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(54) **LAYER-3 SUPPORT IN TRILL NETWORKS**

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CPC H04L 43/50; H04L 43/0852; H04L 43/08; H04B 17/003
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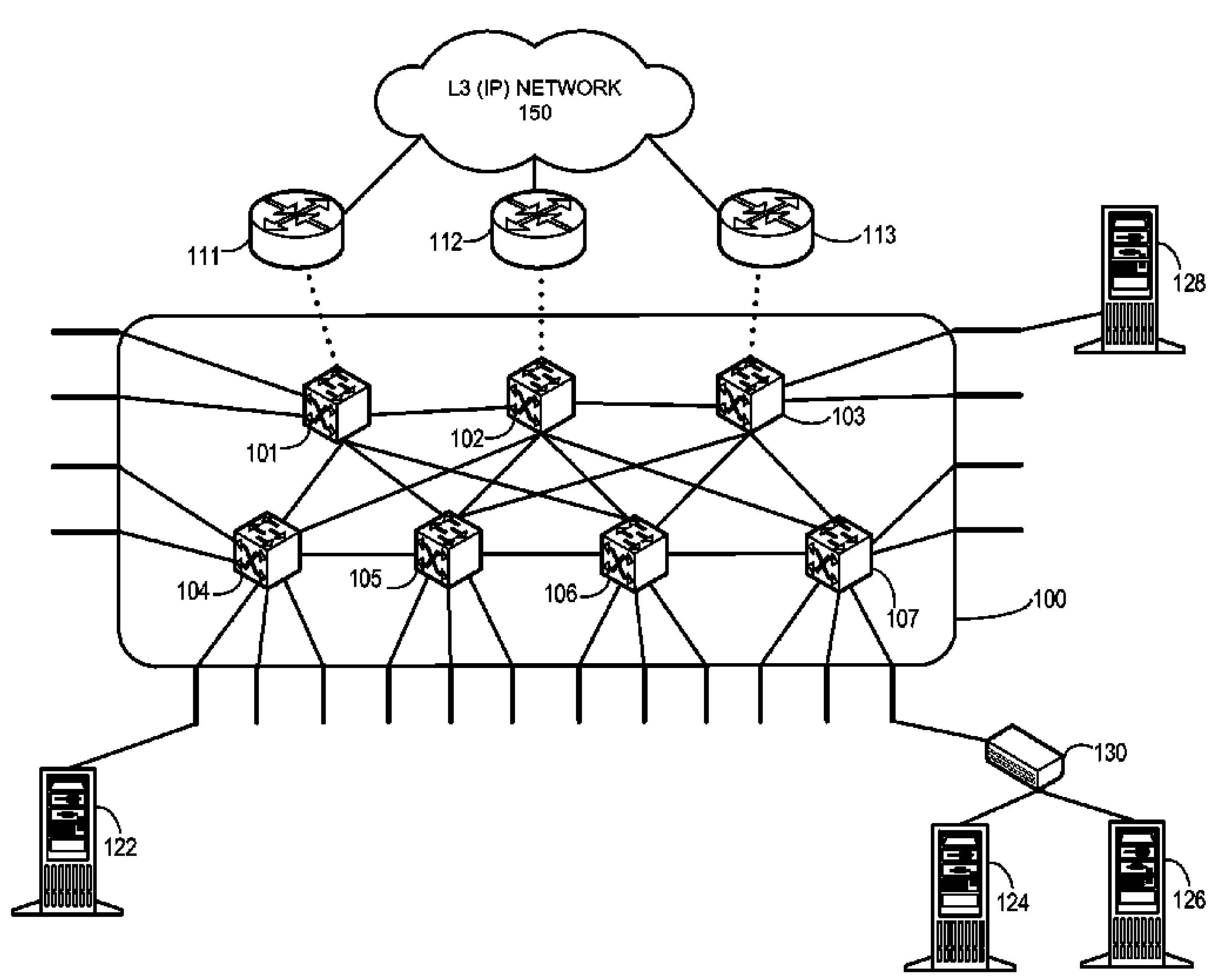
(57) **ABSTRACT**

One embodiment of the present invention provides a switch. The switch includes an IP header processor and a forwarding mechanism. The IP header processor identifies a destination IP address in a packet encapsulated with an inner Ethernet header, a TRILL header, and an outer Ethernet header. The forwarding mechanism determines an output port and constructs a new header for the packet based on the destination IP address. The switch also includes a packet processor which determines whether (1) an inner destination media access control (MAC) address corresponds to a local MAC address assigned to the switch; (2) a destination RBridge identifier corresponds to a local RBridge identifier assigned to the switch; and (3) an outer destination MAC address corresponds to the local MAC address.

20 Claims, 13 Drawing Sheets



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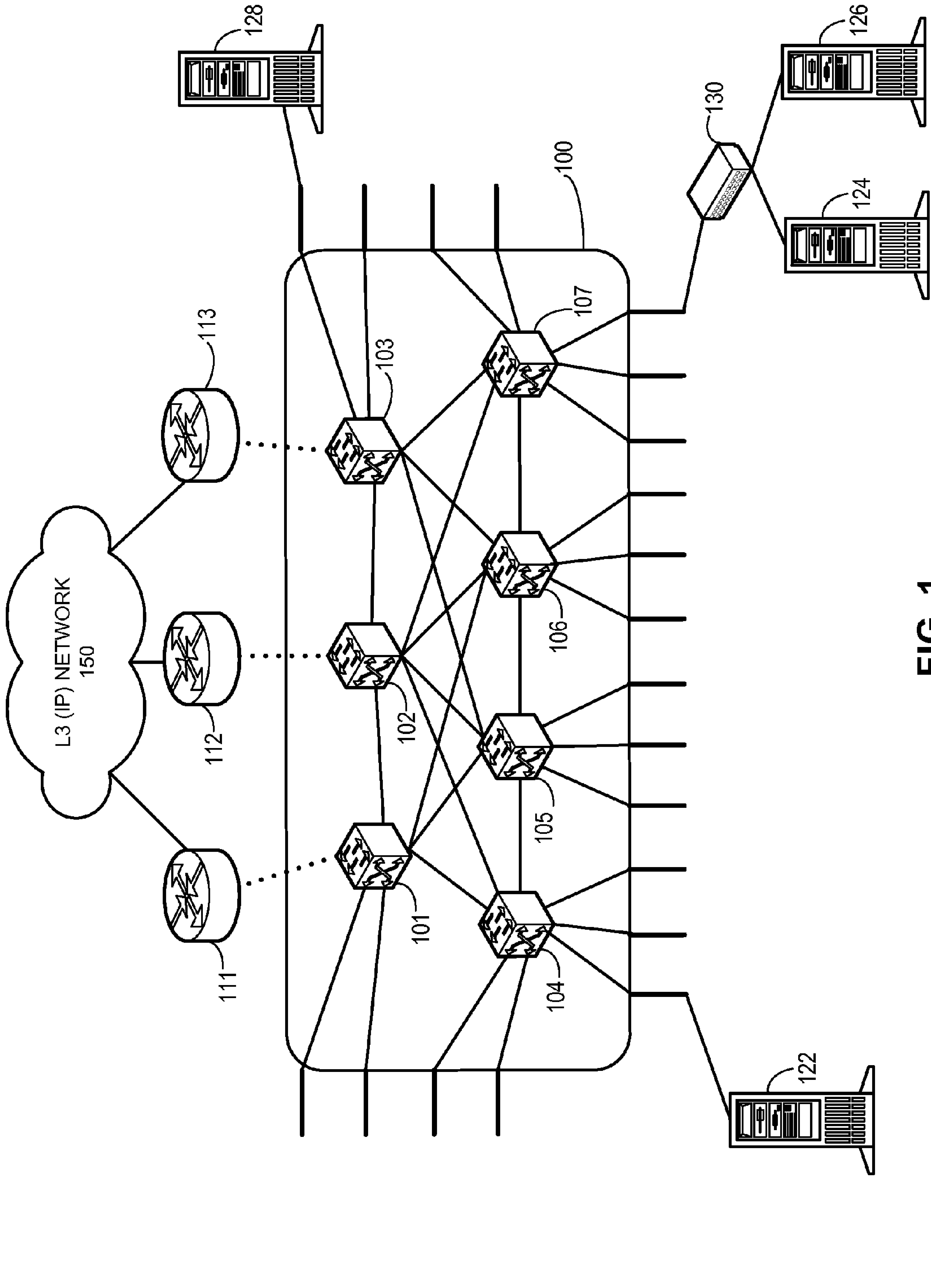

