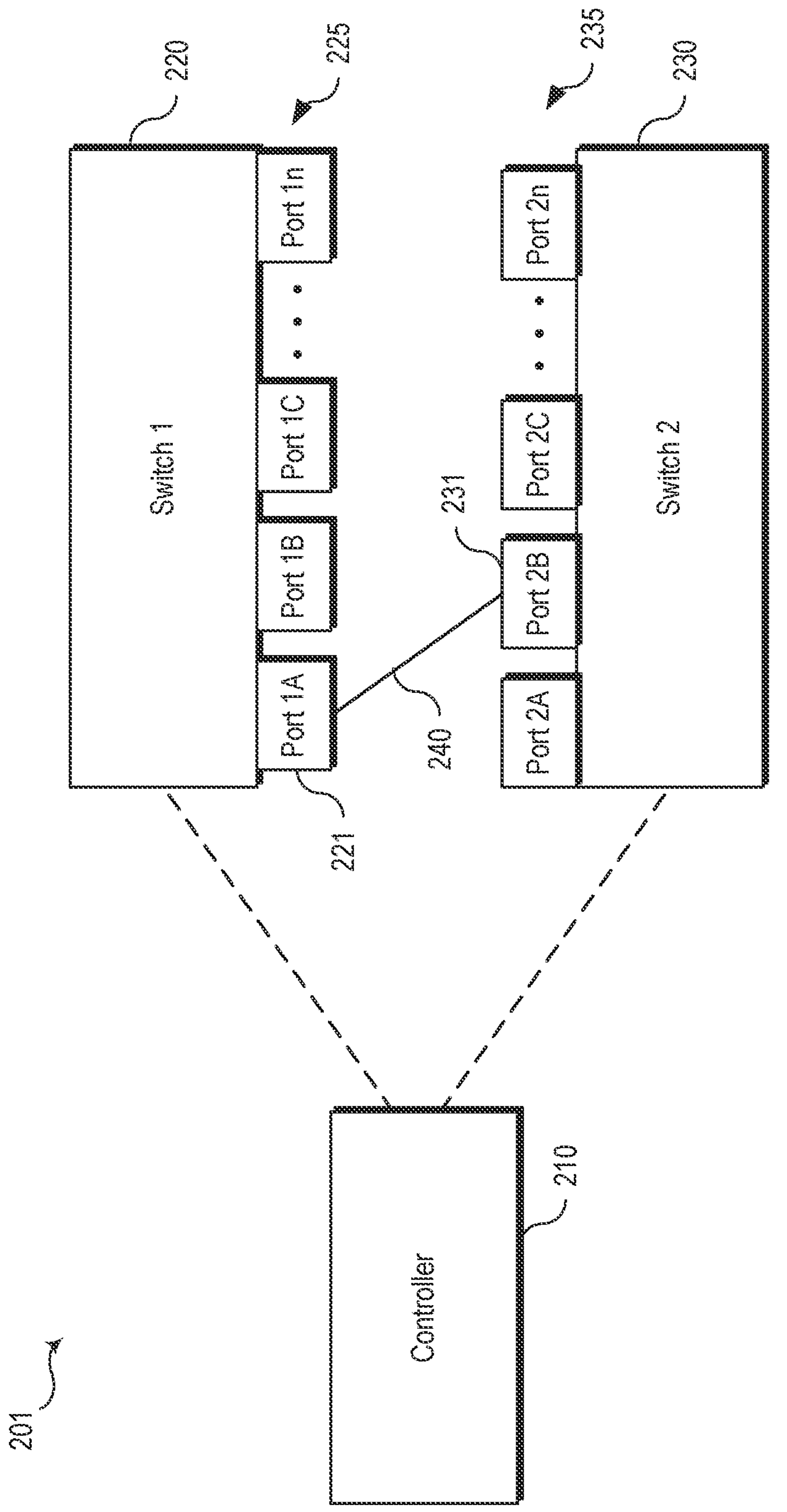
201
Controller
210
Switch 1
220
Port 1A
221
Port 1B
Port 1C
Port 1n
225
240
231
Switch 2
230
Port 2A
Port 2B
Port 2C
Port 2n
235

FIG. 2C

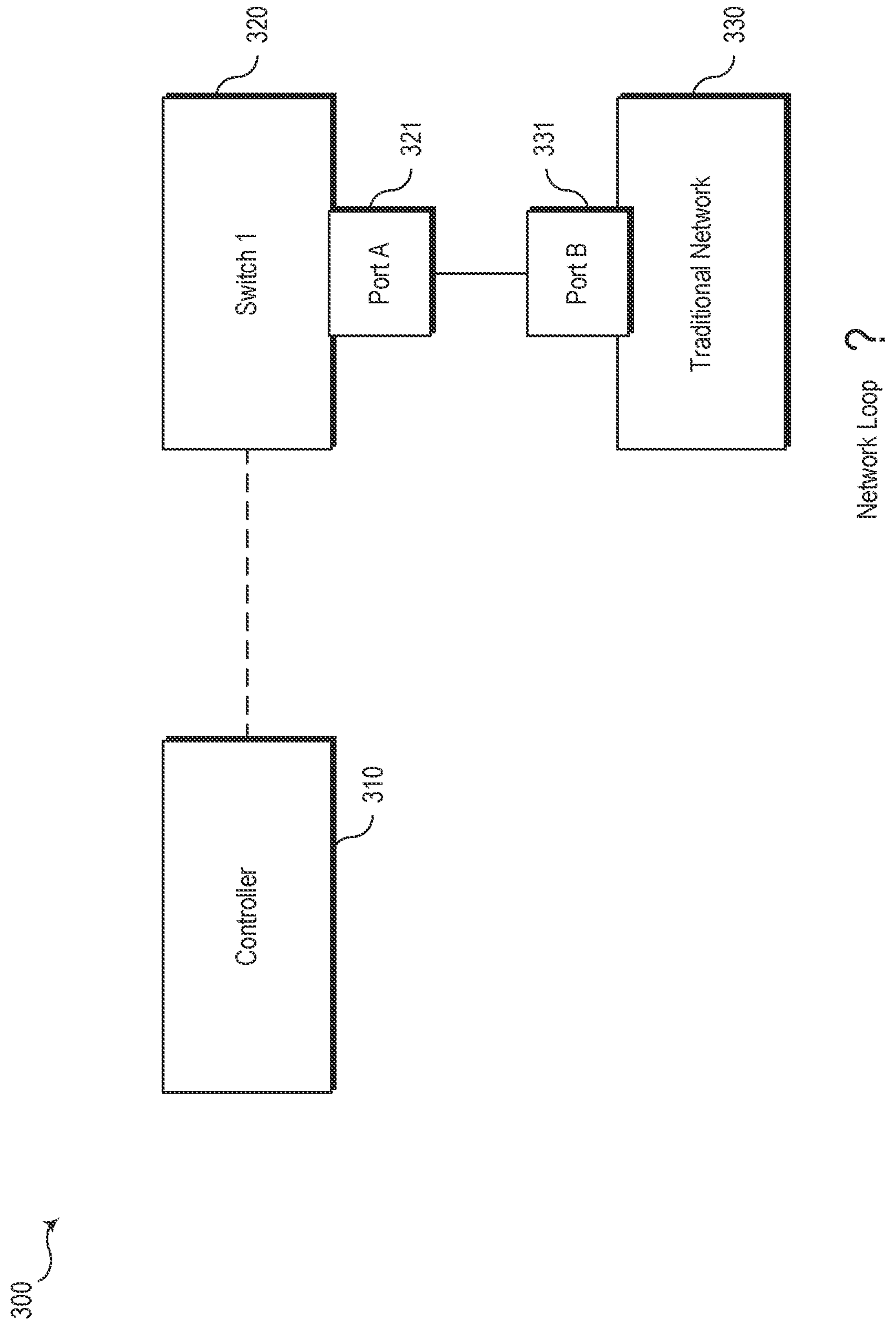
300
Controller
310
Switch 1
320
Port A
321
Port B
331
Traditional Network
330
Network Loop
?

