US012395432B2

(12) **United States Patent**
Kim et al.

(10) **Patent No.:** **US 12,395,432 B2**
(45) **Date of Patent:** **Aug. 19, 2025**

(54) **SWITCH-BASED WORKLOAD DISTRIBUTION FOR VIRTUALIZED RANs**

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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 426 days.

(21) Appl. No.: **17/331,782**

(22) Filed: **May 27, 2021**

(65) **Prior Publication Data**

US 2022/0385577 A1 Dec. 1, 2022

(51) **Int. Cl.**
H04L 47/12 (2022.01)
H04L 12/46 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***H04L 47/12*** (2013.01); ***H04L 12/4641*** (2013.01); ***H04L 47/30*** (2013.01);
(Continued)

(58) **Field of Classification Search**
CPC H04L 47/12; H04L 12/4641; H04L 47/30; H04L 69/22; H04L 47/746; H04L 47/822;
(Continued)

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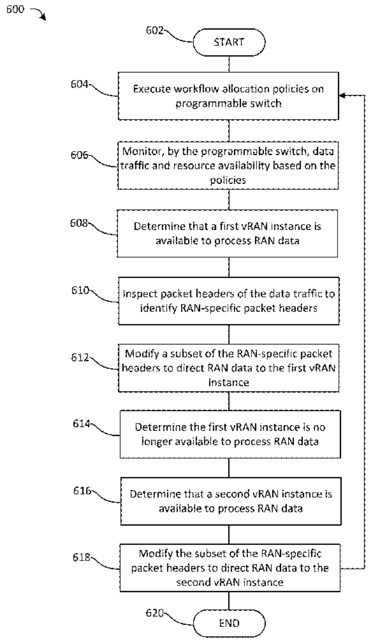
Primary Examiner — Jung H Park

(57) **ABSTRACT**

Aspects of the present disclosure relate to allocating workloads to vRANs via programmable switches at far-edge cloud datacenters. Traditionally, traffic allocation is handled by dedicated servers running load-balancing software. However, rerouting RAN traffic to such servers increases both energy and capital costs, degrades end-to-end performance, and requires additional physical space, all of which are undesirable or even infeasible for a RAN far-edge datacenter. Since switches are located in the path of data traffic, workflow policies can be designed to inspect packet headers of incoming traffic, evaluate real-time network information, determine available vRAN instances, and update the packet headers to steer the incoming traffic for processing. As network conditions change, the workflow policies enable the switch to dynamically redirect workloads to alternative vRANs for processing. As a result, RAN processing efficiency and fault tolerance are improved—even with changing network conditions and spikes in data traffic.

20 Claims, 11 Drawing Sheets


600
602
START
604
Execute workflow allocation policies on programmable switch
606
Monitor, by the programmable switch, data traffic and resource availability based on the policies
608
Determine that a first vRAN instance is available to process RAN data
610
Inspect packet headers of the data traffic to identify RAN-specific packet headers
612
Modify a subset of the RAN-specific packet headers to direct RAN data to the first vRAN instance
614
Determine the first vRAN instance is no longer available to process RAN data
616
Determine that a second vRAN instance is available to process RAN data
618
Modify the subset of the RAN-specific packet headers to direct RAN data to the second vRAN instance
620
END

(51) **Int. Cl.**

H04L 47/30	(2022.01)
H04L 69/22	(2022.01)
H04W 24/04	(2009.01)
H04W 28/084	(2023.01)
H04W 84/04	(2009.01)

(52) **U.S. Cl.**

CPC ***H04L 69/22*** (2013.01); ***H04W 24/04*** (2013.01); ***H04W 28/084*** (2023.05); *H04W 84/042* (2013.01)

(58) **Field of Classification Search**

CPC H04L 67/1008; H04L 41/0894; H04L 41/0895; H04L 47/726; H04L 47/78; H04L 47/828; H04L 43/0805; H04L 43/0888; H04W 24/04; H04W 28/0289; H04W 84/042

See application file for complete search history.