L3 (IP) NETWORK
150
111
112
113
100
101
102
103
104
105
106
107
122
124
126
128
130

FIG. 1

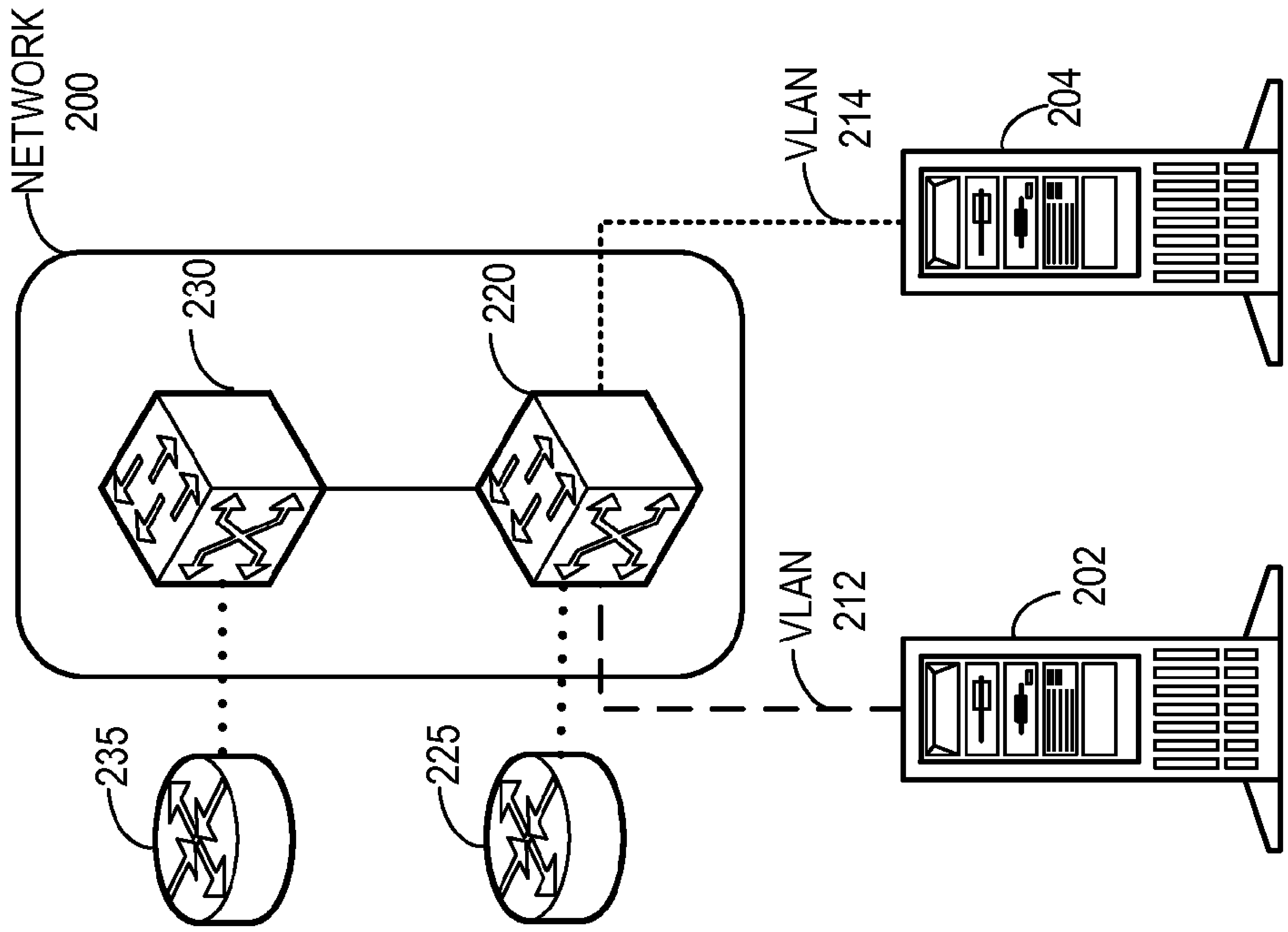

NETWORK 200
230
220
235
225
VLAN 212
VLAN 214
202
204

FIG. 2B

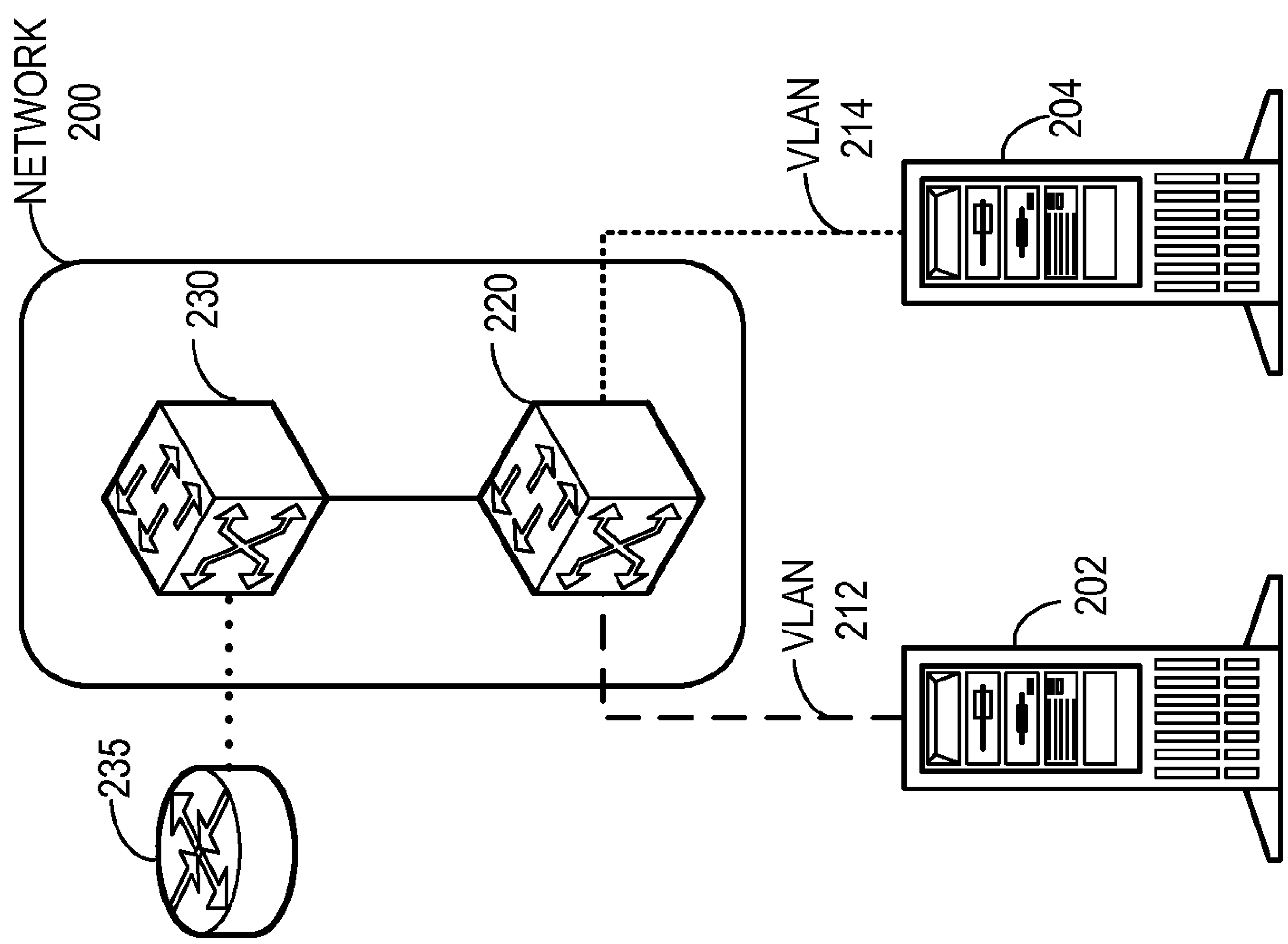
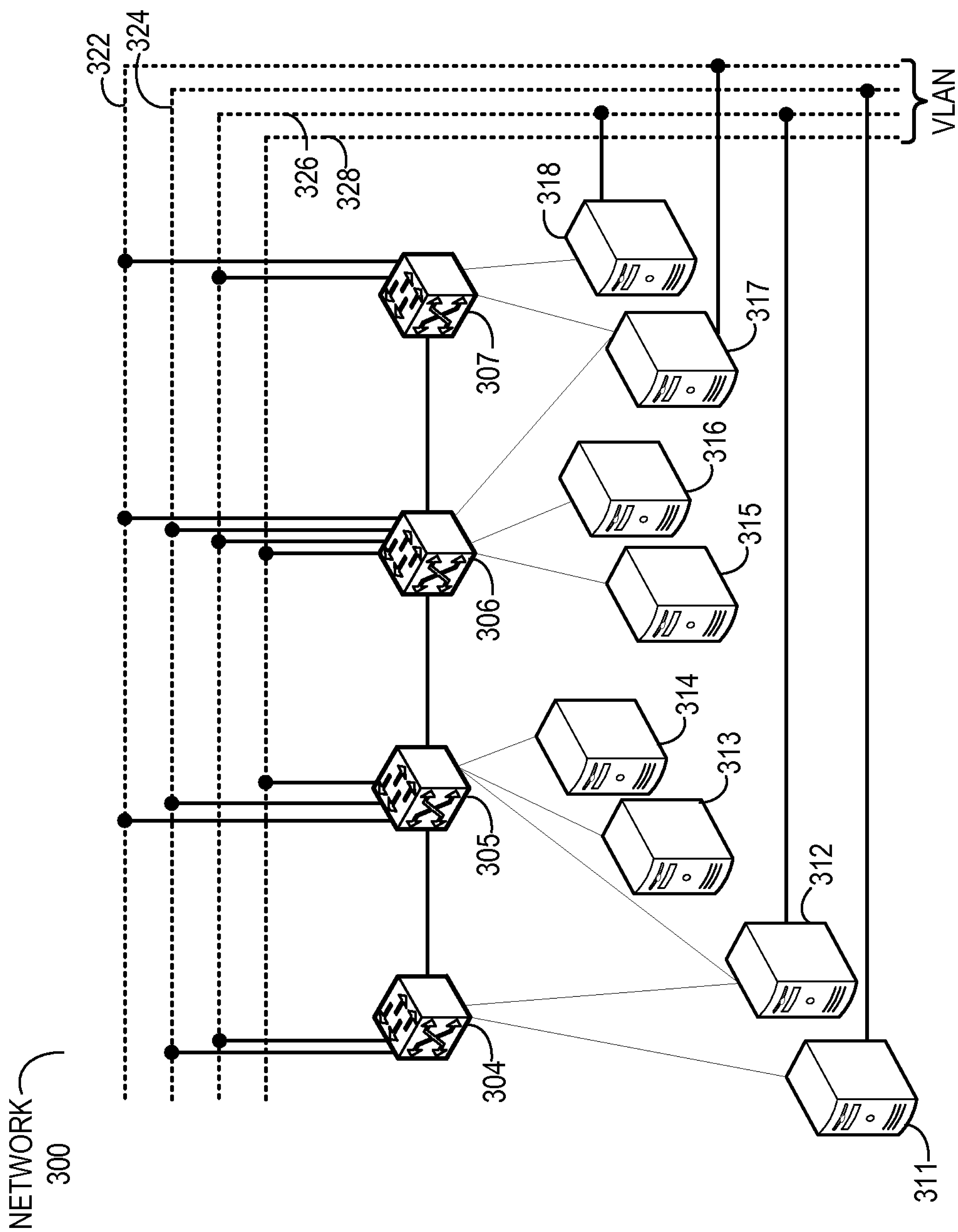

NETWORK 200
230
220
235
VLAN 212
VLAN 214
202
204

FIG. 2A


NETWORK 300
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305
306
307
311
312
313
314
315
316
317
318
322
324
326
328
VLAN

FIG. 3A

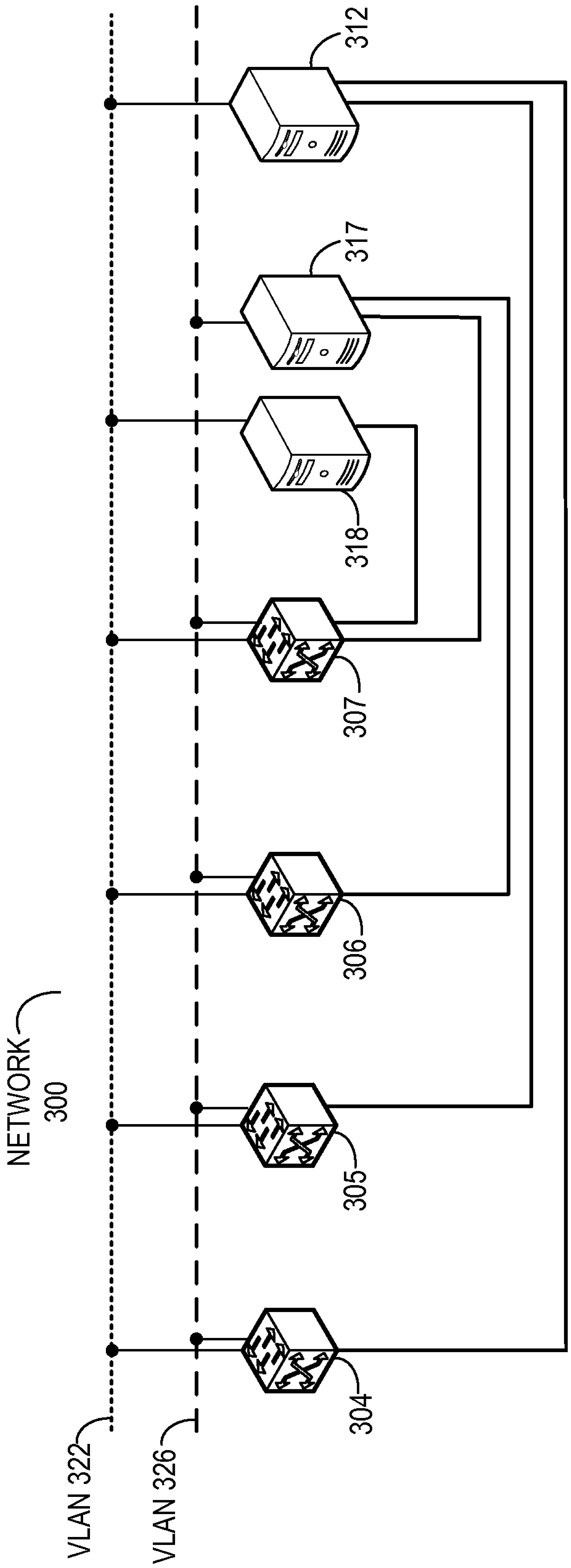


FIG. 3B

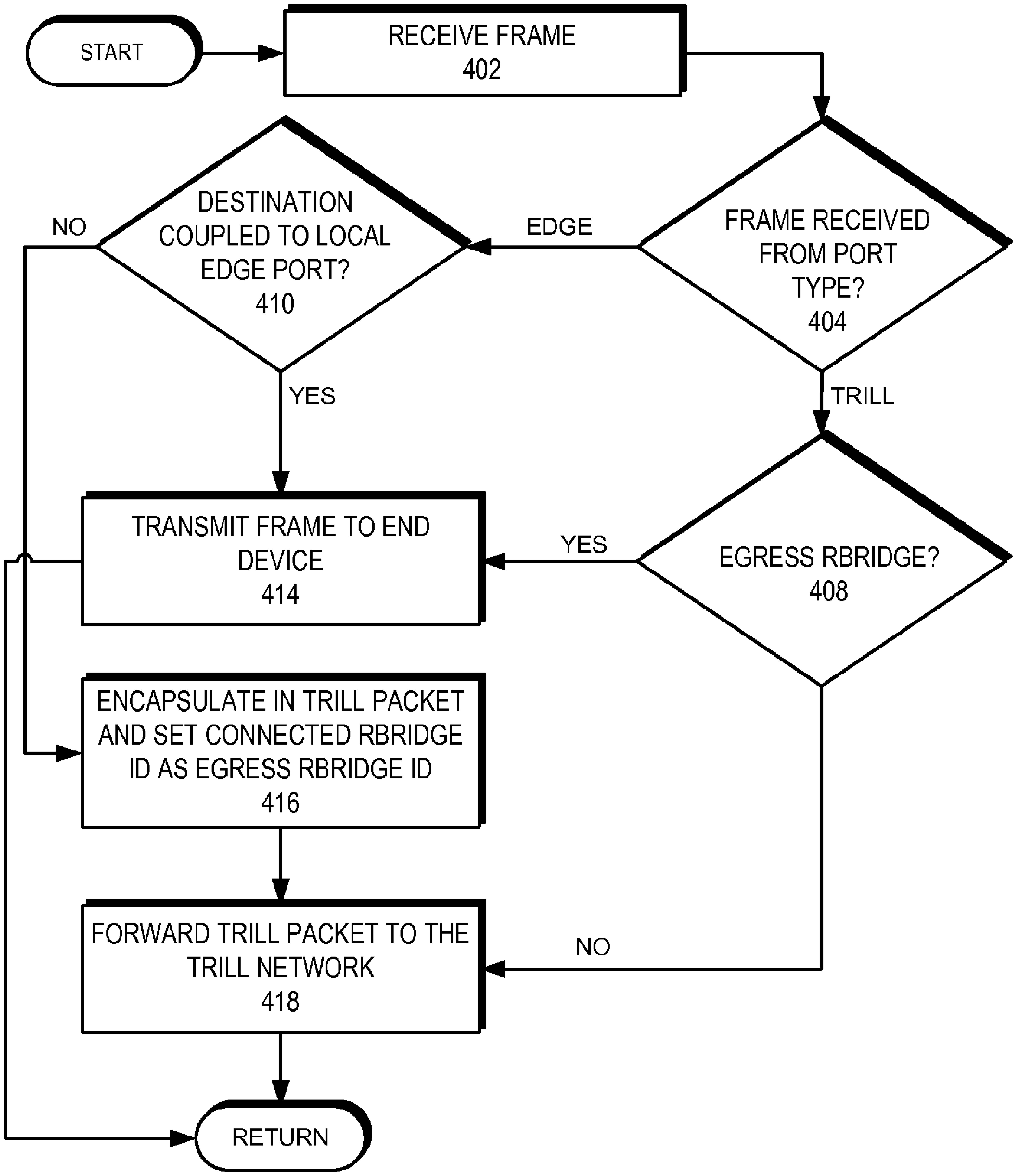

START
RECEIVE FRAME
402
FRAME RECEIVED FROM PORT TYPE?
404
EDGE
DESTINATION COUPLED TO LOCAL EDGE PORT?
410
NO
YES
TRILL
EGRESS RBRIDGE?
408
YES
TRANSMIT FRAME TO END DEVICE
414
ENCAPSULATE IN TRILL PACKET AND SET CONNECTED RBRIDGE ID AS EGRESS RBRIDGE ID
416
NO
FORWARD TRILL PACKET TO THE TRILL NETWORK
418
RETURN