FIG. 3A

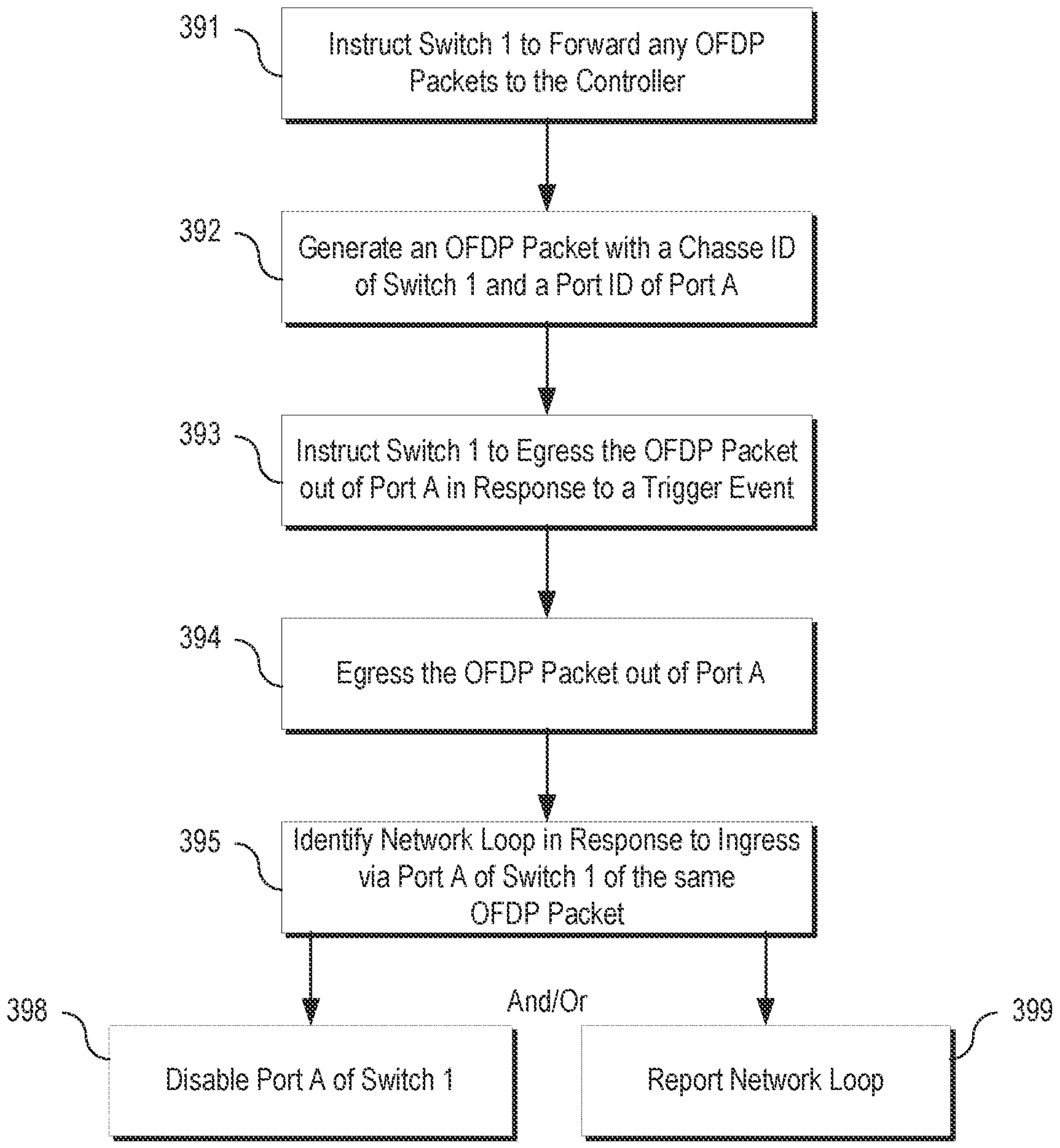
391
Instruct Switch 1 to Forward any OFDP Packets to the Controller
392
Generate an OFDP Packet with a Chasse ID of Switch 1 and a Port ID of Port A
393
Instruct Switch 1 to Egress the OFDP Packet out of Port A in Response to a Trigger Event
394
Egress the OFDP Packet out of Port A
395
Identify Network Loop in Response to Ingress via Port A of Switch 1 of the same OFDP Packet
And/Or
398
Disable Port A of Switch 1
399
Report Network Loop

FIG. 3B

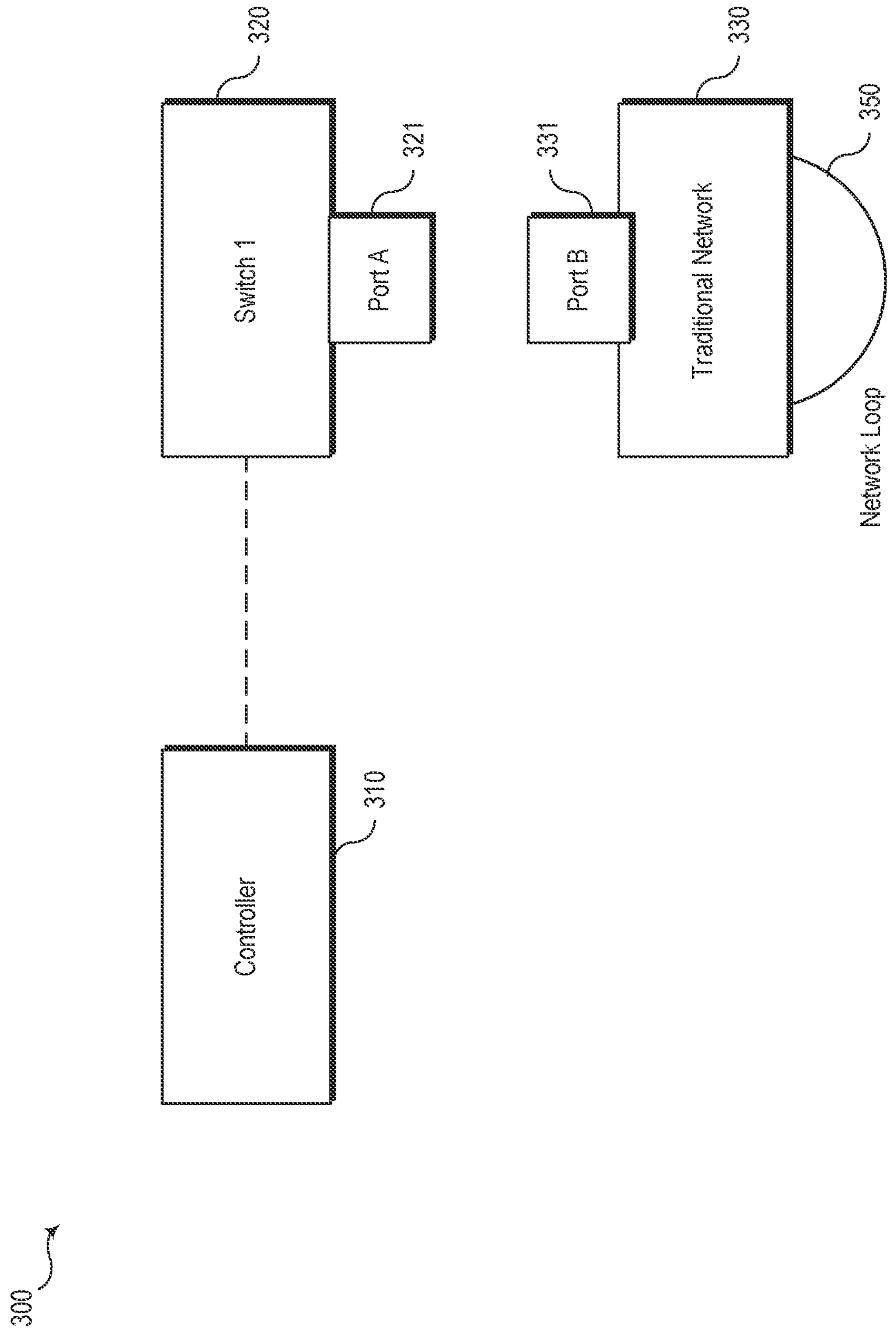
300
Controller
310
Switch 1
320
Port A
321
Port B
331
Traditional Network
330
350
Network Loop