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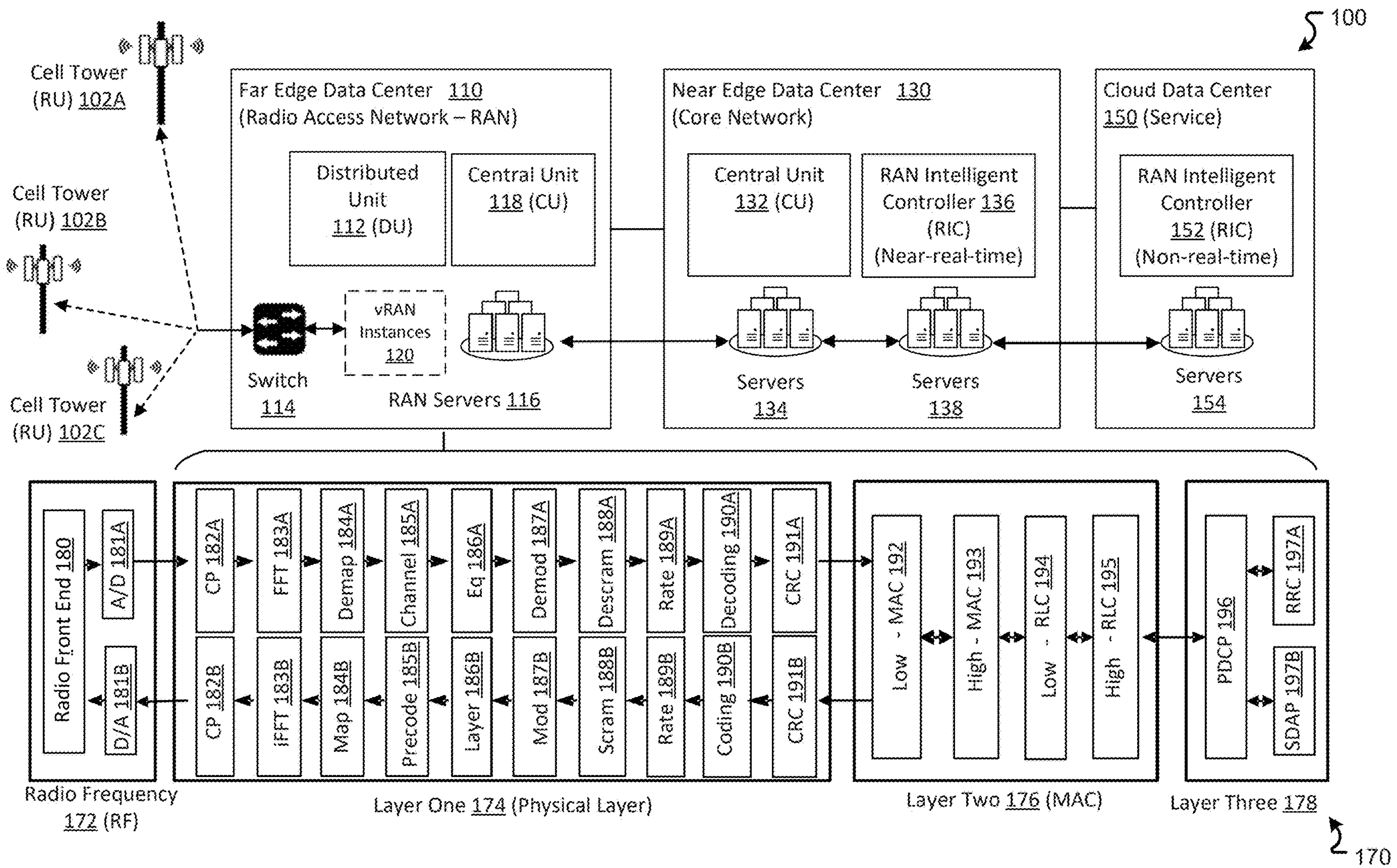

100
Cell Tower
(RU) 102A
Cell Tower
(RU) 102B
Cell Tower
(RU) 102C
Far Edge Data Center 110
(Radio Access Network – RAN)
Distributed
Unit
112 (DU)
Central Unit
118 (CU)
vRAN
Instances
120
Switch
114
RAN Servers 116
Near Edge Data Center 130
(Core Network)
Central Unit
132 (CU)
RAN Intelligent
Controller 136
(RIC)
(Near-real-time)
Servers
134
Servers
138
Cloud Data Center
150 (Service)
RAN Intelligent
Controller
152 (RIC)
(Non-real-time)
Servers
154
Radio Front End 180
A/D 181A
D/A 181B
Radio Frequency
172 (RF)
CP 182A
FFT 183A
Demap 184A
Channel 185A
Eq 186A
Demod 187A
Descram 188A
Rate 189A
Decoding 190A
CRC 191A
CP 182B
iFFT 183B
Map 184B
Precode 185B
Layer 186B
Mod 187B
Scram 188B
Rate 189B
Coding 190B
CRC 191B
Layer One 174 (Physical Layer)
Low - MAC 192
High - MAC 193
Low - RLC 194
High - RLC 195
Layer Two 176 (MAC)
PDCP 196
RRC 197A
SDAP 197B
Layer Three 178
170

FIG. 1

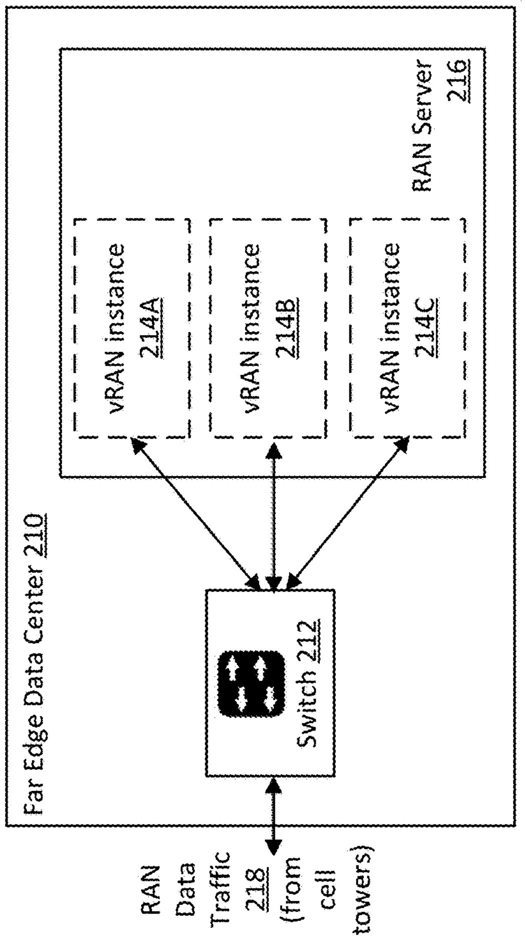

200
Far Edge Data Center 210
Switch 212
RAN Server 216
vRAN instance 214A
vRAN instance 214B
vRAN instance 214C
RAN Data Traffic 218 (from cell towers)