FIG. 4A

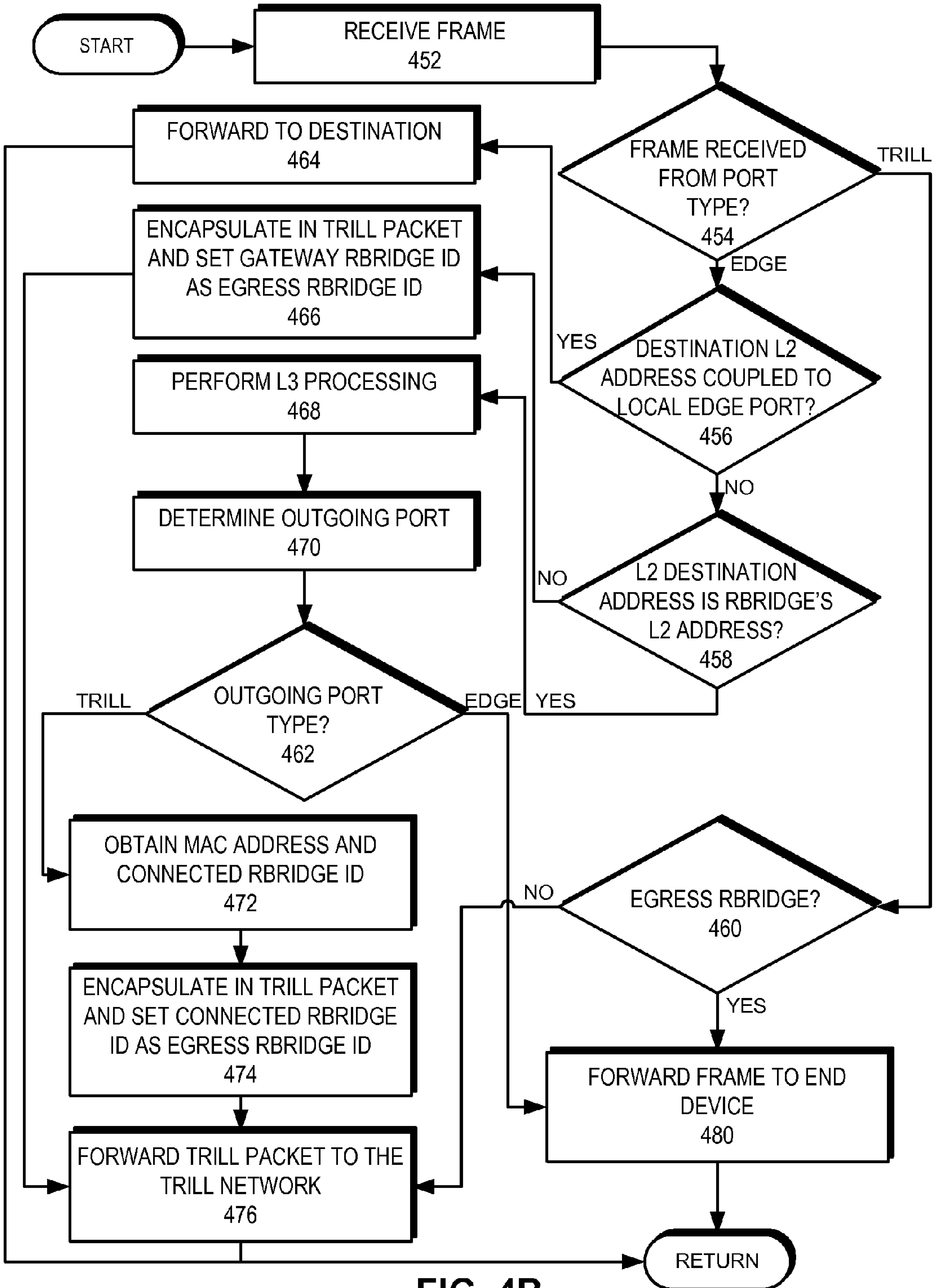

START
RECEIVE FRAME
452
FRAME RECEIVED FROM PORT TYPE?
454
TRILL
EDGE
FORWARD TO DESTINATION
464
ENCAPSULATE IN TRILL PACKET AND SET GATEWAY RBRIDGE ID AS EGRESS RBRIDGE ID
466
YES
DESTINATION L2 ADDRESS COUPLED TO LOCAL EDGE PORT?
456
PERFORM L3 PROCESSING
468
NO
DETERMINE OUTGOING PORT
470
NO
L2 DESTINATION ADDRESS IS RBRIDGE'S L2 ADDRESS?
458
TRILL
OUTGOING PORT TYPE?
462
EDGE
YES
OBTAIN MAC ADDRESS AND CONNECTED RBRIDGE ID
472
NO
EGRESS RBRIDGE?
460
YES
ENCAPSULATE IN TRILL PACKET AND SET CONNECTED RBRIDGE ID AS EGRESS RBRIDGE ID
474
FORWARD FRAME TO END DEVICE
480
FORWARD TRILL PACKET TO THE TRILL NETWORK
476
RETURN

FIG. 4B

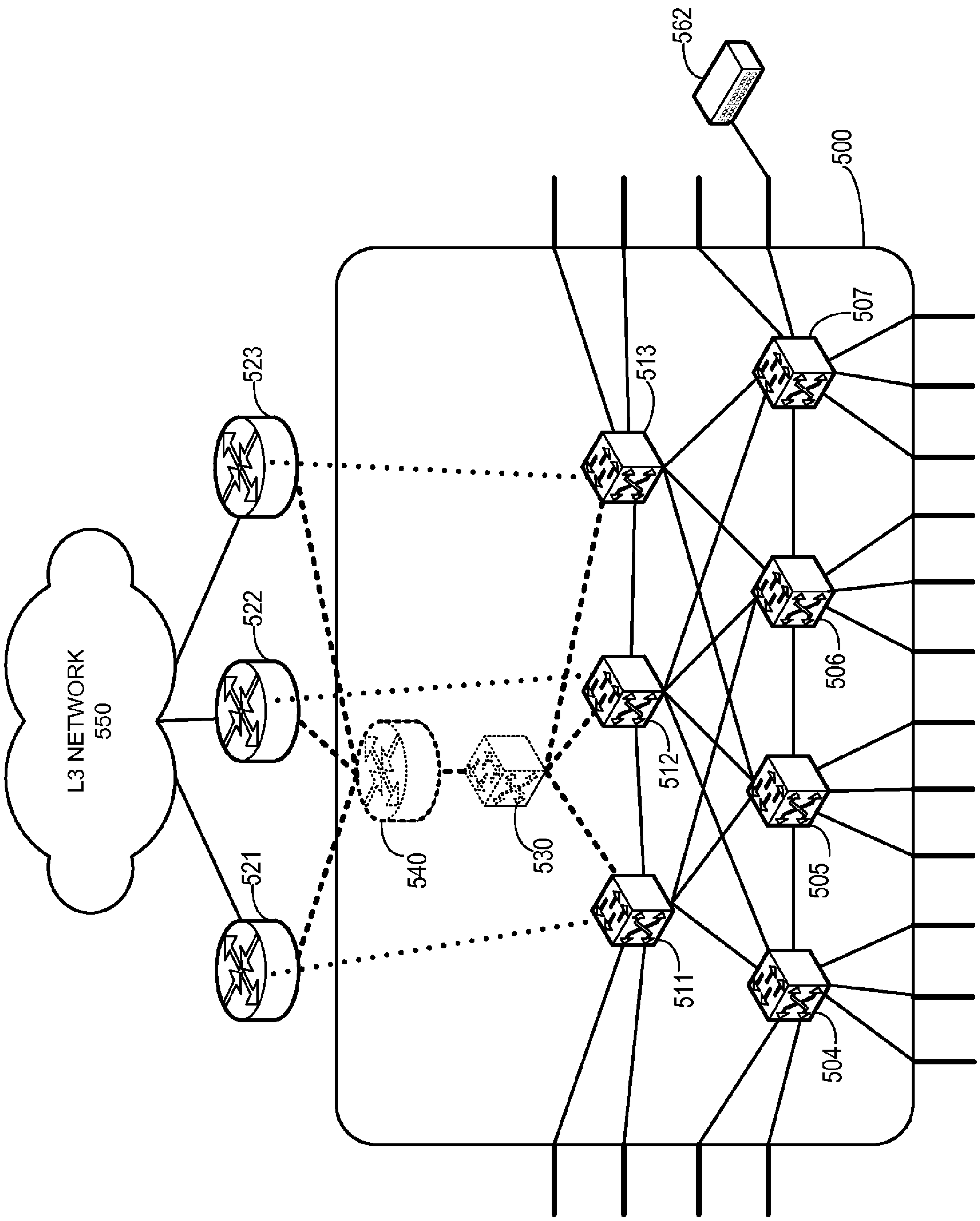

L3 NETWORK
550
521
522
523
540
530
511
512
513
504
505
506
507
500
562

FIG. 5

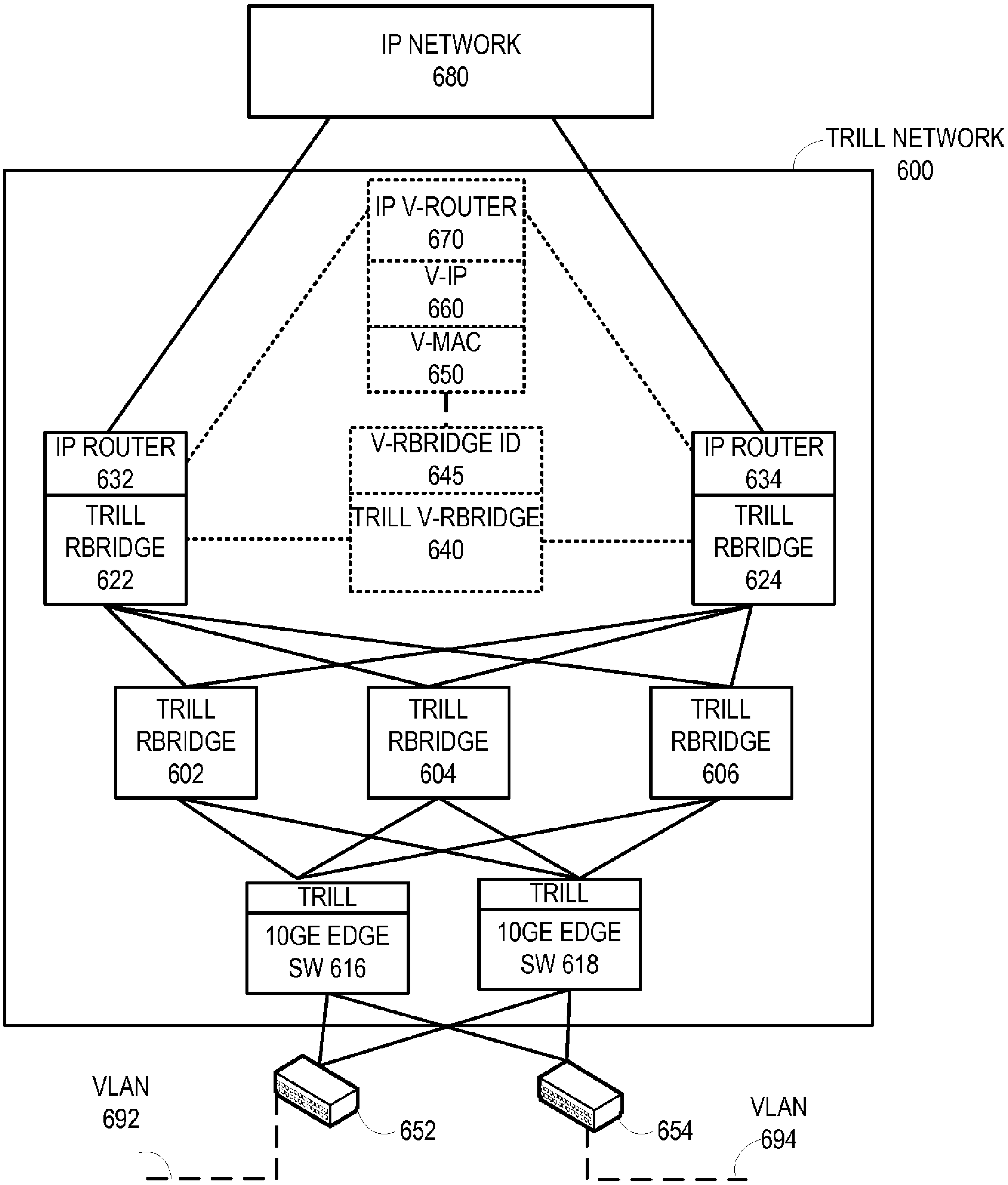
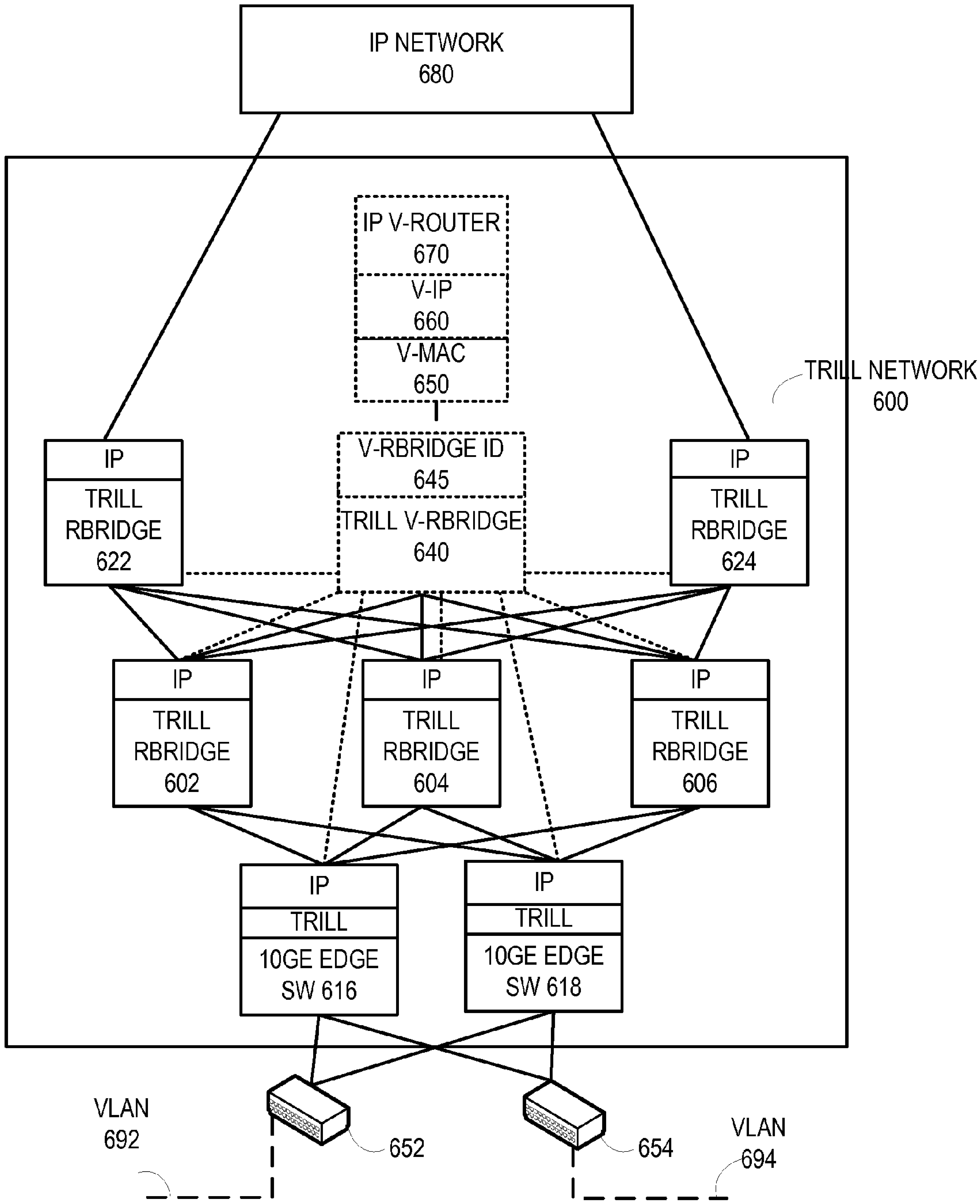