FIG. 3C

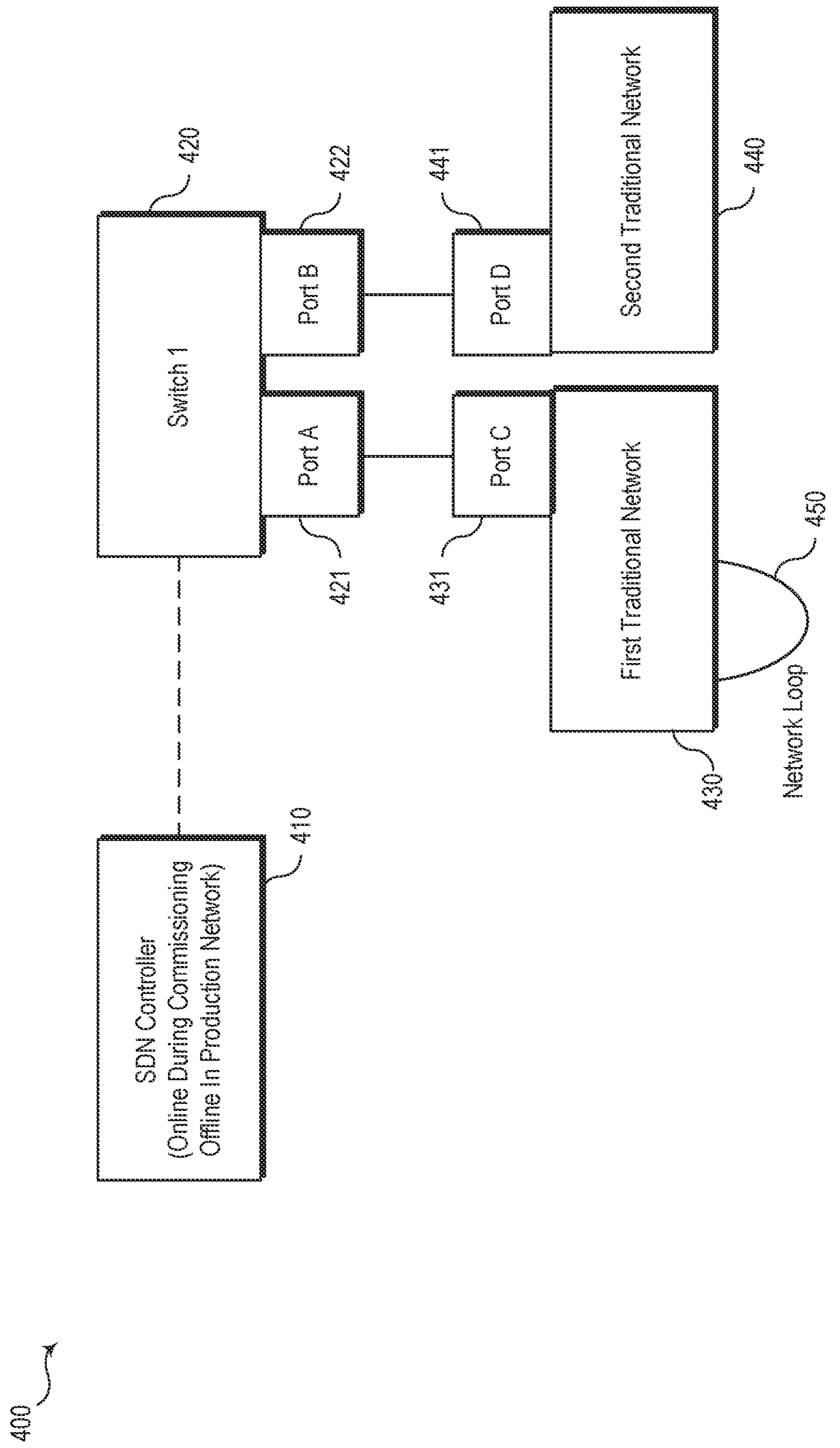
400
SDN Controller
(Online During Commissioning
Offline In Production Network)
410
Switch 1
420
Port A
421
Port B
422
Port C
431
Port D
441
First Traditional Network
430
Second Traditional Network
440
Network Loop
450

FIG. 4A

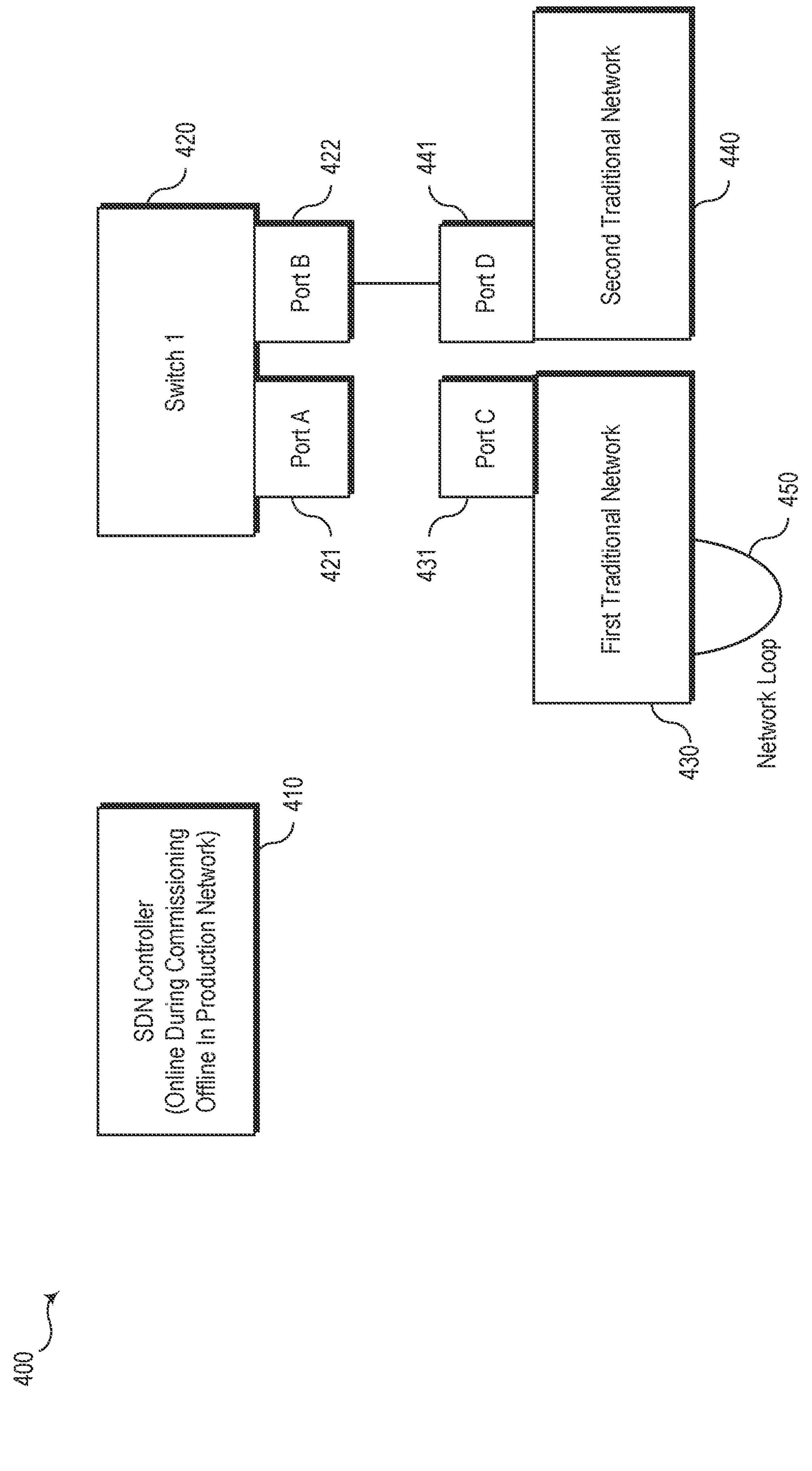
400
SDN Controller (Online During Commissioning Offline in Production Network)
410
Switch 1
420
Port A
421
Port B
422
Port C
431
Port D
441
First Traditional Network
430
Second Traditional Network
440
Network Loop
450