FIG. 2A

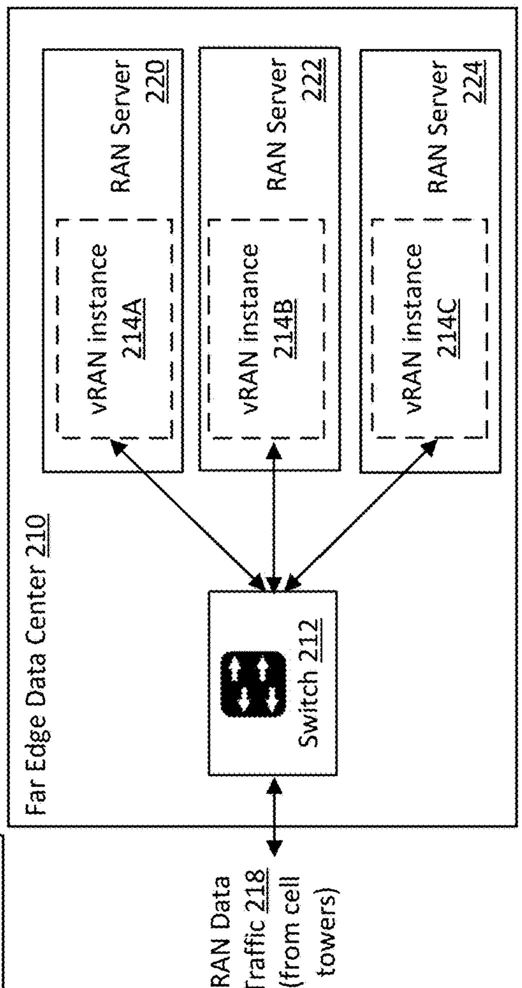

Far Edge Data Center 210
Switch 212
RAN Server 220
RAN Server 222
RAN Server 224
vRAN instance 214A
vRAN instance 214B
vRAN instance 214C
RAN Data Traffic 218 (from cell towers)