IP NETWORK
680
TRILL NETWORK
600
IP V-ROUTER
670
V-IP
660
V-MAC
650
V-RBRIDGE ID
645
TRILL V-RBRIDGE
640
IP ROUTER
632
TRILL
RBRIDGE
622
IP ROUTER
634
TRILL
RBRIDGE
624
TRILL
RBRIDGE
602
TRILL
RBRIDGE
604
TRILL
RBRIDGE
606
TRILL
10GE EDGE
SW 616
TRILL
10GE EDGE
SW 618
VLAN
692
652
654
VLAN
694

FIG. 6A


IP NETWORK
680
IP V-ROUTER
670
V-IP
660
V-MAC
650
TRILL NETWORK
600
V-RBRIDGE ID
645
TRILL V-RBRIDGE
640
IP
TRILL
RBRIDGE
622
IP
TRILL
RBRIDGE
624
IP
TRILL
RBRIDGE
602
IP
TRILL
RBRIDGE
604
IP
TRILL
RBRIDGE
606
IP
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SW 616
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TRILL
10GE EDGE
SW 618
VLAN
692
652
654
VLAN
694

FIG. 6B

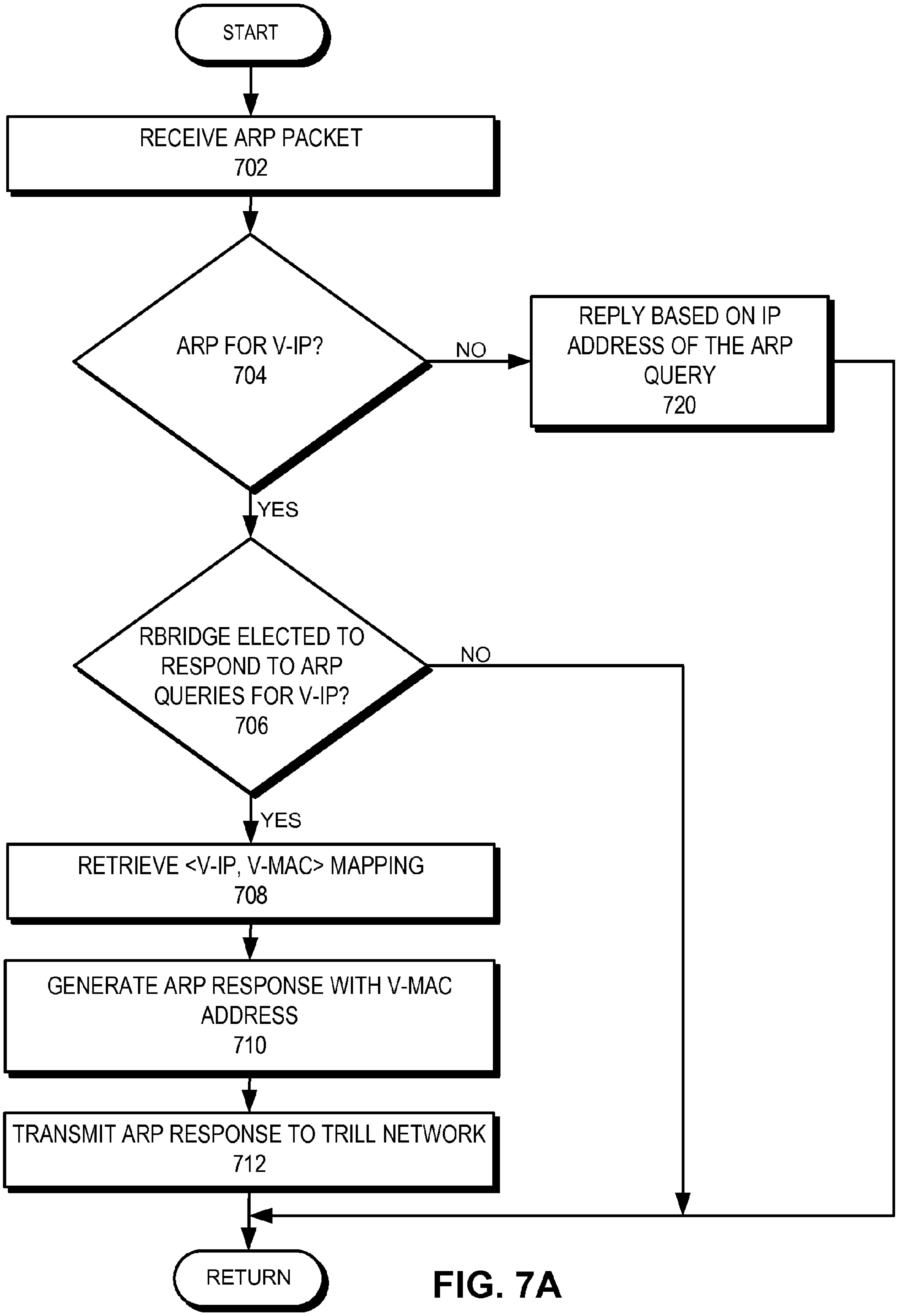

START
RECEIVE ARP PACKET
702
ARP FOR V-IP?
704
NO
REPLY BASED ON IP ADDRESS OF THE ARP QUERY
720
YES
RBRIDGE ELECTED TO RESPOND TO ARP QUERIES FOR V-IP?
706
NO
YES
RETRIEVE <V-IP, V-MAC> MAPPING
708
GENERATE ARP RESPONSE WITH V-MAC ADDRESS
710
TRANSMIT ARP RESPONSE TO TRILL NETWORK
712
RETURN

FIG. 7A

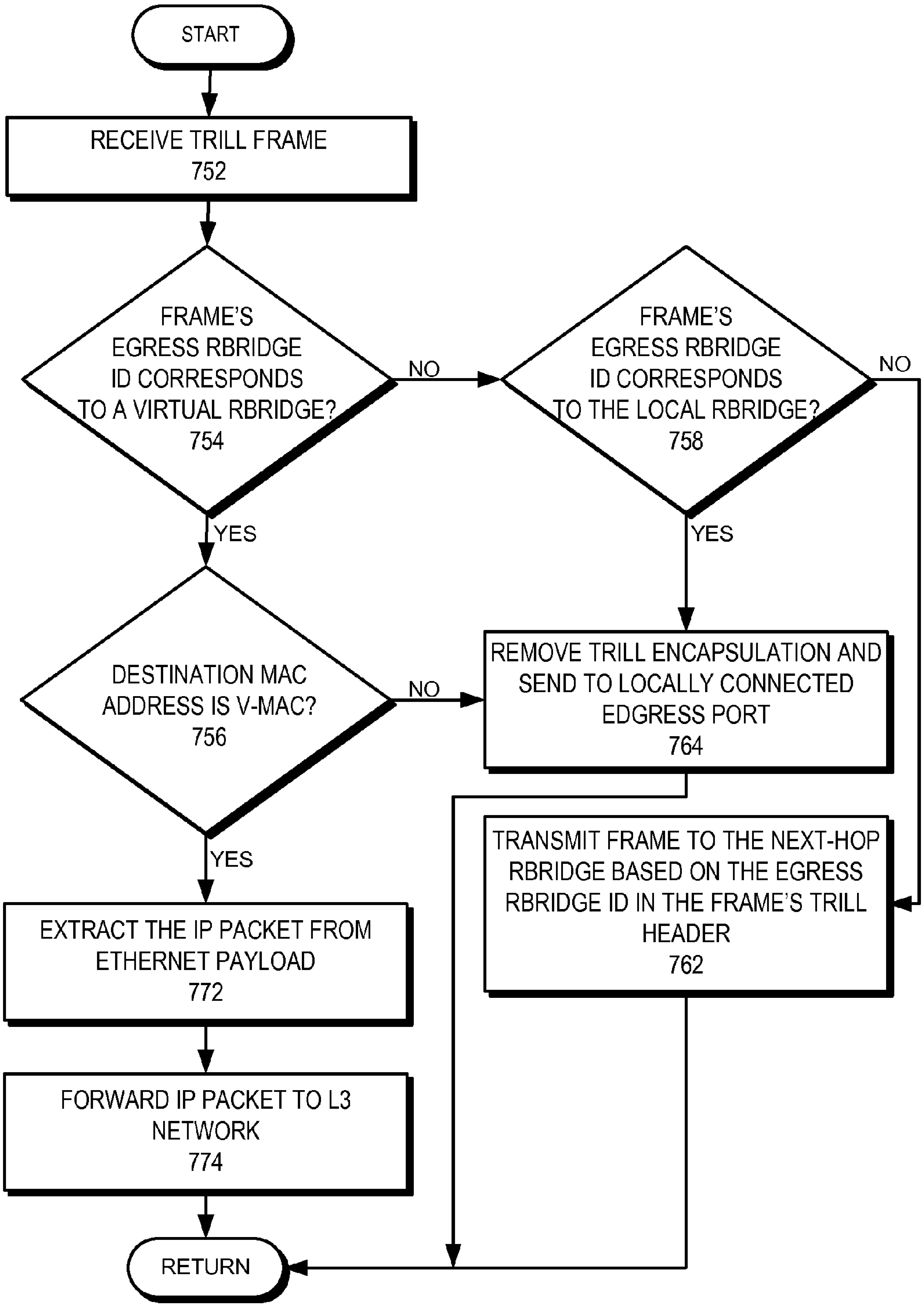
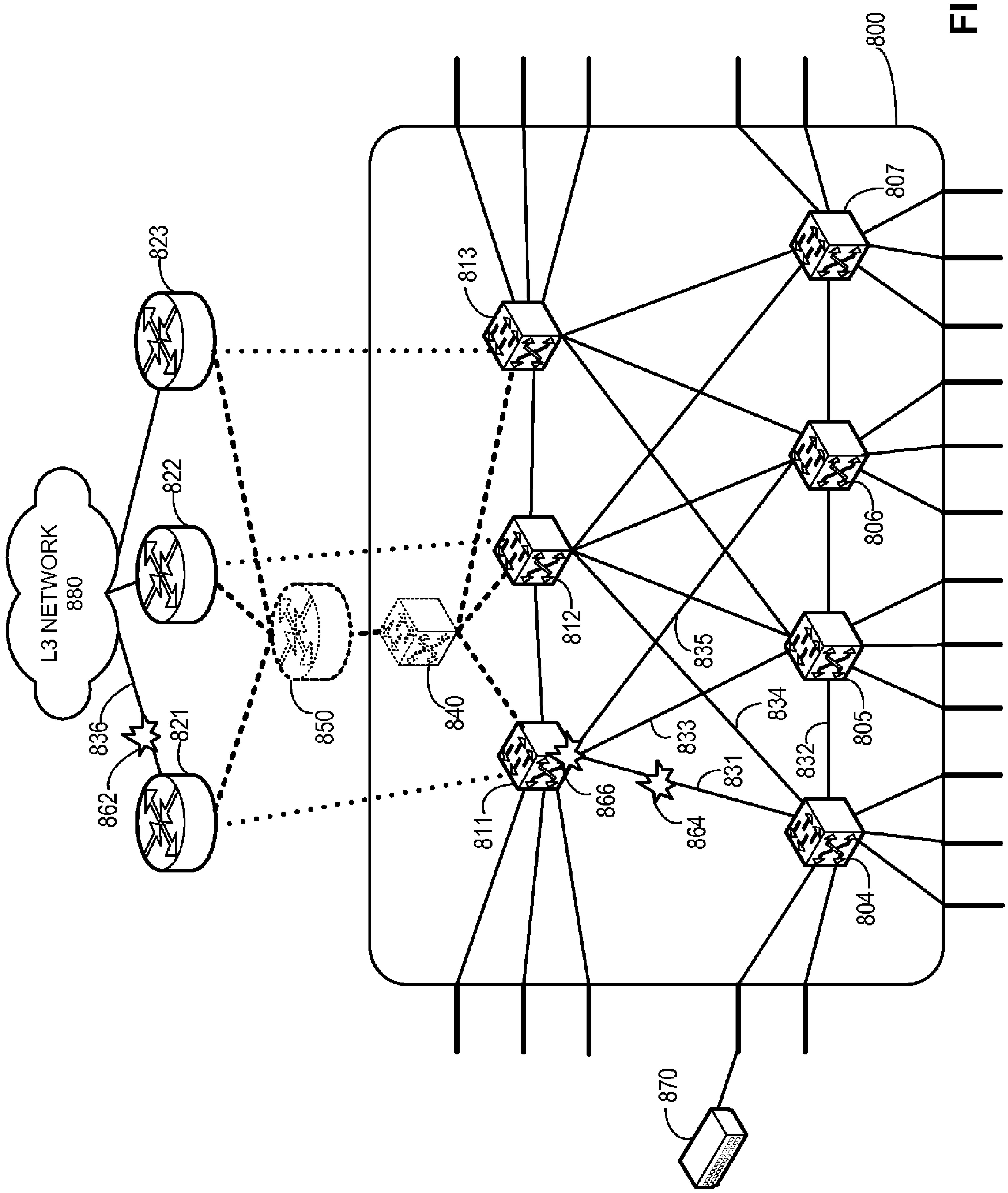