FIG. 4B

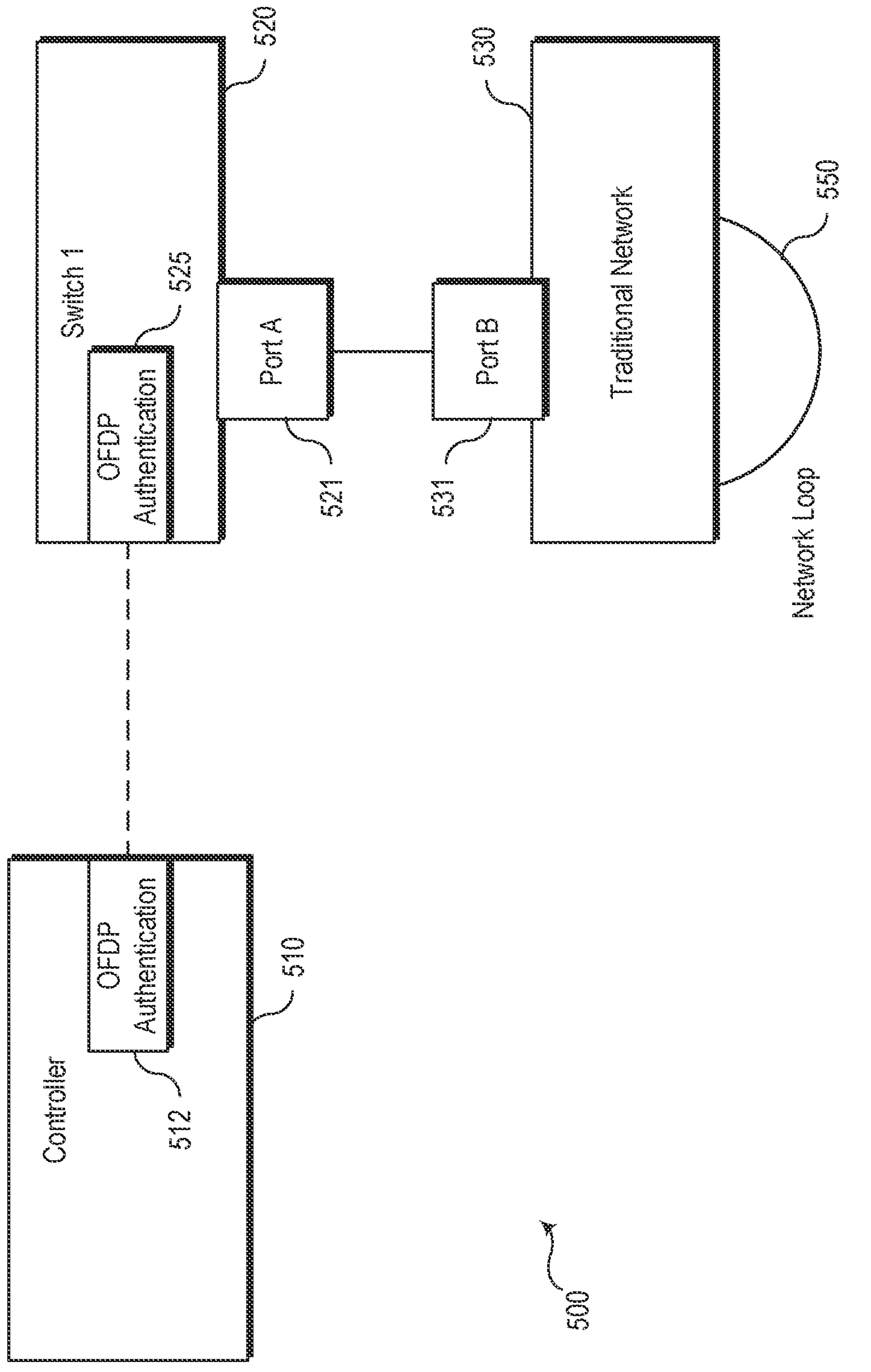
Switch 1
520
OFDP Authentication
525
Port A
521
Port B
531
530
Traditional Network
550
Network Loop
Controller
OFDP Authentication
512
510
500

FIG. 5

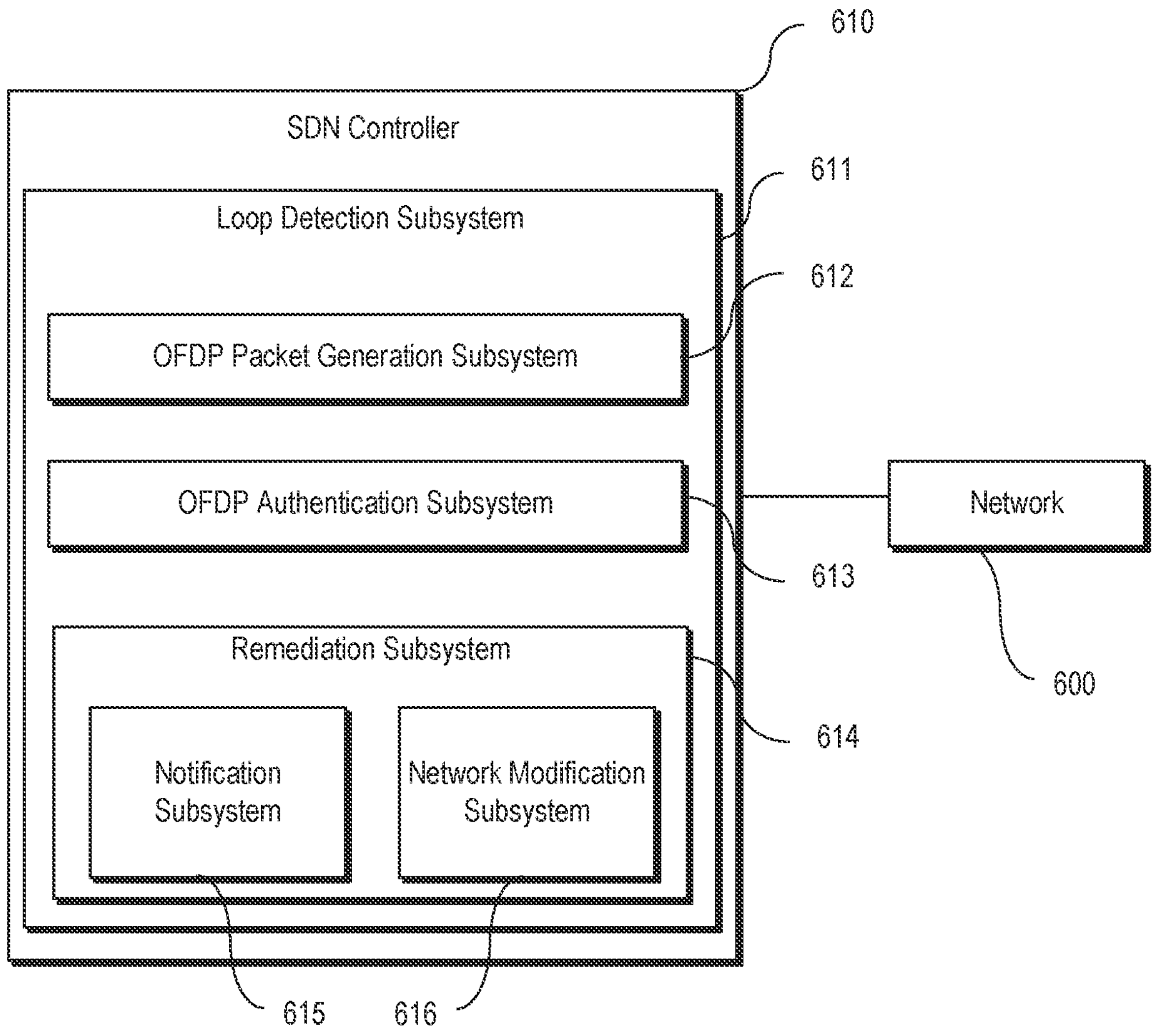
610
SDN Controller
611
Loop Detection Subsystem
612
OFDP Packet Generation Subsystem
OFDP Authentication Subsystem
613
Network
600
Remediation Subsystem
614
Notification Subsystem
Network Modification Subsystem
615
616