FIG. 2B

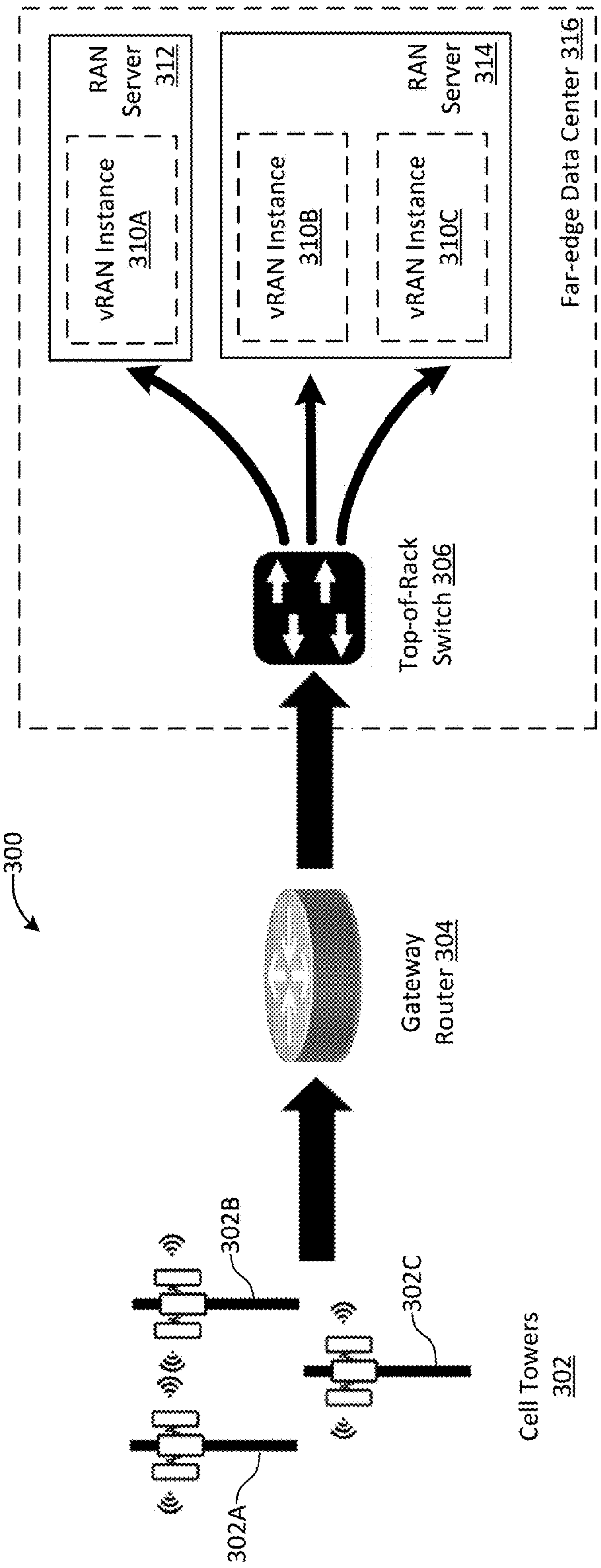
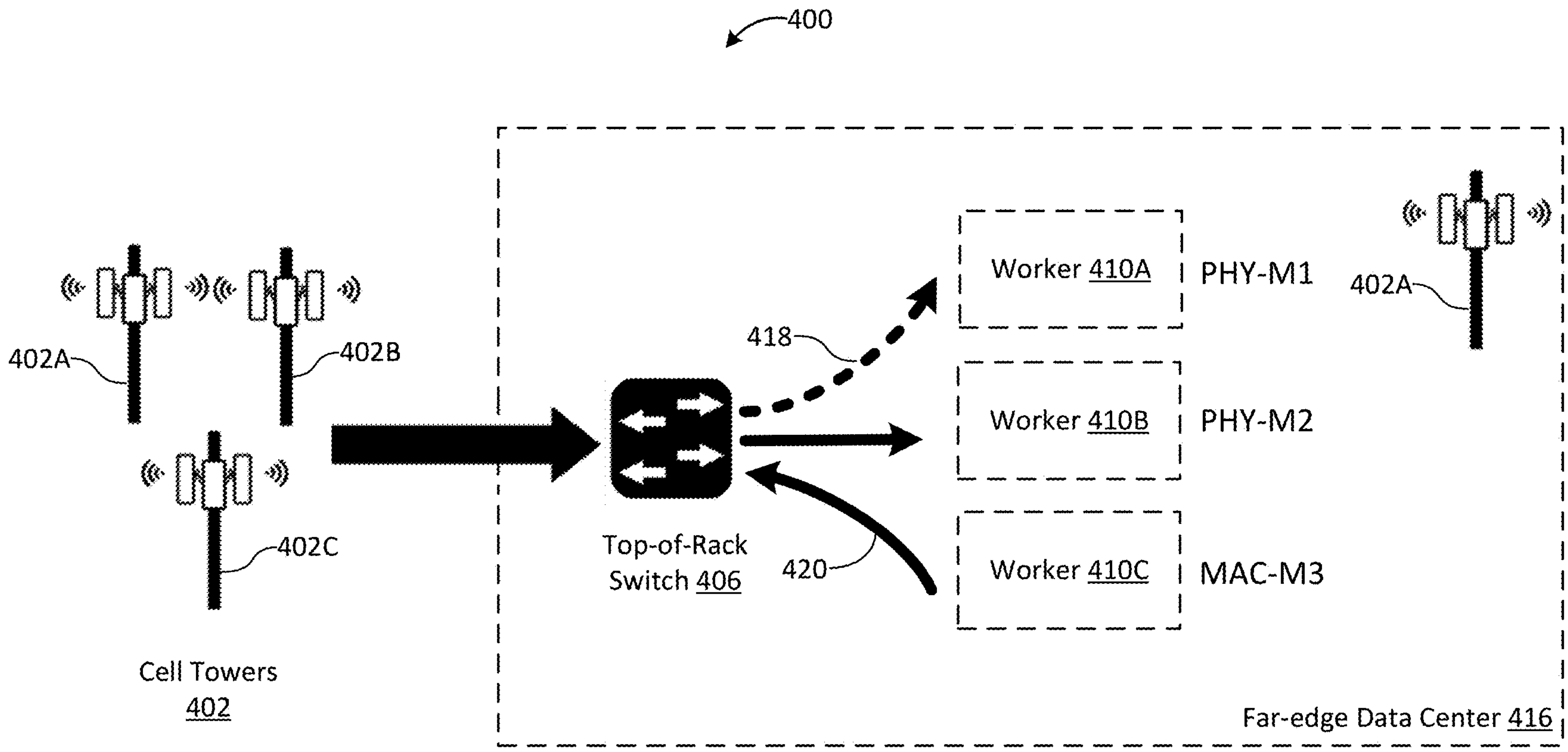
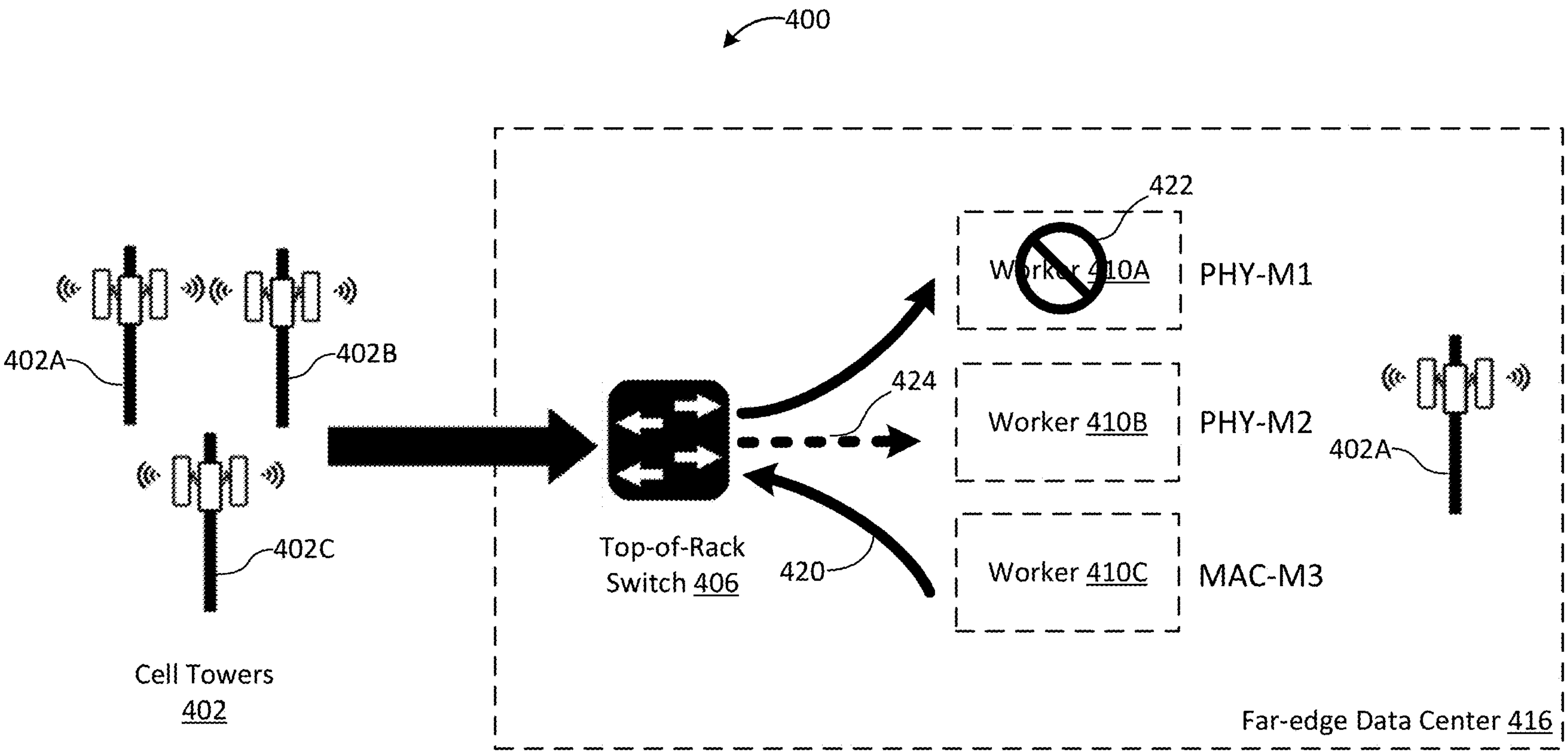