START
RECEIVE TRILL FRAME
752
FRAME'S EGRESS RBRIDGE ID CORRESPONDS TO A VIRTUAL RBRIDGE?
754
NO
FRAME'S EGRESS RBRIDGE ID CORRESPONDS TO THE LOCAL RBRIDGE?
758
NO
YES
YES
DESTINATION MAC ADDRESS IS V-MAC?
756
NO
REMOVE TRILL ENCAPSULATION AND SEND TO LOCALLY CONNECTED EDGRESS PORT
764
TRANSMIT FRAME TO THE NEXT-HOP RBRIDGE BASED ON THE EGRESS RBRIDGE ID IN THE FRAME'S TRILL HEADER
762
YES
EXTRACT THE IP PACKET FROM ETHERNET PAYLOAD
772
FORWARD IP PACKET TO L3 NETWORK
774
RETURN

FIG. 7B



L3 NETWORK
880
821
822
823
836
862
850
840
811
812
813
866
864
831
832
833
834
835
804
805
806
807
800
870

FIG. 8

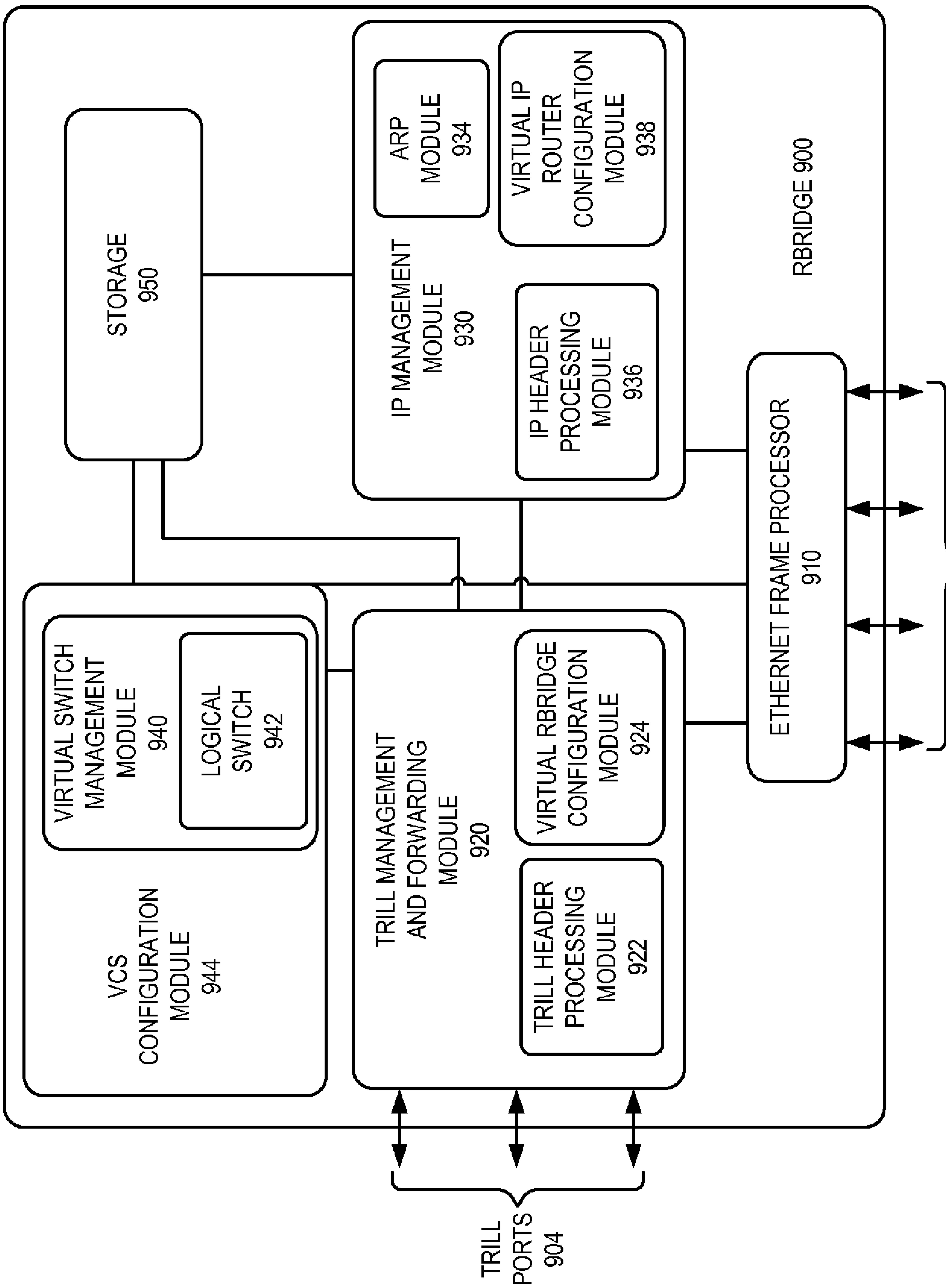

STORAGE 950
IP MANAGEMENT MODULE 930
ARP MODULE 934
VIRTUAL IP ROUTER CONFIGURATION MODULE 938
IP HEADER PROCESSING MODULE 936
RBRIDGE 900
VCS CONFIGURATION MODULE 944
VIRTUAL SWITCH MANAGEMENT MODULE 940
LOGICAL SWITCH 942
TRILL MANAGEMENT AND FORWARDING MODULE 920
VIRTUAL RBRIDGE CONFIGURATION MODULE 924
TRILL HEADER PROCESSING MODULE 922
ETHERNET FRAME PROCESSOR 910
EDGE PORTS 902
TRILL PORTS 904

FIG. 9

LAYER-3 SUPPORT IN TRILL NETWORKS

RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Application No. 61/481,643, titled "Layer-3 Support in Virtual Cluster Switching," by inventors Phanidhar Koganti, Anoop Ghanwani, Suresh Vobbilisetty, Rajiv Krishnamurthy, Nagarajan Venkatesan, and Shunjia Yu, filed 2 May 2011, and U.S. Provisional Application No. 61/503,265, titled "IP Routing in VCS," by inventors Phanidhar Koganti, Anoop Ghanwani, Suresh Vobbilisetty, Rajiv Krishnamurthy, Nagarajan Venkatesan, and Shunjia Yu, filed 30 Jun. 2011, which are incorporated by reference herein.

The present disclosure is related to U.S. patent application Ser. No. 13/087,239, titled "Virtual Cluster Switching," by inventors Suresh Vobbilisetty and Dilip Chatwani, filed 14 Apr. 2011, and U.S. patent application Ser. No. 12/725,249, titled "Redundant Host Connection in a Routed Network," by inventors Somesh Gupta, Anoop Ghawani, Phanidhar Koganti, and Shunjia Yu, filed 16 Mar. 2010, the disclosures of which are incorporated by reference herein.

BACKGROUND

1. Field

The present disclosure relates to network design. More specifically, the present disclosure relates to a method and system for constructing a scalable switching system that supports layer-3 routing while facilitating automatic configuration.

2. Related Art

The growth of the Internet has brought with it an increasing demand for bandwidth. As a result, equipment vendors race to build larger and faster switches with versatile capabilities, such as layer-3 forwarding, to move more traffic efficiently. However, the size of a switch cannot grow infinitely. It is limited by physical space, power consumption, and design complexity, to name a few factors. Furthermore, switches with higher capability are usually more complex and expensive. More importantly, because an overly large and complex system often does not provide economy of scale, simply increasing the size and capability of a switch may prove economically unviable due to the increased per-port cost.

One way to increase the throughput of a switch system is to use switch stacking. In switch stacking, multiple smaller-scale, identical switches are interconnected in a special pattern to form a larger logical switch. The amount of required manual configuration and topological limitations for switch stacking becomes prohibitively tedious when the stack reaches a certain size, which precludes switch stacking from being a practical option in building a large-scale switching system.

Meanwhile, layer-2 (e.g., Ethernet) switching technologies continue to evolve. More routing-like functionalities, which have traditionally been the characteristics of layer-3 (e.g., Internet Protocol or IP) networks, are migrating into layer-2. Notably, the recent development of the Transparent Interconnection of Lots of Links (TRILL) protocol allows Ethernet switches to function more like routing devices. TRILL overcomes the inherent inefficiency of the conventional spanning tree protocol, which forces layer-2 switches to be coupled in a logical spanning-tree topology to avoid looping. TRILL allows routing bridges (RBridges) to be coupled in an arbitrary topology without the risk of looping by implementing routing functions in switches and including a hop count in the TRILL header.

While TRILL brings many desirable features to layer-2 networks, some issues remain unsolved when layer-3 processing is desired.

SUMMARY

One embodiment of the present invention provides a switch. The switch includes an IP header processor and a forwarding mechanism. The IP header processor identifies a destination IP address in a packet encapsulated with an inner Ethernet header, a TRILL header, and an outer Ethernet header. The forwarding mechanism determines an output port and constructs a new header for the packet based on the destination IP address. The switch also includes a packet processor which determines whether (1) an inner destination media access control (MAC) address corresponds to a local MAC address assigned to the switch; (2) a destination RBridge identifier (RBridge ID) corresponds to a local RBridge identifier assigned to the switch; and (3) an outer destination MAC address corresponds to the local MAC address.

In a variation on this embodiment, the packet processor determines a first virtual local area network (VLAN) tag in the inner Ethernet header, wherein the new header includes a new inner Ethernet header which comprises a second VLAN tag.

In a variation on this embodiment, the switch includes a control mechanism which forms a virtual cluster switch in conjunction with one or more additional switches.

In a variation on this embodiment, the virtual cluster switch is an Ethernet fabric switch functioning as a logical Ethernet switch.

In a variation on this embodiment, the switch includes a switching mechanism switches the packet between VLANs based on the destination IP address.

In a variation on this embodiment, the RBridge identifier is a virtual RBridge identifier and the destination IP address is a virtual IP address assigned to a virtual IP router associated with the virtual RBridge identifier.

In a variation on this embodiment, the virtual IP router is formed by operating the switch in conjunction with at least another physical switch as a single logical router.

BRIEF DESCRIPTION OF THE FIGURES

FIG. **1** illustrates an exemplary TRILL network that includes a plurality of RBridges with IP processing capabilities, in accordance with an embodiment of the present invention.

FIG. **2**A illustrates an exemplary configuration of end devices belonging to different VLANs and coupled to a TRILL network, wherein one RBridge is IP capable, in accordance with an embodiment of the present invention.

FIG. **2**B illustrates an exemplary configuration of end devices belonging to different VLANs and coupled to a TRILL network, wherein all RBridges are IP capable, in accordance with an embodiment of the present invention.

FIG. **3**A illustrates an exemplary TRILL network with multiple VLANs, in accordance with an embodiment of the present invention.

FIG. **3**B illustrates an exemplary TRILL network with multiple VLANs, wherein each RBridge belongs to all VLANs, in accordance with an embodiment of the present invention.

FIG. **4**A presents a flowchart illustrating the process of an RBridge transmitting a frame, in accordance with an embodiment of the present invention.

FIG. 4B presents a flowchart illustrating the process of an IP-capable RBridge transmitting a frame, in accordance with an embodiment of the present invention.

FIG. 5 illustrates an exemplary network where a virtual RBridge and an associated virtual IP router are created based on a plurality of physical gateway RBridges with IP processing capabilities, in accordance with an embodiment of the present invention.

FIG. 6A illustrates an exemplary configuration of how a virtual RBridge and an associated virtual IP router can be logically coupled to a number of gateway RBridges in a TRILL network, in accordance with an embodiment of the present invention.

FIG. 6B illustrates an exemplary configuration of how a virtual RBridge and an associated virtual IP router can be logically coupled to all RBridges in a TRILL network where each RBridge has IP processing capability, in accordance with an embodiment of the present invention.

FIG. 7A presents a flowchart illustrating the process of a gateway RBridge associated with a virtual RBridge responding to an Address Resolution Protocol (ARP) query, in accordance with an embodiment of the present invention.

FIG. 7B presents a flowchart illustrating the process of a gateway RBridge associated with a virtual RBridge forwarding a TRILL frame, in accordance with an embodiment of the present invention.

FIG. 8 illustrates a scenario where one of the RBridges associated with the virtual RBridge experiences a link failure and/or a node failure, in accordance with an embodiment of the present invention.

FIG. 9 illustrates an exemplary architecture of a switch with IP processing capabilities, in accordance with an embodiment of the present invention.

DETAILED DESCRIPTION

The following description is presented to enable any person skilled in the art to make and use the invention, and is provided in the context of a particular application and its requirements. Various modifications to the disclosed embodiments will be readily apparent to those skilled in the art, and the general principles defined herein may be applied to other embodiments and applications without departing from the spirit and scope of the present invention. Thus, the present invention is not limited to the embodiments shown, but is to be accorded the widest scope consistent with the claims.

Overview

In embodiments of the present invention, the problem of providing scalable and flexible layer-3 (e.g., IP) support in a TRILL network is solved by facilitating IP routing in a number of RBridges in the TRILL network. The availability of IP processing within a TRILL network allows cross-layer-2-domain traffic (e.g., traffic across different VLANs) to be forwarded within a TRILL network, which reduces forwarding overhead. Usually, the IP router portion of one of these IP-capable RBridges is assigned as a default gateway router to an end device coupled to a TRILL network. Wherever the end device sends a frame to outside of its local network (e.g., a VLAN), the frame is forwarded to and processed by the IP router portion of the RBridge. This layer-3 processing occurs within the TRILL network. Note that, in a conventional TRILL network, such layer-3 processing has to be done by an IP router residing outside the TRILL network.