FIG. 6

PROGRAMMABLE NETWORK DETECTION OF NETWORK LOOPS

RELATED APPLICATIONS

This application claims priority to U.S. Provisional Patent Application No. 63/334,755 filed on Apr. 26, 2022, titled "Programmable Network Detection of Network Loops," which application is hereby incorporated by reference in its entirety.

TECHNICAL FIELD

This disclosure relates to network loop detection. This disclosure also relates to software-defined network (SDN) architectures, processors, memory, network interfaces, computer-executable instructions, electrical infrastructure, and the like.

BRIEF DESCRIPTION OF THE DRAWINGS

Non-limiting and non-exhaustive examples of the disclosure are described with reference to the figures described below.

FIG. **1** illustrates a conceptual representation of a software-defined network (SDN) system including a control plane, a data plane, and a plurality of data consumer/producer devices, according to one embodiment.

FIG. **2**A illustrates a block diagram of an SDN architecture that includes an SDN controller and two switches, according to one embodiment.

FIG. **2**B illustrates a flow chart of an example method for determining a network model using open flow discovery protocol (OFDP) packets, according to one embodiment.

FIG. **2**C illustrates an updated network model of the SDN architecture in FIG. **2**A based on a detected link, according to one embodiment.

FIG. **3**A illustrates another block diagram of an SDN architecture that includes an SDN controller, a switch, and a traditional network, according to one embodiment.

FIG. **3**B illustrates a flow chart of an example method to detect and remediate a network loop, according to one embodiment.

FIG. **3**C illustrates the detection of a network loop that includes port A of the first switch, according to one embodiment.

FIG. **4**A illustrates an SDN controller used during commissioning to detect network loops, where the SDN controller is removed or placed offline during post-commissioning operation, according to one embodiment.

FIG. **4**B illustrates the SDN controller offline and disconnected with port A of the first network switch disabled to eliminate a previously detected network loop, according to one embodiment.

FIG. **5** illustrates a network architecture with an SDN controller that implements an OFDP authentication protocol, according to one embodiment.

FIG. **6** illustrates an SDN controller with a loop detection subsystem to detect a ring network loop formed between three network switches, according to one embodiment.

DETAILED DESCRIPTION

Communication networks (such as operational technology (OT) networks) may utilize a variety of technologies, including software-defined network (SDN) networking technologies. In an SDN, a controller may regulate communi-

cations on the network. SDN networking technologies offer a variety of advantages, such as deny-by-default security, latency guarantees, deterministic transport capabilities, redundancy, fail-over planning, etc. An SDN allows a programmatic change control platform, which allows an entire communication network to be managed as a single asset, simplifies the understanding of the network, and enables continuous monitoring of a network. In an SDN, the systems that decide where the traffic is sent (i.e., the control plane) are separated from the systems that perform the forwarding of the traffic in the network (i.e., the data plane).

The control plane may be used to optimize the usage of network resources by creating specific data flows through the communication network. A data flow, as the term is used herein, refers to a set of parameters used to match and take action based on network packet contents. Data flows may permit dedicated paths based on a variety of criteria that offer significant control and precision to operators of the network. In contrast, in large traditional networks, trying to match a network-discovered data path with an application-desired data path may be a challenging task involving changing configurations in many devices. To compound this problem, the management interfaces and feature sets used on many devices are not standardized. Further, network administrators often need to reconfigure the network to avoid loops, gain route convergence speed, and prioritize certain classes of applications.

Significant complexity in managing a traditional network in the context of an OT network arises from the fact that each network device (e.g., a switch or router) includes both control logic and data forwarding logic. For example, in a traditional network router, routing protocols such as Routing Information Protocol (RIP) or Open Shortest Path First (OSPF) constitute the control logic that determines how a packet should be forwarded. The paths determined by the routing protocol are encoded in routing tables, which are then used to forward packets. Similarly, in a Layer **2** device such as a network bridge (or network switch), configuration parameters and/or a Spanning Tree Algorithm (STA) constitute the control logic that determines the path of the packets. Thus, the control plane in a traditional network is distributed in a switching fabric (network device), and as a consequence, changing the forwarding behavior of a network involves changing the configurations of many (potentially all) network devices.

In contrast, in an SDN, a controller embodies the control plane and determines how packets (or frames) should flow (or be forwarded) in the network. The controller communicates this information to the network devices, which constitute the data plane. The controller may set forwarding tables in network devices that establish how data is to be routed. This enables centralized configuration and management of a network. In addition to simplifying the management of a network, an SDN architecture may also enable monitoring and troubleshooting features that may be beneficial for use in OT networks. Such features may include, but are not limited to, mirroring a data-selected flow rather than mirroring a whole port; alarming on bandwidth when a communication channel gets close to saturation; providing metrics (e.g., counters and meters for quality of service, packet counts, errors, drops, or overruns, etc.) for a specified flow; and permitting the monitoring of specified applications rather than monitoring based on virtual local area networks (VLAN) or media access control (MAC) addresses.

Configuration of an SDN may be challenging because each communication flow between hosts must be configured or the traffic between the hosts may be blocked due to the deny-by-default security policy. The inventors of the present application have recognized that portions of the configuration of an SDN may be automated in various ways consistent with the present disclosure to reduce the configuration burden. In various embodiments, an SDN controller may be configured to detect network loops. Further, various embodiments may include an SDN controller that, upon detection of a network loop, takes steps to avoid or eliminate traffic on the network loop.

In some aspects, the techniques described herein relate to an SDN controller that includes a loop detection subsystem. The loop detection subsystem operates to place a network flow on a first switch to forward any received open flow discovery protocol (OFDP) packets to the SDN controller and cause the first switch to egress a query OFDP packet out of a first port of the first switch. The loop detection subsystem detects that the first port on the first switch is attached to a network loop based on the query OFDP packet being ingressed by the first port of the first switch. In response, the SDN controller implements a remedial action to address the detected network loop.