300
302A
302B
302C
Cell Towers 302
Gateway Router 304
Top-of-Rack Switch 306
vRAN Instance 310A
RAN Server 312
vRAN Instance 310B
vRAN Instance 310C
RAN Server 314
Far-edge Data Center 316

FIG. 3



*Each vRAN Instance corresponds to a virtual machine (M) (or "Worker") for processing cell tower workloads

FIG. 4A



*Each vRAN Instance corresponds to a virtual machine (M) (or "Worker") for processing cell tower workloads

FIG. 4B

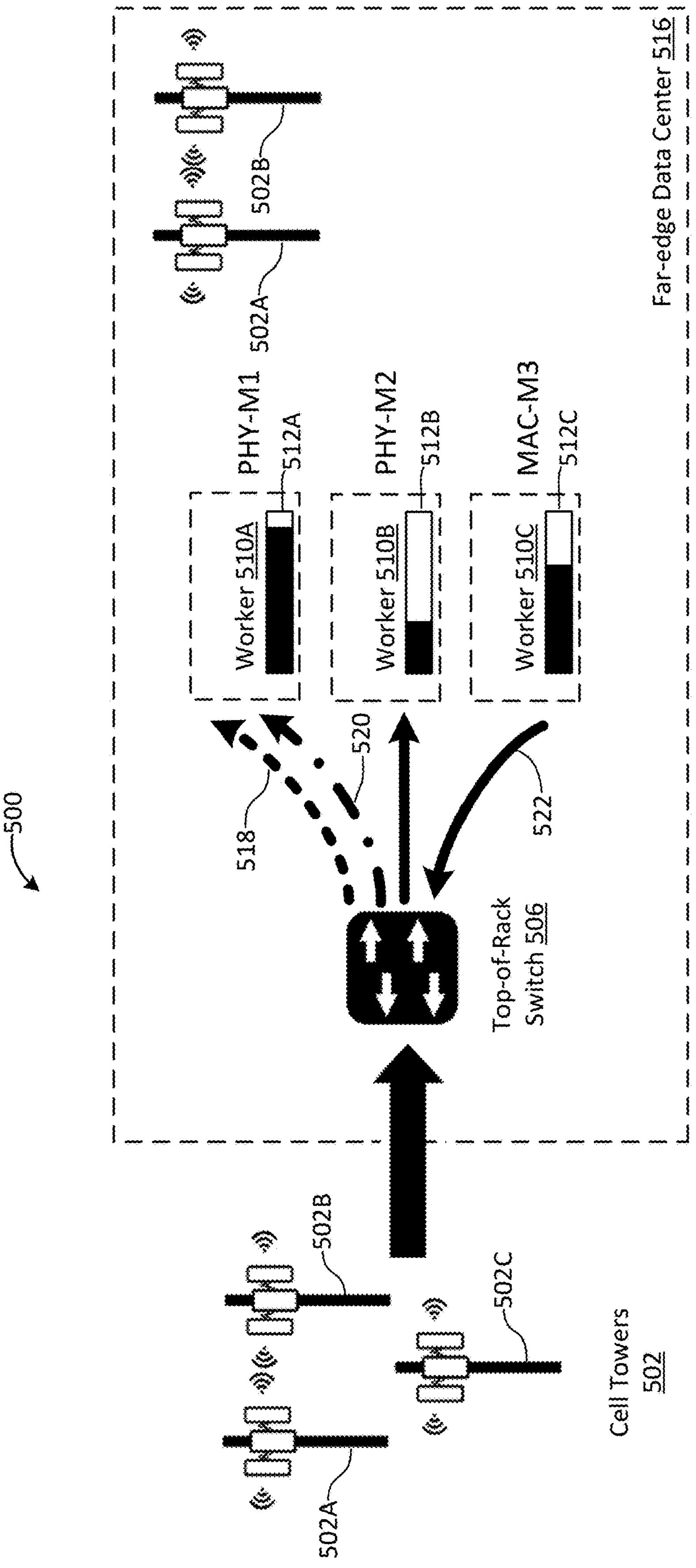

500
502A
502B
502C
Cell Towers 502
Far-edge Data Center 516
Top-of-Rack Switch 506
518
520
522
Worker 510A
PHY-M1
512A
Worker 510B
PHY-M2
512B
Worker 510C
MAC-M3
512C
502A
502B