In some embodiments, the end-device may be coupled to the TRILL network via an ingress RBridge without IP processing capability. Under such a scenario, the TRILL RBridge portion of an IP-capable RBridge acts as an egress RBridge and the IP router portion of the RBridge can act as the default gateway router. A frame from the end device is received at the ingress RBridge and encapsulated in a TRILL packet, wherein the TRILL packet sets the egress RBridge identifier as the destination RBridge identifier, and the MAC address of the egress RBridge as the inner destination MAC address. The packet is then forwarded though the TRILL network and reaches the egress RBridge, where the outer destination MAC address of the packet is the MAC address of the egress RBridge. The IP router portion of the egress RBridge then processes the IP header in the frame and makes the layer-3 forwarding decision based on the destination IP address of the frame.

In some embodiments, the IP router portion of an IP-capable RBridge may be associated with multiple VLANs associated with the TRILL network. If the destination end device of the frame belongs to one of the associated VLANs, the IP router can obtain the MAC address of the destination end device using ARP requests within that VLAN. The corresponding RBridge of the IP router then sets the RBridge to which the destination end device is coupled as the egress RBridge and forwards the frame to the egress RBridge over the TRILL network.

Although the present disclosure is presented using examples based on the TRILL protocol, embodiments of the present invention are not limited to TRILL networks, or networks defined in a particular Open System Interconnection Reference Model (OSI reference model) layer.

The term "RBridge" refers to routing bridges, which are bridges implementing the TRILL protocol as described in IETF Request for Comments (RFC) "Routing Bridges (RBridges): Base Protocol Specification," available at http://tools.ietf.org/html/rfc6325, which is incorporated by reference herein. Embodiments of the present invention are not limited to applications among RBridges. Other types of switches, routers, and forwarders can also be used.

In this disclosure, the term "edge port" refers to a port which sends/receives data frames in native Ethernet format. The term "TRILL port" refers to a port which sends/receives data frames encapsulated with a TRILL header and outer MAC header.

The term "end device" refers to a network device that is typically not TRILL-capable. "End device" is a relative term with respect to the TRILL network. However, "end device" does not necessarily mean that the network device is an end host. An end device can be a host, a conventional layer-2 switch, or any other type of network device. Additionally, an end device can be coupled to other switches or hosts further away from the TRILL network. In other words, an end device can be an aggregation point for a number of network devices to enter the TRILL network.

The term "IP-capable RBridge" refers to a physical RBridge that can process and route IP packets. An IP-capable RBridge can be coupled to a layer-3 network and can forward IP packets from end devices to the layer-3 network. A number of IP-capable RBridges can form a virtual RBridge and a corresponding virtual IP router, thereby facilitating a virtual gateway router for end devices that supports redundancy and load-balancing. In this disclosure, an RBridge which forms a virtual RBridge and a virtual IP router is also referred to as a "gateway" RBridge. A gateway RBridge responds to ARP requests for the virtual IP address with a virtual MAC address. In various embodiments, any arbitrary number of gateway RBridges can form the virtual RBridge. As gateway RBridges can process both TRILL and IP packets, in this disclosure the term "gateway RBridge" can refer to a physical RBridge in a TRILL network or a physical router in an IP network.

The term "IP router" refers to the IP-capable portion of an RBridge or a stand-alone IP router. In this disclosure, the terms "IP router" and "router" are used interchangeably.

The term "frame" refers to a group of bits that can be transported together across a network. "Frame" should not be interpreted as limiting embodiments of the present invention to layer-2 networks. "Frame" can be replaced by other terminologies referring to a group of bits, such as "packet," "cell," or "datagram."

The term "RBridge identifier" refers to a group of bits that can be used to identify an RBridge. Note that the TRILL standard uses "RBridge ID" to denote a 48-bit intermediate-system-to-intermediate-system (IS-IS) System ID assigned to an RBridge, and "RBridge nickname" to denote a 16-bit value that serves as an abbreviation for the "RBridge ID." In this disclosure, "RBridge identifier" is used as a generic term and is not limited to any bit format, and can refer to "RBridge ID" or "RBridge nickname" or any other format that can identify an RBridge.

Network Architecture

FIG. **1** illustrates an exemplary TRILL network that includes a plurality of RBridges with IP processing capabilities, in accordance with an embodiment of the present invention. As illustrated in FIG. **1**, a TRILL network **100** includes RBridges, **101**, **102**, **103**, **104**, **105**, **106**, and **107**. RBridges **101**, **102**, and **103** are IP capable and coupled to a layer-3 network **150** as IP routers, **111**, **112**, and **113**, respectively. For example, RBridge **101** and IP router **111** are the same physical device (represented by dotted lines), where its TRILL RBridge portion is denoted by RBridges **101** and its IP router portion is denoted by router **111**. Similarly, RBridge **102** and IP router **112**, and RBridge **103** and IP router **113**, are the same physical devices, respectively.

RBridges in network **100** use edge ports to communicate to end devices and TRILL ports to communicate to other RBridges. For example, RBridge **104** is coupled to end device **122** via an edge port and to RBridges **105**, **101**, and **102** via TRILL ports. An end host coupled to an edge port may be a host machine or an aggregation node. For example, end devices **122**, **124**, **126**, and **128** are host machines, wherein end devices **122** and **128** are directly coupled to network **100**, and end devices **124** and **126** are coupled to network **100** via their aggregation node, a layer-2 bridge **130**.

In FIG. **1**, end device **128** is directly coupled to RBridge **103**. Hence, IP router **113** can act as the default gateway for end device **128**. Consequently, all frames from end device **128** destined to IP network **150** are received at IP router **113** and forwarded to network **150**. On the other hand, RBridge **104** couples end device **122** to network **100** and acts as the ingress RBridge for all frames from end device **122**. One of the IP-capable RBridges (e.g., RBridge **101**) acts as the egress RBridge for frames from end device **122** to network **150**. Under such a scenario, the frame destined to network **150** is encapsulated in a TRILL packet with the RBridge identifier of RBridge **101** as the destination RBridge identifier, and the MAC address of RBridge **101** as the inner destination MAC address. The TRILL packet is then forwarded to RBridge **101**, where the outer destination MAC address of the packet is the MAC address of RBridge **101**. IP router **111** then processes the IP header in the frame and makes the layer-3 forwarding decision based on the destination IP address of the frame.

During operation that does not involve layer-3 processing in RBridges, an end device coupled to the TRILL network may select the default gateway from a layer-3 network and use the corresponding IP address as a default gateway router address. For example, in FIG. **1**, end device **128** selects the default gateway router from IP network **150**. Any frame destined to network **150** from end device **128** is sent to the default gateway. Under such a scenario, if end devices **122** and **128** are on different VLANs, any communication between these end devices will go through network **150**. If end device **128** sends a frame to end device **122**, the frame first goes to the default gateway in network **150**. Consequently, the default gateway processes the IP header in the frame and makes layer-3 forwarding decision toward end device **122**. As a result, routing and bandwidth management will be inefficient and the frame will incur higher latency.

In embodiments of the present invention, as illustrated in FIG. **1**, each frame destined to end device **122** from end device **128**, wherein the end devices are on different VLANs, is received at RBridge **103**. IP router **113** processes the IP header in the frame and makes the forwarding decision toward end device **122** (which involves forwarding the frame on end device **122**'s VLAN through TRILL network **100**). Consequently, RBridge **103** forwards the frame to a corresponding egress RBridge **104** over TRILL network **100**. RBridge **104**, in turn, transmits the frame to end device **122**. Hence, enabling layer-3 support on RBridges in a TRILL network provides higher efficiency in routing and bandwidth management.

In some embodiments, the TRILL network may be a virtual cluster switch (VCS). In a VCS, any number of RBridges in any arbitrary topology may logically operate as a single switch. Any new RBridge may join or leave the VCS in "plug-and-play" mode without any manual configuration.

Note that TRILL is only used as a transport between the switches within network **100**. This is because TRILL can readily accommodate native Ethernet frames. Also, the TRILL standards provide a ready-to-use forwarding mechanism that can be used in any routed network with arbitrary topology. Embodiments of the present invention should not be limited to using only TRILL as the transport. Other protocols (such as multi-protocol label switching (MPLS)), either public or proprietary, can also be used for the transport.

Routine Across VLANs

FIG. **2**A illustrates an exemplary configuration of how end devices belonging to different VLANs and coupled to a TRILL network, wherein one RBridge is IP capable, in accordance with an embodiment of the present invention. In this example, a TRILL network **200** includes TRILL RBridges **220** and **230**. End device **202** is coupled to RBridge **220** over VLAN **212**, and end device **204** is coupled to RBridge **220** over VLAN **214**.

In the example in FIG. **2**A, RBridge **230** is IP capable and IP router **235** is the IP router portion of RBridge **230** (denoted in dotted line). IP router **235** functions as a default gateway router for end devices **202** and **204**. Consequently, although RBridge **220** couples both end devices **202** and **204** to network **200**, any traffic between end devices **202** and **204** will be routed via IP router **235** because end devices **202** and **204** belong to different VLANs. For example, if end device **202** sends a frame to end device **204**, it first assembles an IP packet with end device **204**'s IP address. Based on its local forwarding table, end device **202** realizes that it does not have a direct route to end device **204**, and therefore needs to send the packet to gateway router **235**. Hence, end device **202** encapsulates the IP packet in an Ethernet frame, whose destination MAC address is set to be gateway router **235**'s MAC address. Note that, if end device **202** has no knowledge of IP router **235**'s MAC address, end device **202** can send out an ARP request corresponding to the IP address of router **235**. Router **235** then replies to the ARP request with its MAC address. Subsequently, end device **202** forwards the frame to RBridge **230** via ingress RBridge **220**. IP router **235**, in turn, receives the frame and removes its layer-2 header (including the VLAN tag corresponding to VLAN **212**). IP router **235** then performs a lookup in its IP forwarding table based on the packet's destination IP address, and encapsulates the packet with a new Ethernet header which includes a VLAN tag corresponding VLAN **214**. RBridge **230** then encapsulates the Ethernet frame with a TRILL header and forwards it to end device **204** via egress RBridge **220**.

FIG. **2**B illustrates an exemplary configuration of end devices belonging to different VLANs and coupled to a TRILL network, wherein all RBridges are IP capable, in accordance with an embodiment of the present invention. In this example, a TRILL network **200** includes TRILL RBridges **220** and **230**. End device **202** is coupled to RBridge **220** over VLAN **212**, and end device **204** is coupled to RBridge **220** over VLAN **214**.

In the example in FIG. **2**B, both RBridges **220** and **230** are IP capable and IP routers **225** and **235** are the IP router portion of RBridges **220** and **230**, respectively. Under such a scenario, IP router **225** can be the default gateway router for end devices **202** and **204**. Consequently, any traffic between end devices **202** and **204** can be routed via IP router **225**. For example, if end device **202** sends a frame to end device **204**, it assembles an IP packet with end device **204**'s IP address, encapsulates the IP packet in an Ethernet frame with destination MAC address as router **225**'s MAC address, and forwards the frame to RBridge **225** via ingress RBridge **220**. Note that, if end device **202** has no knowledge of IP router **225**'s MAC address, end device **202** obtains the IP address of router **225** using ARP. IP router **225**, in turn, receives the frame, performs a lookup in its IP forwarding table, encapsulates the packet with a new Ethernet header which includes a VLAN tag corresponding VLAN **214**, and forwards it to end device **204** via egress RBridge **220**. As the cross-layer-2-domain frame does not need to traverse through TRILL network **200**, IP-processing capability at RBridge **220** thereby reduces the bandwidth usage in network **200**.

Distributed Layer-3 Processing

In some embodiments, layer-3 processing capabilities can be distributed to multiple or all TRILL RBridges. In some embodiments, layer-3 processing capabilities associated different the VLANs can be distributed selectively across multiple RBridges. FIG. **3**A illustrates an exemplary TRILL network with multiple VLANs, in accordance with an embodiment of the present invention. In the example in FIG. **3**A, network **300** includes RBridges **304**, **305**, **306**, and **307**. Each of these RBridges is IP capable. RBridge **304** is coupled to end devices **311** and **312**; RBridge **305** is coupled to end devices **312**, **313**, and **314**; RBridge **306** is coupled to end devices **315**, **316**, and **317**; and RBridge **307** is coupled to end devices **317** and **318**. RBridges **305** and **306** belong to VLAN **328**; RBridges **304**, **306**, and **307**, and end devices **312** and **318** belong to VLAN **326**; RBridges **304**, **305**, and **306**, and end device **311** belong to VLAN **324**; and RBridges **305**, **306**, and **307**, and end device **317** belong to VLAN **322**.

In some embodiments, a layer-3 interface on an RBridge corresponding to a VLAN is a Switch Virtual Interface (SVI). For example, RBridge **304** in FIG. **3**A has SVIs for VLANs **324** and **326** (although these SVIs can be on the same physical interface). Consequently, RBridge **304** and end device **318**, and RBridge **304** and end device **311**, are on the same VLAN segment. If end device **311** sends a frame to end device **318**, the destination is outside of VLAN **324**. Consequently, end device **318** sets the destination MAC address of the frame as the MAC address of the SVI on VLAN **324** at RBridge **304**, which is the layer-3 gateway on VLAN **324**. End device **318** then forwards the frame to RBridge **304**. Upon receiving the frame, RBridge **304** recognizes that the frame's destination MAC address is a local MAC address. RBridge **304** then removes the frame's Ethernet header, performs a lookup in its IP forwarding table based on the frame's destination IP address, and encapsulates the frame with a new Ethernet header with a destination MAC address corresponding to end device **318** in VLAN **326**. Finally, RBridge **304** forwards the frame to end device **318** via egress RBridge **307**.

However, when end device **311** sends a frame to end device **317**, RBridge **304** cannot forward the frame to end device **317** because RBridge **304** does not have an SVI on VLAN **322**, to which end device **317** belongs. As a result, upon receiving a frame destined to end device **317** from end device **311**, RBridge encapsulates the frame using a TRILL header with egress RBridge identifier corresponding to RBridge **306** because it has SVIs to all VLANs. RBridge **304** then forwards the frame to RBridge **306**. The frame is routed though the TRILL network and reaches RBridge **306** when the outer destination MAC addresses match the MAC address of RBridge **306**. Upon receiving the frame, RBridge **306** recognizes that the frame's outer destination MAC address is a local MAC address. RBridge **306** then removes the TRILL encapsulations, encapsulates the IP packet with a new Ethernet header with a destination MAC address corresponding to end device **317** in VLAN **322**, and forwards the frame accordingly.