The remedial action implemented by the loop detection subsystem may include the transmission of a notification indicating the existence of a network loop and/or disabling the first port on the first switch. The query OFDP packet may be initially egressed in response to a link-up event detected by the first port of the first switch. That is, the SDN controller may operate to detect a network loop by, in part, generating a query OFDP packet each time a link-up event is detected on each port of each switch within the network. Accordingly, the SDN controller may operate to evaluate each new connection to determine if a loop has been created. The identification of a loop may result in the port being disabled to break the network loop and/or a warning being provided.

In some instances, the SDN controller may cause a query OFDP packet to be egressed on a periodic basis, such as at the expiration of an automatically resetting timer. For example, the SDN controller may evaluate one or more ports on one or more switches within the network every few seconds, minutes, hours, etc.

In some instances, the SDN controller may cause a query OFDP packet to be egressed in response to a traffic monitoring subsystem detecting an increase in network traffic that exceeds a threshold level. In such embodiments, unexpected or abnormal increases in network traffic may prompt the SDN controller to test for network loops on one or more ports of one or more network switches.

In some implementations, the SDN controller is used only during the commissioning or setup of a network. As described above, the SDN controller may be used to configure the network switches and other devices in the network. After commissioning, the SDN controller may be removed from the network or otherwise disabled from operation. In such embodiments, the loop detection and remediation techniques, systems, and methods described herein are used during commissioning and then disabled or no longer implemented during the post-commissioning or production phase of the network operation. Explicit disabling of the loop detection approaches described herein may be used to prevent malicious attackers from using OFDP packets to disable ports or switches within an operational network. In some embodiments, switches may be configured to explicitly ignore OFDP packets during a post-commissioning phase (e.g., during a production or normal operational phase).

In other embodiments, the SDN controller may cause one or more switches or other computing devices within the network to continue to implement the loop detection and remediation approaches described herein. For example, the SDN controller may program the first switch to implement the functions of the loop detection subsystem after commissioning, such that loop detection continues to be implemented after the SDN controller is disconnected during production.

The presently described systems and methods can be used to create or operate a communications network that includes a data network to convey data communications between computing devices, one or more switches, and an SDN controller (at least during commissioning, setup, or maintenance). The SDN controller may include an OFDP packet generation subsystem, a loop detection subsystem, and a remediation subsystem. In some embodiments, the SDN controller may further include an OFDP authentication subsystem, as described herein. The embodiments of the disclosure will be best understood by reference to the drawings. It will be readily understood that the components of the disclosed embodiments, as generally described and illustrated in the figures herein, could be arranged and designed in a wide variety of different configurations. Thus, the following detailed description of the embodiments of the systems and methods of the disclosure is not intended to limit the scope of the disclosure, as claimed, but is merely representative of possible embodiments of the disclosure. In addition, the steps of a method do not necessarily need to be executed in any specific order, or even sequentially, nor do the steps need to be executed only once, unless otherwise specified.

In some cases, well-known features, structures, or operations are not shown or described in detail. Furthermore, the described features, structures, or operations may be combined in any suitable manner in one or more embodiments. It will also be readily understood that the components of the embodiments, as generally described and illustrated in the figures herein, could be arranged and designed in a wide variety of different configurations. For example, throughout this specification, any reference to "one embodiment," "an embodiment," or "the embodiment" means that a particular feature, structure, or characteristic described in connection with that embodiment is included in at least one embodiment. Thus, the quoted phrases, or variations thereof, as recited throughout this specification are not necessarily all referring to the same embodiment.

Several aspects of the embodiments disclosed herein may be implemented as software modules. As used herein, a software module may include any type of computer instruction or computer-executable code located within a memory device that is operable in conjunction with appropriate hardware to implement the programmed instructions. A software module may, for instance, comprise one or more physical or logical blocks of computer instructions, which may be organized as a routine, program, object, component, data structure, etc., that performs one or more tasks or implements particular data types.

Embodiments may be provided as a computer program product including a non-transitory machine-readable medium having stored thereon instructions that may be used to program a computer or other electronic device to perform processes described herein. The non-transitory machine-readable medium may include but is not limited to, hard drives, ROMs, RAMs, EPROMs, EEPROMs, solid-state memory devices, or other types of machine-readable media suitable for storing electronic instructions. In some embodiments, the computer or another electronic device may include a processing device such as a microprocessor, microcontroller, logic circuitry, or the like. The processing device may further include one or more special-purpose processing devices such as an application-specific integrated circuit (ASIC), a programmable logic device (PLD), a field programmable gate array (FPGA), or another customizable or programmable device.

FIG. **1** illustrates a conceptual representation of a software-defined network (SDN) system **100** including a control plane **102**, a data plane **104**, and a plurality of data consumer/producer devices **116***a*-**116***c* consistent with embodiments of the present disclosure. The control plane **102** directs the flow of data through the data plane **104**. More specifically, an SDN controller **112** may communicate with a plurality of network devices **106***a*-**106***d* via an interface **114** to communicate data flows **118** that are implemented by each network device **106***a*-**106***d*. The controller **112** may specify rules for routing traffic through the data plane **104** based on a variety of criteria.

Each network device **106***a*-**106***d* may store a plurality of data flows used to route traffic. In one specific embodiment, the data flows may be stored in or implemented by a Field Programmable Gate Array (FPGA). An FPGA may be a logical choice for use in network devices because FPGAs may provide both the configurability and speed suitable for SDN applications. The data flows may be received from the controller **112**. Corruption of the data flows may result in data packets being misdirected or dropped. Misdirecting or dropping data packets may result in the maloperation of equipment that utilizes information in the misdirected or dropped data packets.

As illustrated, the data plane **104** includes a plurality of network devices **106***a*-**106***d* in communication with one another via a plurality of physical links **120***a*-**120***d*. In various embodiments, the network devices **106***a*-**106***d* may be embodied as switches, multiplexers, and other types of network devices. The physical links **120***a*-**120***d* may be embodied as Ethernet, fiber optic, and other forms of data communication channels. As illustrated, the physical links **120***a*-**120***d* between the network devices **106***a*-**106***d* may provide redundant connections such that a failure of one of the physical links **120***a*-**120***d* is incapable of completely blocking communication with an affected network device. In some embodiments, the physical links **120***a*-**120***d* may provide an N−1 redundancy or better.

The data consuming/producing devices **116***a*-**116***c* may represent a variety of devices that produce or consume data within an electric power transmission and distribution system. For example, data-consuming/producing devices **116***a*-**116***c* may be embodied as a pair of transmission line relays configured to monitor an electrical transmission line. The transmission line relays may monitor various aspects of the electric power flowing through the transmission line (e.g., voltage measurements, current measurements, phase measurements, synchrophasors, etc.) and may communicate the measurements to implement a protection strategy for the transmission line. Traffic between the transmission line relays may be routed through the data plane **104** using a plurality of data flows implemented by the controller **112**. The data consuming/producing devices **116***a*-**116***c* may be embodied by a wide range of devices consistent with embodiments of the present disclosure.

Applications **110***a*-**110***c* represent a variety of applications operating in an application plane. The controller **112** may expose an application programming interface (API) that the applications **110***a*-**110***c* can use to configure the data plane **104**. In this scenario, the controller **112** may act as an interface to the data plane **104** while the control logic resides in the applications **110***a*-**110***c*. The configuration of the controller **112** and applications **110***a*-**110***c* may be tailored to meet a wide variety of specific needs.

The controller **112** may support automated configuration **108** based on approved services, parameters, and data metrics. Upon detection of a communication associated with an approved service and parameters, the controller **112** may generate corresponding data flow(s) **118**. In some embodiments, the automated configuration **108** may occur during a commissioning phase, while in other embodiments, an automated configuration **108** may be ongoing while system **100** is in operation.