FIG. 5A

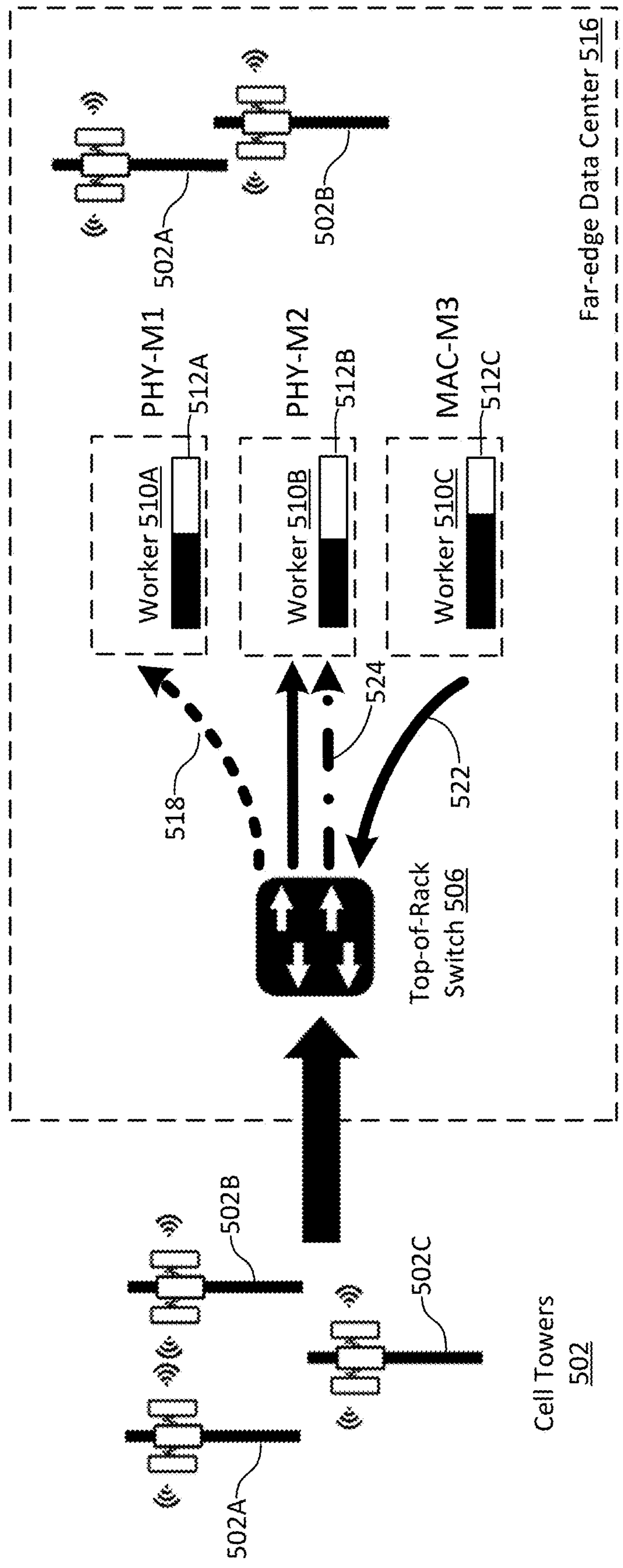
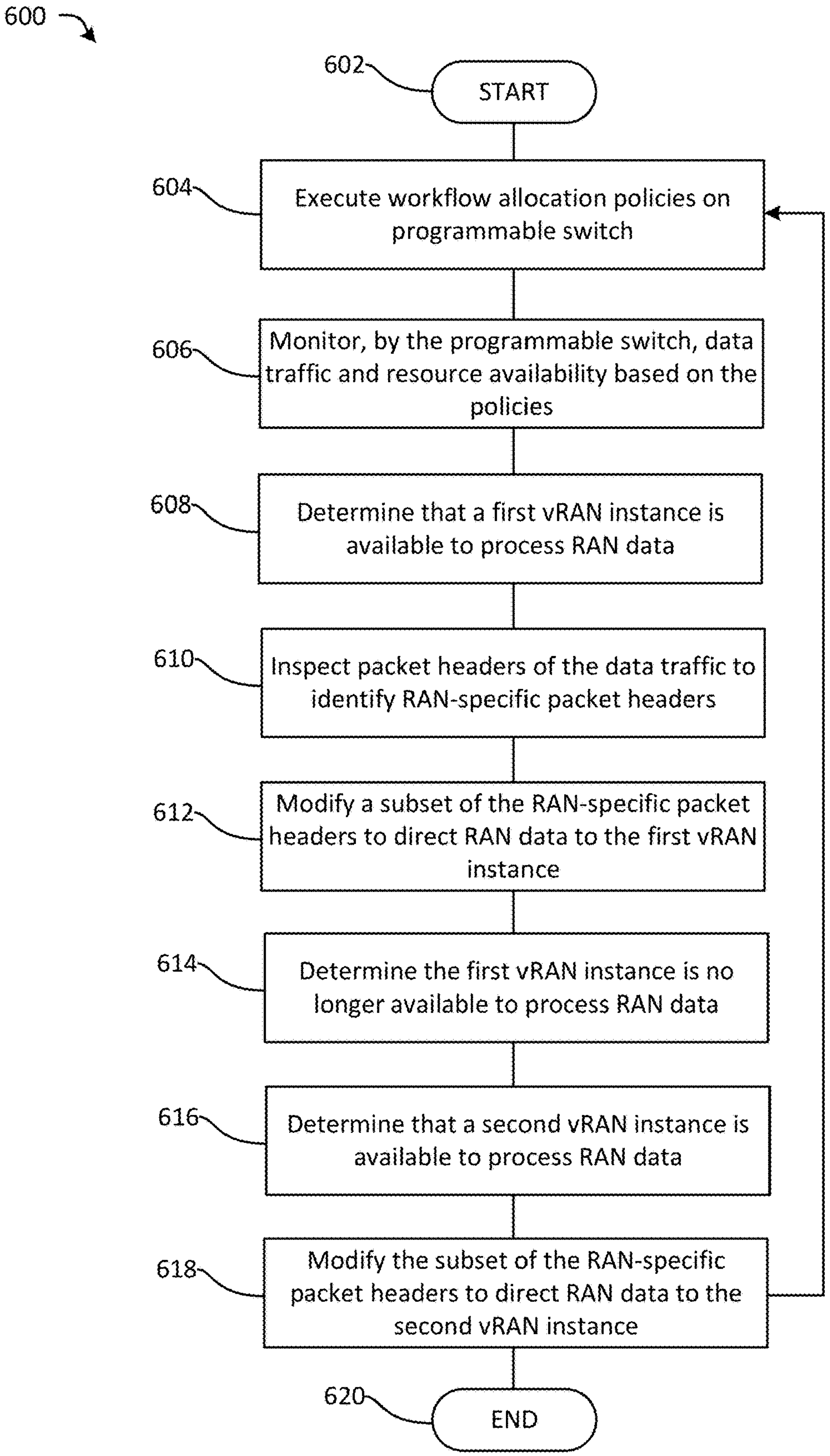