FIG. **3**B illustrates an exemplary TRILL network with multiple VLANs, wherein each RBridge belongs to all VLANs, in accordance with an embodiment of the present invention. In this example, TRILL network **300** includes RBridges **304**, **305**, **306**, and **307**. Each of these RBridges is IP capable. End device **312** is coupled to RBridges **304** and **305**, end device **317** is coupled to RBridges **306** and **307**, and end device **318** is coupled to RBridge **307**. All RBridges in network **300** have SVIs for VLANs **322** and **326**. End devices **312** and **318** belong to VLAN **322**, and end device **317** belongs to VLAN **326**.

In this example, if end device **317** sends a frame to end device **318**, the frame can be routed on layer-3 at RBridge **307** because RBridge **307** has SVIs for VLANs **322** and **326**. As the frame does not travel to any other RBridge in network **300**, it incurs lower latency while saving bandwidth in network **300**. Similarly, if end device **317** sends a frame to end device **312**, the frame can be routed on layer-3 at the IP router portion of either RBridge **306** or **307** as both have SVIs for VLANs **322** and **326**. If all RBridges in the TRILL network have SVIs for all VLANs, inter-VLAN switching is possible at each RBridge.

Frame Processing

FIG. **4**A presents a flowchart illustrating the process of an RBridge transmitting a frame, in accordance with an embodiment of the present invention. During operation, an RBridge receives a frame (operation **402**) and determines the type of port at which the frame was received (operation **404**). If the frame is received at an edge port, then the RBridge checks whether the destination is coupled to a local edge port (operation **410**). If the destination is not coupled to a local edge port, the RBridge encapsulates the frame in a TRILL packet and sets the RBridge identifier of the RBridge to which the end device is coupled as the egress RBridge identifier (operation **416**). The RBridge then forwards the TRILL packet to the TRILL network (operation **418**). Note that the MAC learning process allows an RBridge to learn about the port to which the end device is coupled.

If the frame is received on an edge port and the destination is coupled to a local edge port (operation **410**), then the

RBridge transmits the frame to the destination end device coupled to a local edge port (operation **414**).

If the frame is received from a TRILL port (operation **404**), the RBridge checks whether itself is the egress RBridge of the TRILL packet (operation **408**). If not, then the RBridge forwards the TRILL packet to the TRILL network (operation **418**). Otherwise, the RBridge transmits the frame to the destination end device coupled to a local edge port (operation **414**).

FIG. **4**B presents a flowchart illustrating the process of an IP-capable RBridge transmitting a frame, in accordance with an embodiment of the present invention. The exemplary process in FIG. **4**B is also applicable to embodiments with distributed layer-3 processing, as described in conjunction with FIG. **3**A. During operation, an RBridge receives a frame (operation **452**) and determines the type of port at which the frame is received (operation **454**). If the frame is received at an edge port, then the RBridge inspects the frame to determine whether the end device with the destination MAC address is coupled to a local edge port (operation **456**). If so, the frame is forwarded to the destination via the TRILL network (operation **464**), as described in conjunction with FIG. **4**A.

If the frame's destination MAC address is not coupled to a local edge port, then the RBridge determines whether the frame's destination MAC address is the RBridge's MAC address (operation **458**). If the destination MAC address is not the RBridge's MAC address, then the RBridge encapsulates the frame in a TRILL packet and sets the RBridge identifier of a gateway RBridge as the egress RBridge identifier (operation **466**). The RBridge then forwards the TRILL packet to the TRILL network (operation **476**). On the other hand, if the frame's destination MAC address is the RBridge's MAC address (operation **458**), then the RBridge performs layer-3 processing on the frame (operation **468**) and determines the outgoing port (operation **470**).

The RBridge then determines the type of the outgoing port (operation **462**). If the outgoing port is an edge port, which means the destination end device is coupled locally, the RBridge forwards the frame, which is Ethernet encapsulated with the end device's MAC address as the destination MAC address, to the destination end device (operation **480**). In some embodiments, the end device can be a layer-3 (e.g., IP) router. If the outgoing port is a TRILL port, then the end device is connected to a remote RBridge. Hence, the RBridge obtains the RBridge identifier of the RBridge to which the destination end device is coupled to based on the MAC address of the destination end device (operation **472**). The RBridge then encapsulates the frame in a TRILL packet and sets the obtained RBridge identifier as the egress RBridge identifier (operation **474**). The RBridge then forwards the TRILL packet to the TRILL network (operation **476**).

If the frame is received from a TRILL port (operation **454**), the RBridge checks whether itself is the egress RBridge of the TRILL packet (operation **460**). If not, then the RBridge forwards the TRILL packet to the TRILL network (operation **476**). Otherwise, the RBridge forwards the frame to the destination end device coupled to a local edge port (operation **480**). In some embodiments, the end device can be a layer-3 router, in which case the forwarding includes layer-3 processing on the frame.

Virtual Switch Formation

In some embodiments, a number of TRILL RBridges with IP processing capabilities may act as layer-3 routers for an end device. These RBridges can form a virtual RBridge, which is assigned with a virtual RBridge identifier. Furthermore, these RBridges form a virtual IP router, which is assigned with a virtual IP address and a corresponding virtual MAC address. This virtual IP router operates as a default gateway router, which can provide redundancy and load balancing.

FIG. **5** illustrates an exemplary network where a virtual RBridge and an associated virtual IP router are created based on a plurality of physical gateway RBridges with IP processing capabilities, in accordance with an embodiment of the present invention. As illustrated in FIG. **5**, a TRILL network **500** includes RBridges **504**, **505**, **506**, **507**, **511**, **512**, and **513**. RBridges **511**, **512**, and **513** operate as gateway RBridges and are coupled to a layer-3 network **150** as IP routers **521**, **522**, and **523**, respectively. For example, gateway RBridge **511** and IP router **521** are same physical device (represented by dotted lines), where its TRILL RBridge portion is denoted by gateway RBridge **511** and its IP router portion is denoted by IP router **521**. Similarly, gateway RBridge **512** and IP router **522**, and gateway RBridge **513** and IP router **523** are the same physical devices, respectively.

Gateway RBridges **511**, **512**, and **513** form a virtual RBridge **530** by operating as a single logical RBridge in TRILL network **500**. Similarly, the corresponding IP routers **521**, **522**, and **523** form a virtual IP router **540** by operating as a single logical IP router. An end device **562** coupled to network **500** through RBridge **507** can use virtual IP router **540** as the default gateway router to layer-3 network **550**.

In embodiments of the present invention, as illustrated in FIG. **1**, Virtual RBridge **530** is considered to be logically coupled to gateway RBridges **511**, **512**, and **513**, optionally with zero-cost links represented by dashed lines. Furthermore, gateway RBridges **511**, **512**, and **513** can advertise their respective connectivity (optionally via zero-cost links) to virtual RBridge **530**. As a result, other RBridges in the TRILL network can learn that virtual RBridge **530** is reachable via gateway RBridges **511**, **512**, and **513**, and establish TRILL paths to virtual RBridge **530** using a corresponding virtual RBridge identifier through these gateway RBridges.

All the IP-layer router portions of these gateway RBridges are configured to operate as the layer-3 gateway router (i.e., virtual IP router **540**) for end device **562**. End device **562** uses virtual IP router **540** as the default gateway. Because virtual RBridge **530** is associated with virtual IP router **540**, incoming frames from end device **562** destined to network **550** are marked with virtual RBridge **530**'s identifier as the egress RBridge identifier. Consequently, all frames from end device **562** to network **550** are delivered to one of the gateway RBridges **511**, **512**, and **513**. Hence, load balancing can be achieved among gateway RBridges **511**, **512**, and **513** for frames sent to virtual RBridge **530**.

FIG. **6**A illustrates an exemplary configuration of how a virtual RBridge and an associated virtual IP router can be logically coupled to a number of gateway RBridges in a TRILL network, in accordance with an embodiment of the present invention. In this example, a TRILL network **600** includes a number of TRILL RBridges **602**, **604**, and **606**. Network **600** also includes RBridges **616** and **618**, each with a number of edge ports which can be coupled to external networks. For example, RBridges **616** and **618** are coupled with end devices **652** and **654** via 10GE edge ports. RBridges in network **600** are in communication with each other using TRILL protocol.

Also included in network **600** are RBridges **622** and **624**, which are layer-3 capable and coupled to an IP network **680**. Gateway RBridges **622** and **624** form virtual RBridge **640** with a virtual RBridge identifier **645**. Physically co-located IP Routers **632** and **634** within gateway RBridges **622** and **624**, respectively, form a virtual IP router **670** which is assigned a virtual IP address **660** and a virtual MAC address **650**. Virtual IP address **660** maps to virtual MAC address **650** for ARP requests directed to virtual IP router **670**. Furthermore, virtual RBridge identifier **645** is associated with virtual MAC address **650**. End devices **652** and **654** can set virtual IP address **660** as their default gateway router address and use ARP to obtain virtual MAC address **650**. End devices **652** and **654** send frames with virtual MAC address **650** as the destination address into network **600**. The frames are encapsulated in TRILL packets and routed toward virtual RBridge **640** using the corresponding virtual RBridge identifier **645**.

In some embodiments, a virtual IP address can be assigned for each VLAN associated with a TRILL network. For example, in FIG. **6**A, end device **652** may belong to VLAN **692**, and end device **654** may belong to VLAN **694**. Different virtual IP addresses may be used for VLANs **692** and **694**, respectively. End devices **652** and **654** then use the virtual IP address associated with VLAN **692** and VLAN **694** as their respective default gateway router addresses. Consequently, end devices **652** and **654** perceive virtual IP router **670** to be in VLAN **692** and VLAN **694**, respectively. For ARP requests for either virtual IP address, the same virtual MAC address **650** is sent in reply. All data frames injected to TRILL network **600** with virtual MAC address **650** as the destination MAC address are routed toward virtual RBridge **640**.

Note that in one embodiment, the virtual MAC address is known to all RBridges in the network **600**. Otherwise, both IP routers **632** and **634** receive a frame forwarded to virtual MAC address **650** and results in packet duplication. Hence, after formation of virtual RBridge **640** and virtual IP router **670**, all RBridges in network **600** are provided with the knowledge about virtual MAC address **650**. That is, virtual MAC address **650** is always "known" to all ingress RBridges in network **600**, and frames destined to virtual MAC address **650** are routed through network **600** using TRILL unicast.

In some embodiments, only one gateway RBridge is elected to reply to ARP requests for the virtual IP address. This election can also be VLAN specific.

FIG. **6**B illustrates an exemplary configuration of how a virtual RBridge and an associated virtual IP router can be logically coupled to all RBridges in a TRILL network where each RBridge has IP processing capability, in accordance with an embodiment of the present invention. In this example, all RBridges in TRILL network **600** have IP processing capabilities. Even though only RBridges **622** and **624** are connected to an IP network, IP processing capacity at all RBridges enables them to route across VLANs, as described in conjunction with FIG. **3**B. For example, any traffic between VLANs **692** and **694** can be switched at RBridges **616** and **618** without requiring the traffic to travel to another RBridge in network **600**.

In some embodiments, all RBridges in network **600** are associated with virtual RBridge **640** and a virtual IP router **670**, and share a virtual RBridge identifier **645**, a virtual IP address **660**, and a virtual MAC address **650**. In some embodiments, all RBridges in network **600** may be connected to IP network **680**.

ARP and Frame Processing in a Virtual Switch

FIG. **7**A presents a flowchart illustrating the process of a gateway RBridge associated with a virtual RBridge responding to an Address Resolution Protocol (ARP) query, in accordance with an embodiment of the present invention. Upon receiving an ARP request packet for an IP address (operation **702**), the gateway RBridge checks whether the ARP request is for a virtual IP address (operation **704**). If not, the gateway RBridge responds based on the IP address in the ARP request (assuming that IP address is the gateway RBridge's physical IP address) (operation **720**). Otherwise, the gateway RBridge checks whether it is elected to respond to an ARP request for the virtual IP address (operation **706**). If not, the ARP request is discarded. Otherwise the gateway RBridge retrieves the virtual MAC address for the virtual IP address (operation **708**) and generates an ARP reply containing the virtual MAC address (operation **710**). The gateway RBridge transmits the ARP reply to the TRILL network (operation **712**). Note that an ARP request is disseminated in the TRILL network using multicast and each IP-capable RBridge, including the one elected to respond to ARP requests for the virtual IP address, receives the query. However, the ARP reply is sent as a unicast transmission in the TRILL network to the end device.

FIG. **7**B presents a flowchart illustrating the process of a gateway RBridge associated with a virtual RBridge forwarding a TRILL frame, in accordance with an embodiment of the present invention. Upon receiving a TRILL frame (operation **752**), the RBridge checks whether the egress RBridge identifier in the TRILL header of the frame corresponds to a virtual RBridge (operation **754**). If the identifier does not correspond to the virtual RBridge, the RBridge inspects whether the egress RBridge identifier in the TRILL header of the frame corresponds to the local RBridge. If not, then the TRILL frame is forwarded to the next-hop RBridge based on the egress RBridge identifier (operation **762**). Otherwise, the RBridge removes the TRILL encapsulation and send the frame to a local egress port (operation **764**). If the RBridge identifier corresponds to the virtual RBridge, the RBridge checks whether the destination MAC address of the Ethernet frame encapsulated in the TRILL frame is the associated virtual MAC address (operation **756**). If so, then the frame is destined to an IP network the gateway RBridge is coupled to. Hence, the IP packet is extracted from the Ethernet payload of the frame (operation **772**). The gateway RBridge checks the IP address of the IP packet and performs layer-3 IP forwarding toward the IP network (operation **774**). On the other hand, if the destination MAC address is not the virtual MAC address, then the virtual RBridge is for multi-homed layer-2 end devices. Accordingly, the RBridge removes the TRILL encapsulation and send the frame to locally connected egress port (operation **764**). Operation of virtual RBridges for multi-homed end devices, such as forwarding multicast frames, is specified in the U.S. Patent Publication No. 2010/0246388, titled "Redundant Host Connection in a Routed Network," the disclosure of which is incorporated herein in its entirety.