OFDP is a derivative of Link Layer Discovery Protocol (LLDP) that uses a different destination multicast MAC (media access control) address. The different MAC address ensures the packets are forwarded past traditional switches that would otherwise drop LLDP packets so true links between programmable switches can be discovered.

FIG. **2**A illustrates a block diagram of an SDN architecture **200** that includes an SDN controller **210**, a first network switch **220**, and a second network switch **230**, according to one embodiment. During the commissioning phase of the network, the SDN controller **210** may not know about links between ports **225** of the first network switch **220** and ports **235** of the second network switch **230**.

FIG. **2**B illustrates a flow chart of an example method for determining a network model using OFDP packets, according to one embodiment. For example, the illustrated method can be used to identify a link between one of the ports **225** of the first network switch **220** and one of the ports **235** of the second network switch **230** in the SDN architecture **200** of FIG. **2**A.

As illustrated, the SDN controller **210** instructs, at **290**, the second network switch **230** to forward any OFDP packets to the SDN controller **210** along with identification of which port ingressed the packet. The SDN controller **210** may generate (e.g., generate itself or cause the first network switch **220** to generate) an OFDP packet, at **292**. The SDN controller **210** may instruct, at **294**, the first network switch **220** to egress the OFDP packet out of port 1A **221**.

In the event that a connection exists between port 1A **221** of the first network switch **220** and port 2B **231** of the second network switch **230**, the second network switch **230** will forward, at **296**, the OFDP packet to the SDN controller **210** with an indication that the packet was ingressed in port 2B **231**. The SDN controller **210** updates the network data model, at **298**, to include the link between port 1A **221** of the first network switch **220** and port 2B **231** of the second network switch **230**.

FIG. **2**C illustrates an updated network model of the SDN architecture **201** in FIG. **2**A based on a detected link **240** between port 1A **221** of the first network switch **220** and port 2B **231** of the second network switch **230**, according to one embodiment. OFDP packets are used by SDN controllers, as described above, to discover links between devices in a communications network.

Network loops are a problem that frequently occurs in traditional switch networks, sometimes resulting in what is referred to as a broadcast storm. A broadcast storm is where all multicast and broadcast packets (e.g., ethernet frames) are repeatedly replicated within the network. Broadcast storms consume bandwidth on the network and can even result in degradation to the point that the network is rendered nonfunctional. Network loops can also appear in SDN networks, but they are often isolated to only one specific traffic type or a subset of specific traffic types, which makes the network loops much harder to detect.

FIG. **3**A illustrates another block diagram of an SDN architecture **300** that includes a controller **310**, a switch **320**, and a traditional network **330**, according to one embodiment. The controller **310** leverages components, protocols, and packet types relating to OFDP link discovery to identify and remediate network loops.

As illustrated, the controller **310** manages the switch **320**, which is connected via port A **321** to port B **331** of the traditional (e.g., unmanaged) network **330** that may include any number of network and/or computing devices. One or more network loops may exist in the traditional network **330**. For example, a network loop may be accidentally created by the simple connection of a cable between two ports of the same unmanaged switch. In such a situation, port A **321** of the switch **320** managed by the controller **310** is connected to the network loop. The SDN architecture **300** may include any number of other managed switches and network connections that are not connected to the network loop. In fact, the switch **320** may even be connected to other ports within the traditional network **330** that are not part of the network loop. The controller **310** may be configured to detect the network loop and disable the port connected to the network loop without disabling or disrupting other connections and ports within the network.

FIG. **3**B illustrates a flow chart of an example method to detect and remediate a network loop in the SDN architecture **300** of FIG. **3**A, according to one embodiment. The controller **310** may instruct (e.g., program or place a network flow on) the switch **320** to cause the switch **320** to forward any OFDP packets it receives to the controller **310**, at **391**. The controller **310** may generate, at **392**, or cause the switch **320** to generate, a query OFDP packet with a chasse ID of the switch **320** and a port ID of port A **321**. The OFDP packet is referred to as a "query" OFDP packet in that it is used as part of the inquiry to discover network loops. The query OFDP packet may be implemented according to the OFDP subset of the LLDP.

The controller **310** instructs, at **393**, the switch **320** to egress the query OFDP packet out of port A **321** in response to a trigger event. The trigger event may be, for example, a timer expiration, detection of a link-up event when a cable is plugged into a port, detection of an abnormal increase in network traffic (e.g., network traffic is detected above a threshold level or detected as increases above a threshold rate of increase). The switch **320** egresses the query OFDP packet out of port A **321**, at **394**. The controller **310** detects that a network loop exists based on the same query OFDP packet being ingressed via port A **321** of the switch **320**, at **395**. Accordingly, the controller **310** detects the network loop because the query OFDP packet is egressed out of port A **321** and returns to port A **321** for ingress after a short period of time.

In many instances, the network loop may result in the query packet being ingressed many dozens of times in a very short period of time. Each detected event may indicate a network loop. A notification subsystem of the controller **310** may consolidate the events into a single notification to report, at **399**, the existence of the network loop and/or report that port A **321** of the switch **320** has been disabled, at **398**, or otherwise communicatively disconnected from the port B **331** of the traditional network **330**.

FIG. **3**C illustrates the detection of a network loop **350** that includes port A **321** of the switch **320**, according to one embodiment. The link between port A **321** and port B **331** is severed to preserve the integrity and functionality of other

connections in the network (not shown) and/or otherwise eliminate the continuous replication of broadcast and multicast frames. Severing the link between port A **321** and port B **331** does not fix or remove the network loop **350** in the traditional network **330**. Rather, severing the link prevents the broadcast storm within the network.

FIG. **4**A illustrates an SDN controller **410** used during the commissioning of an SDN network **400** to detect a network loop **450**, where the SDN controller **410** is removed or placed offline during post-commissioning operation, according to one embodiment. In the illustrated embodiment, a switch **420** includes port A **421** and port B **422**. Port A **421** of the switch **420** provides a link to components within a first traditional network **430** via port C **432**. Port B **422** of the switch **420** provides a link to components within the second traditional network **440**. The first traditional network **430** is independent from the second traditional network **440**.

The first traditional network **430** is illustrated with a network loop **450**. Utilizing the systems and methods described herein, including the method illustrated in FIG. **3**B, the SDN controller **410** may generate OFDP packets to query the functionality of port B **422** to discover that no network loops are present in the second traditional network **440**. The SDN controller **410** may generate OFDP packets to query the functionality of port A **421** and discover that the network loop **450** results in the query OFDP packet being returned to port A **421** after going through the network loop **450** in the first traditional network. As described herein, the SDN controller **410** may remediate the problem by disconnecting or disabling port A **421** during the commissioning of the SDN network **400** so as to eliminate the network loop **450** from impacting the performance of the SDN network **400**, or at least the programmable portions of the SDN network **400**. The SDN network **400** can be placed into production and the SDN controller **410** can be removed with port A **421** disabled.

FIG. **4**B illustrates the SDN controller **410** offline and disconnected with port A **421** of the network switch **420** disabled to eliminate a previously detected network loop in the first traditional network **430**, according to one embodiment. The SDN-managed switch **420** maintains a link between port B **422** and port D **433** of the second traditional network **440** since this link was not impacted by the detected network loop **450** in the first traditional network **430**. Similarly, any other SDN-managed switches (not shown) and other components (not shown) in the SDN network **400** may be unaffected by the disabled port A **421**, such that most of the SDN network **400** is able to function without interruption.