Cell Towers 502
502A
502B
502C
Top-of-Rack Switch 506
518
524
522
Worker 510A
512A
PHY-M1
Worker 510B
512B
PHY-M2
Worker 510C
512C
MAC-M3
502A
502B
Far-edge Data Center 516

FIG. 5B


600
602
START
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Execute workflow allocation policies on programmable switch
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616
Determine that a second vRAN instance is available to process RAN data
618
Modify the subset of the RAN-specific packet headers to direct RAN data to the second vRAN instance
620
END

FIG. 6

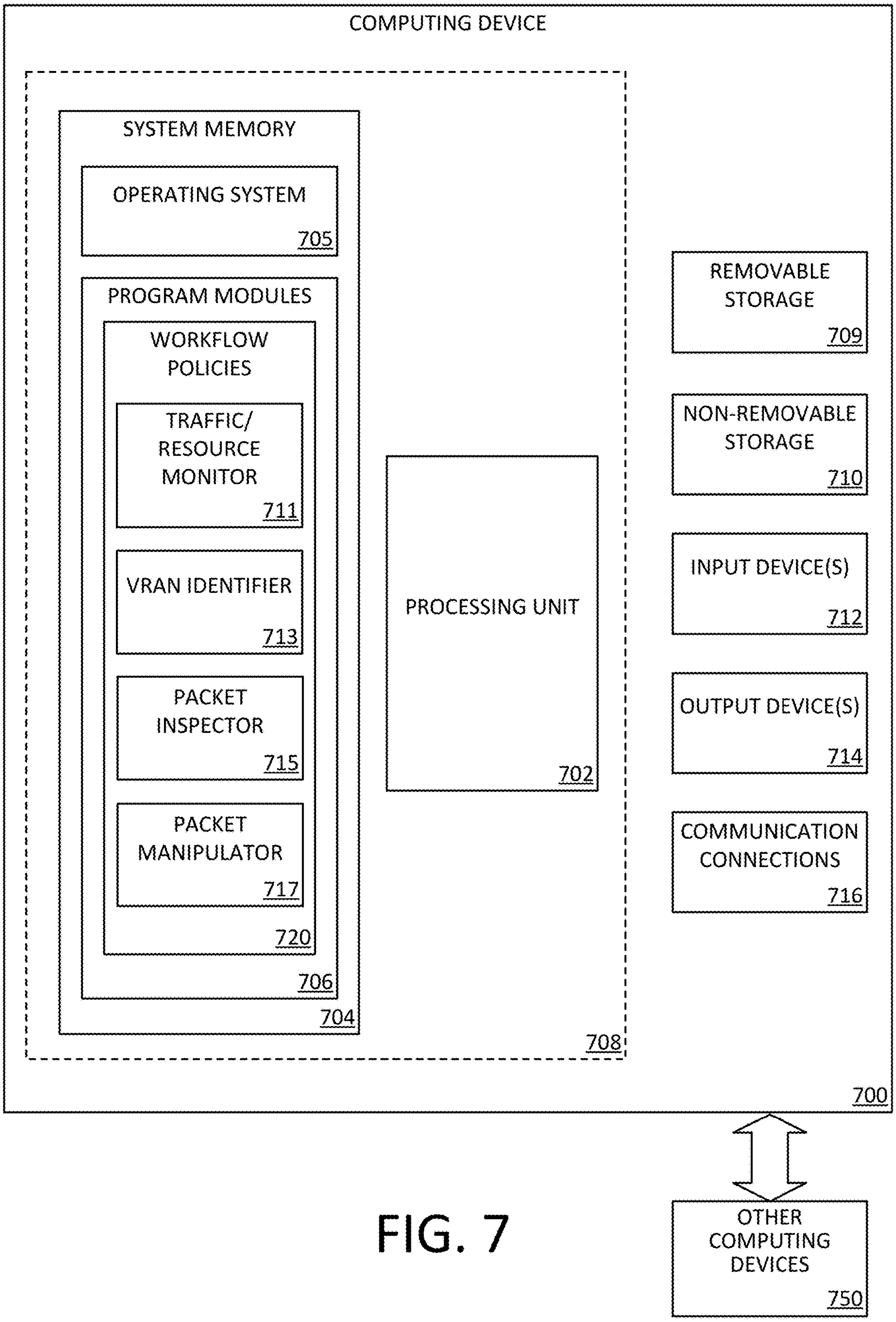
COMPUTING DEVICE
SYSTEM MEMORY
OPERATING SYSTEM
705
PROGRAM MODULES
WORKFLOW POLICIES
TRAFFIC/ RESOURCE MONITOR
711
VRAN IDENTIFIER
713
PACKET INSPECTOR
715
PACKET MANIPULATOR
717
720
706
704
PROCESSING UNIT
702
708
REMOVABLE STORAGE
709
NON-REMOVABLE STORAGE
710
INPUT DEVICE(S)
712
OUTPUT DEVICE(S)
714
COMMUNICATION CONNECTIONS
716
700
OTHER COMPUTING DEVICES
750