Failure Handling

FIG. **8** illustrates a scenario where one of the RBridges associated with the virtual RBridge experiences a link failure and/or a node failure, in accordance with an embodiment of the present invention. In this example, in a TRILL network **800**, RBridges **811**, **812**, and **813** form a virtual RBridge **840**, and their respective IP-router portions denoted as IP routers **821**, **822**, and **823** form a virtual IP router **850**. Also included are four RBridges **804**, **805**, **806**, and **807**. An end device **870** is connected to network **800** using RBridge **804** as the ingress RBridge. Virtual IP router **850** is set as a default gateway router for end device **870**. Hence, all frames destined to network **880** from end device **870** have the virtual MAC address assigned to virtual IP router **850** as the destination MAC address. Note that these frames can be forwarded by gateway RBridges **811**, **812**, and **813** for load balancing. Gateway RBridges **811**, **812**, and **813** also provide redundancy among each other to handle failures.

Suppose that a failure **864** occurs to link **831** adjacent to gateway RBridge **811**. As a result, link **831** is removed from routing decisions in network **800**. All frames from end device **870** are still using the virtual MAC address as the destination address, and thus are still forwarded to any of the gateway RBridges via alternative links (e.g., links **832**, **833**, and **834**).

Suppose that a failure **862** occurs during operation that fails link **836** adjacent to IP router **821**. Consequently, IP router **821** is disconnected from network **880** and is incapable of forwarding frames to network **880**. Under such a scenario, IP router **821** is removed from virtual IP router **850**. As a result, IP router **821** stops operating as a layer-3 gateway router for end device **870**. However, gateway RBridge **811** still remains connected to network **800** and continues to operate as a regular TRILL RBridge. As virtual IP router **850** still operates as a default gateway for end device **870**, IP routers **822** and **823** can continue to operate as layer-3 gateway routers (as virtual IP router **850**) for end device **870**. Hence, all frames from end device **870** to network **880** are then distributed among gateway RBridges **812** and **813**.

In some embodiments, with failure **862**, an elected gateway RBridge stops responding to ARP requests for the virtual IP address and notifies other gateway RBridges. Consequently, the other gateway RBridges then elect among themselves another gateway RBridge to respond to ARP requests.

In some embodiments, with failure **862**, IP router **821** might not immediately remove its membership from virtual IP router **850** and might continue to receive layer-3 traffic from end devices. Under such circumstances, gateway RBridge **811**, the TRILL counterpart of IP router **821**, forwards the layer-3 traffic with TRILL encapsulation to other gateway RBridges (e.g., gateway RBridge **812**) which, in turn, forward the traffic to network **880**. However, if all similar IP routers suffer link failures and lose their connection to network **880**, IP router **821** along with the other gateway RBridges with link failures are removed from virtual IP router **850**. However, all gateway RBridges continue operating as TRILL RBridges.

Suppose that a node failure **866** occurs at gateway RBridge **811** (and essentially IP router **821** as they are the same physical device). As a result, links **831**, **833**, **835**, and **836** fail as well. Consequently, gateway RBridge **811** and IP router **821** are disconnected from both network **800** and network **880**, and are incapable of transmitting to or receiving from either network. Under such a scenario, IP router **821** is removed from virtual IP router **850** and gateway RBridge **811** is removed from virtual RBridge **840**. As a result, IP router **821** stops operating as a layer-3 gateway node. Furthermore, gateway RBridge **811** is disconnected from network **800** and removed from all TRILL routes in network **800**.

With failure **866**, as virtual IP router **850** still operates as a default gateway for end device **870**, routers **822** and **823** continue operating as layer-3 gateway nodes for end device **870**. Hence, all frames from end device **870** to network **880** are distributed between gateway RBridges **812** and **813**. Furthermore, if IP router **821** had been an elected router, it stops responding to ARP requests for the virtual IP address. Other RBridges coupled to the failed gateway RBridge can detect the failure and notify all RBridges, including other active gateway RBridges. Consequently, the active gateway RBridges can elect another gateway RBridge to respond to ARP requests.

Exemplary Switch System

FIG. **9** illustrates an exemplary architecture of a switch with IP processing capabilities, in accordance with an embodiment of the present invention. In this example, an RBridge **900** includes a number of TRILL ports **904**, a TRILL management and forwarding module **920**, an IP management module **930**, an Ethernet frame processor **910**, and a storage **950**. TRILL management and forwarding module **920** further includes a TRILL header processing module **922**. IP management module **930** further includes an ARP module **934** and an IP header processing module **936**.

TRILL ports **904** include inter-switch communication channels for communication with one or more RBridges. This inter-switch communication channel can be implemented via a regular communication port and based on any open or proprietary format. Furthermore, the inter-switch communication between RBridges is not required to be direct port-to-port communication.

During operation, TRILL ports **904** receive TRILL frames from (and transmit frames to) other RBridges. TRILL header processing module **922** processes TRILL header information of the received frames and performs routing on the received frames based on their TRILL headers, as described in conjunction with FIG. **4**B. TRILL management and forwarding module **920** forwards frames in the TRILL network toward other RBridges and frames destined to a layer-3 node toward the IP management module **930**. IP header processing module **936** forwards frames across VLANs.

In some embodiments, RBridge **900** may form a virtual RBridge and a virtual IP address, wherein TRILL management and forwarding module **920** further includes a virtual RBridge configuration module **924**, and IP management module **930** further includes a virtual IP router configuration module **938**. TRILL header processing module **922** generates the TRILL header and outer Ethernet header for ingress frames corresponding to the virtual RBridge. Virtual RBridge configuration module **924** manages the communication with gateway RBridges and handles various inter-switch communications, such as link and node failure notifications. Virtual RBridge configuration module **924** allows a user to configure and assign the identifier for the virtual RBridges, and decides whether a frame has to be promoted to layer-3, as described in conjunction with FIG. **7**B.

Furthermore, virtual IP router configuration module **938** handles various inter-switch communications, such as layer-3 link failure notifications. Virtual IP router configuration module **938** allows a user to configure and assign virtual IP addresses and a virtual MAC address.

ARP module **934** is responsible for ARP request replies, as described in conjunction with FIG. **4**B. ARP module **934** also maintains mappings between a virtual MAC address and a virtual IP address and stores the mappings in Storage **950**. Storage **950** also includes TRILL and IP routing information.

In some embodiments, gateway RBridge **900** may include a number of edge ports **902**, as described in conjunction with FIG. **1**. Edge ports **902** receive frames from (and transmit frames to) end devices. Ethernet frame processor **910** extracts and processes header information from the received frames. Ethernet frame processor **910** forwards the frames to IP management module **930** if there is no other intermediate RBridge between the end device and RBridge **900**.

In some embodiments, gateway RBridge **900** may include a VCS configuration module **944** that includes a virtual switch management module **940** and a logical switch **942** as described in conjunction with FIG. **1**. VCS configuration module **944** maintains a configuration database in storage **950** that maintains the configuration state of every switch within the VCS. Virtual switch management module **940** maintains the state of logical switch **942**, which is used to join other VCS switches. In some embodiments, logical switch **942** can be configured to operate in conjunction with Ethernet frame processor **910** as a logical Ethernet switch.

Note that the above-mentioned modules can be implemented in hardware as well as in software. In one embodiment, these modules can be embodied in computer-executable instructions stored in a memory which is coupled to one or more processors in gateway RBridge **900**. When executed, these instructions cause the processor(s) to perform the aforementioned functions.

In summary, embodiments of the present invention provide a switch, a method and a system for providing layer-3 support in a TRILL network. In one embodiment, the switch includes an IP header processor and a forwarding mechanism. The IP header processor identifies a destination IP address in a packet encapsulated with an inner Ethernet header, a TRILL header, and an outer Ethernet header. The forwarding mechanism determines an output port and constructs a new header for the packet based on the destination IP address. The switch also includes a packet processor which determines whether (1) an inner destination media access control (MAC) address corresponds to a local MAC address assigned to the switch; (2) a destination RBridge identifier corresponds to a local RBridge identifier assigned to the switch; and (3) an outer destination MAC address corresponds to the local MAC address. Such configuration provides a scalable and flexible solution to enable layer-3 processing in the switch.

The methods and processes described herein can be embodied as code and/or data, which can be stored in a computer-readable non-transitory storage medium. When a computer system reads and executes the code and/or data stored on the computer-readable non-transitory storage medium, the computer system performs the methods and processes embodied as data structures and code and stored within the medium.

The methods and processes described herein can be executed by and/or included in hardware modules or apparatus. These modules or apparatus may include, but are not limited to, an application-specific integrated circuit (ASIC) chip, a field-programmable gate array (FPGA), a dedicated or shared processor that executes a particular software module or a piece of code at a particular time, and/or other programmable-logic devices now known or later developed. When the hardware modules or apparatus are activated, they perform the methods and processes included within them.

The foregoing descriptions of embodiments of the present invention have been presented only for purposes of illustration and description. They are not intended to be exhaustive or to limit this disclosure. Accordingly, many modifications and variations will be apparent to practitioners skilled in the art. The scope of the present invention is defined by the appended claims.

What is claimed is:

1. A switch, comprising:

layer-2 processing circuitry configured to determine that:

outer and inner destination media access control (MAC) addresses of a packet correspond to a MAC address assigned to the switch, wherein the packet is encapsulated with an inner Ethernet header, a routable header, and an outer Ethernet header;

encapsulation circuitry configured to determine that:

a destination switch identifier of the routable header corresponds to a switch identifier assigned to the switch, wherein the routable header is placed between the outer and inner Ethernet headers;

Internet Protocol (IP) processing circuitry configured to lookup a destination IP address of a layer-3 header of the packet in a local layer-3 forwarding table in the switch, wherein the layer-3 header is distinct from the routable header, and wherein the destination IP address is a virtual IP address assigned to a virtual IP router, which is formed based on the switch in conjunction with at least another physical switch to operate as a single router; and

forwarding circuitry configured to determine an output port and construct a new header for the packet based on looking up the destination IP address in the local layer-3 forwarding table.

2. The switch of claim **1**, wherein the layer-2 processing circuitry is further configured to determine a first virtual local area network (VLAN) tag in the inner Ethernet header; and

wherein the new header includes a new inner Ethernet header comprising a second VLAN tag.

3. The switch of claim **1**, wherein the switch is a member of a network of interconnected switches, wherein the network of interconnected switches is controlled as a single logical switch.

4. The switch of claim **1**, further comprising switching circuitry configured to switch the packet between VLANs based on the destination IP address.

5. The switch of claim **1**, wherein the destination switch identifier is a virtual switch identifier; and

wherein the virtual IP router is associated with the virtual switch identifier.

6. The switch of claim **1**, wherein the IP processing circuitry is further configured to map the virtual IP address to a virtual media access control (MAC) address.

7. The switch of claim **1**, further comprising Address Resolution Protocol (ARP) circuitry configured to generate an ARP response for an IP address assigned to the switch, wherein the ARP response comprises a MAC address assigned to the switch.

8. A method, comprising:

determining that:

outer and inner destination media access control (MAC) addresses of a packet correspond to a MAC address assigned to a switch, wherein the packet is encapsulated with an inner Ethernet header, a routable header, and an outer Ethernet header; and

a destination switch identifier of the routable header corresponds to a switch identifier assigned to the switch, wherein the routable header is placed between the outer and inner Ethernet headers;

looking up a destination Internet Protocol (IP) address of a layer-3 header of the packet in a local layer-3 forwarding table in the switch, wherein the layer-3 header is distinct from the routable header, and wherein the destination IP address is a virtual IP address assigned to a virtual IP router, which is formed based on the switch in conjunction with at least another physical switch to operate as a single router; and

determining an output port and constructing a new header for the packet based on looking up the destination IP address in the local layer-3 forwarding table.

9. The method of claim **8**, further comprising:

determining a first virtual local area network (VLAN) tag in the inner Ethernet header; and

including in the new header a new inner Ethernet header comprising a second VLAN tag.

10. The method of claim **8**, wherein the switch is a member of a network of interconnected switches wherein the network of interconnected switches is controlled as a single logical switch.

11. The method of claim **8**, further comprising switching the packet between VLANs based on the destination IP address.

12. The method of claim **8**, wherein the destination switch identifier is a virtual switch identifier; and

wherein the virtual IP router is associated with the virtual switch identifier.

13. The method of claim **8**, further comprising mapping the virtual IP address to a virtual media access control (MAC) address.

14. The method of claim **8**, further comprising generating an Address Resolution Protocol (ARP) response for an IP address assigned to the switch, wherein the ARP response comprises a MAC address assigned to the switch.

15. A computing system, comprising:

a processor; and

a non-transitory computer-readable storage medium storing instructions which when executed by the processor causes the processor to perform a method, the method comprising:

determining that:

outer and inner destination media access control (MAC) addresses of a packet correspond to a MAC address assigned to the computing system, wherein the packet is encapsulated with an inner Ethernet header, a routable header, and an outer Ethernet header; and

a destination switch identifier of the routable header corresponds to a switch identifier is assigned to the computing system;

looking up a destination Internet Protocol (IP) address of a layer-3 header of the packet in a local layer-3 forwarding table in the computing system, wherein the layer-3 header is distinct from the routable header and wherein the destination IP address is a virtual IP address assigned to a virtual IP router, which is formed based on the switch in conjunction with at least another physical switch to operate as a single router; and

determining an output port and constructing a new header for the packet based on looking up the destination IP address in the local-layer-3 forwarding table.

16. The computing system of claim **15**, within the method further comprises:

determining a first virtual local area network (VLAN) tag in the inner Ethernet header; and

including in the new header a new inner Ethernet header comprising a second VLAN tag.

17. The computing system of claim **15**, wherein the computing system is a member of a network of interconnected switches, wherein the network of interconnected switches is controlled as a single logical switch.

18. The computing system of claim **15**,

wherein the destination switch identifier is a virtual switch identifier; and

wherein the virtual IP router is associated with the virtual switch identifier.

19. The computing system of claim **15**, wherein the method further comprises generating an Address Resolution Protocol (ARP) response for an IP address assigned to the computing system, wherein the ARP response comprises a MAC address assigned to the computing system.

20. The computing system of claim **15**, whether the method further comprises switching the packet between VLANs based on the destination IP address.

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