FIG. **5** illustrates a network architecture **500** with an SDN controller **510** that implements an OFDP authentication protocol, according to one embodiment. As illustrated, the SDN controller **510** may include an OFDP authentication module **512** that facilitates the authentication of OFDP packets. A switch **520** may include a corresponding OFDP authentication module **525** to authenticate OFDP packets received from the controller **510**. For example, the controller **510** may add or otherwise utilize a cryptographic hash to prove that the controller **510** is the source of a given OFDP packet. The switch **520** may process the first instance of the OFDP packet to validate its legitimacy. Once validated, the OFDP packet may be transmitted within the SDN network and, if a network loop **550** is present, be returned to the switch **520** via the link between port A **521** and port B **531** of a traditional network **530**.

As in previous embodiments, the detected network loop **550** may result in a notification or disabling of the link between port A **521** and port B **531**. The cryptographic hash, or alternative authentication schema, ensures that malicious attacks cannot be implemented in which fake OFDP packets are generated to erroneously indicate the existence of network loops, which might result in ports being disabled even though no actual network loop exists.

FIG. **6** illustrates an SDN controller **610** of an SDN network **600** with a loop detection subsystem **611** to detect a network loop, as described herein. The SDN controller **610** detects a network loop and remediates the SDN network by disabling one or more ports or connections within the network **600** to prevent continuous replication or circulation of broadcast and multicast frames within the network **600**.

The SDN network controller **610** includes the loop detection subsystem **611** to detect and remediate the network loop. As illustrated, the loop detection subsystem **611** includes an OFDP packet generation subsystem **612**, an OFDP authentication subsystem **613**, and a remediation subsystem **614**. The remediation subsystem **614** includes a notification subsystem **615** and/or a network modification subsystem **616**.

The OFDP packet generation subsystem **612** may operate to generate a query OFDP packet to cause a network switch **620** to egress the query OFDP packet out of port. The loop detection subsystem **611** may place a network flow on a network switch within the network **600** to cause the network switch to forward any received OFDP packets to the SDN controller **610** with information identifying the ingress port.

The OFDP authentication subsystem **613** facilitates the authentication of OFDP packets by, for example, adding a cryptographic hash to all OFDP packets. Network switches within the network **600** can use the cryptographic hash of each received OFDP packet to confirm or validate authenticity. The loop detection subsystem **611** may be configured to detect a network loop in response to the query OFDP packet being received by the same port used to egress the query OFDP packet.

In response to the detection of an undesirable network loop, the remediation subsystem **614** may transmit, via the notification subsystem **615**, a notification to a user indicating the existence of an undesirable network loop and/or disable one or more port or connection of one or network switches within the network **600** via the network modification subsystem **616**.

While specific embodiments and applications of the disclosure have been illustrated and described, it is to be understood that the disclosure is not limited to the precise configurations and components disclosed herein. Accordingly, many changes may be made to the details of the above-described embodiments without departing from the underlying principles of this disclosure. The scope and understanding of this disclosure should, therefore, be determined to encompass at least the following claims.

What is claimed:

1. A software-defined network (SDN) controller, comprising:
- a loop detection subsystem to:
  - place a network flow on a first switch to forward any received open flow discovery protocol (OFDP) packets to the SDN controller, and
  - cause the first switch to egress a query OFDP packet out of a first port of the first switch;
  - detect that the first port on the first switch is attached to a network loop based on the query OFDP packet being ingressed by the first port of the first switch; and

  - implement a remedial action in response to the detected network loop.

2. The SDN controller of claim **1**, wherein the remedial action implemented by the loop detection subsystem comprises transmission of a notification indicating the existence of a network loop involving the first port on the first switch.

3. The SDN controller of claim **1**, wherein the remedial action implemented by the loop detection subsystem comprises disabling the first port on the first switch.

4. The SDN controller of claim **1**, wherein the query OFDP packet is caused to be egressed in response to a link-up event detected by the first port of the first switch.

5. The SDN controller of claim **1**, wherein the query OFDP packet is caused to be egressed in response to the expiration of an automatically resetting timer, such that new query OFDP packets are periodically egressed.

6. The SDN controller of claim **1**, wherein the query OFDP packet is caused to be egressed in response to a traffic monitoring subsystem detecting an increase in network traffic that exceeds a threshold level.

7. The SDN controller of claim **1**, wherein the SDN controller is configured to disable the network flow on the first switch after commissioning, such that the first network flow is not implemented by the first switch in production.

8. The SDN controller of claim **1**, wherein the SDN controller is configured to program the first switch to implement the functions of the loop detection subsystem after commissioning, such that loop detection continues to be implemented after the SDN controller is disconnected during production.

9. The SDN controller of claim **1**, further comprising:
- an authentication subsystem to facilitate authentication of OFDP packets, including the query OFDP packet.

10. A system, comprising:
- a data network to convey data communications between computing devices;
- at least one switch, including a first switch; and
- a software-defined network (SDN) controller in communication with the network, the SDN controller including:
  - an open flow discovery protocol (OFDP) packet generation subsystem to:
    - generate a query OFDP packet for egress out of a first port of a first switch, and
    - cause the first switch to egress the query OFDP packet out of the first port of the first switch;
  - a loop detection subsystem to:
    - place a network flow on the first switch to forward any OFDP packets to the SDN controller, and
    - identify the first port on the first switch as being attached to a network loop in response to the query OFDP packet being received by the first port of the first switch; and
  - a remediation subsystem including at least one of:
    - a notification subsystem to transmit a notification to a user indicating the existence of a network loop involving the first port on the first switch, and
    - a network modification subsystem to disable the first port on the first switch to break the network loop.

11. The system of claim **10**, wherein the remediation subsystem comprises both the notification subsystem to transmit the notification and the network modification subsystem to disable the first port on the first network switch.

12. The system of claim **10**, wherein the SDN controller further comprises:
- an authentication subsystem to facilitate authentication of OFDP packets, including the query OFDP packet; and

wherein the first switch is programmed to authenticate received OFDP packets, including the query OFDP packet prior to egressing the query OFDP packet out of the first port.

13. The system of claim **12**, wherein the authentication subsystem operates to add a cryptographic hash to all OFDP packets, including the query OFDP packet.

14. The system of claim **10**, wherein the OFDP packet generation subsystem causes the query OFDP packet to be egressed in response to a link-up event detected on the first port of the first switch.

15. The system of claim **10**, wherein the OFDP packet generation subsystem causes the query OFDP packet to be egressed in response to the expiration of a timer, such that new query OFDP packets are periodically egressed.

16. The system of claim **10**, wherein the OFDP packet generation subsystem causes the query OFDP packet to be egressed in response to a traffic monitoring subsystem detecting an increase in network traffic that exceeds a threshold level.

17. The system of claim **10**, wherein the loop detection subsystem places the network flow on the first switch to forward any OFDP packets to the SDN controller only during a network commissioning phase, and wherein the loop detection subsystem places a different flow on the first switch after commissioning to cause the first switch to ignore OFDP packets during a post-commissioning, production phase.

18. A method to detect and remediate a network loop, comprising:

instructing a first switch to forward any open flow discovery protocol (OFDP) packets to a software-defined network (SDN) controller;

generating a query OFDP packet for egress out of a first port of the first switch;

causing the first switch to egress the query OFDP packet out of the first port;

identifying the first port on the first switch as being attached to a network loop in response to the query OFDP packet being received by the first port of the first switch; and

disabling the first port on the first switch to break the network loop.

19. The method of claim **18**, further comprising:

adding a cryptographic hash to the query OFDP packet to facilitate authentication by the first switch.

20. The method of claim **18**, further comprising:

transmitting a notification to a user indicating the existence of the network loop involving the first port on the first switch.

21. The method of claim **18**, further comprising:

disconnecting the SDN controller from the first switch after network commissioning is complete, such that network detection and port disabling are implemented only during network commissioning and not during normal operation.

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