FIG. 7

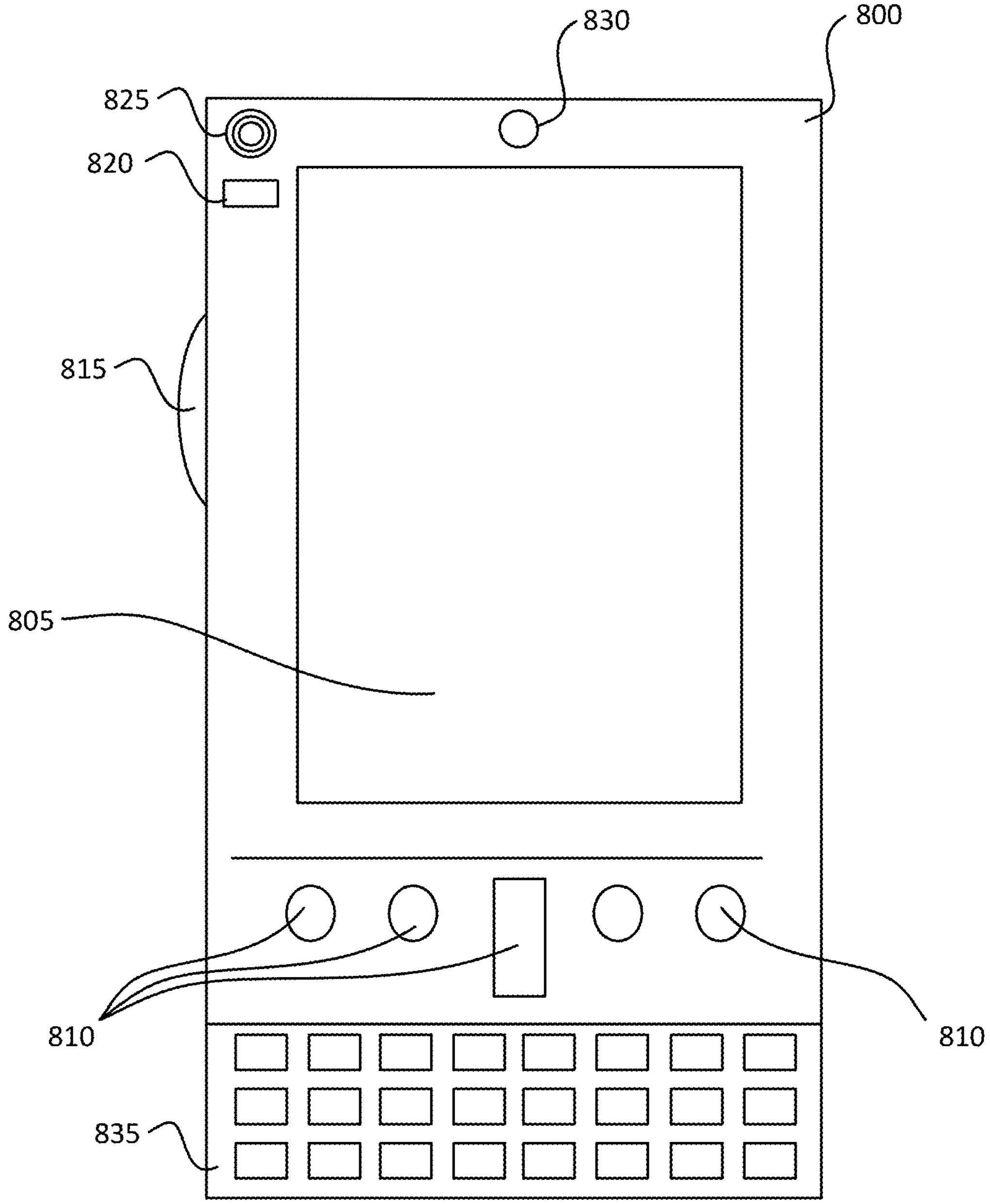

FIG. 8A

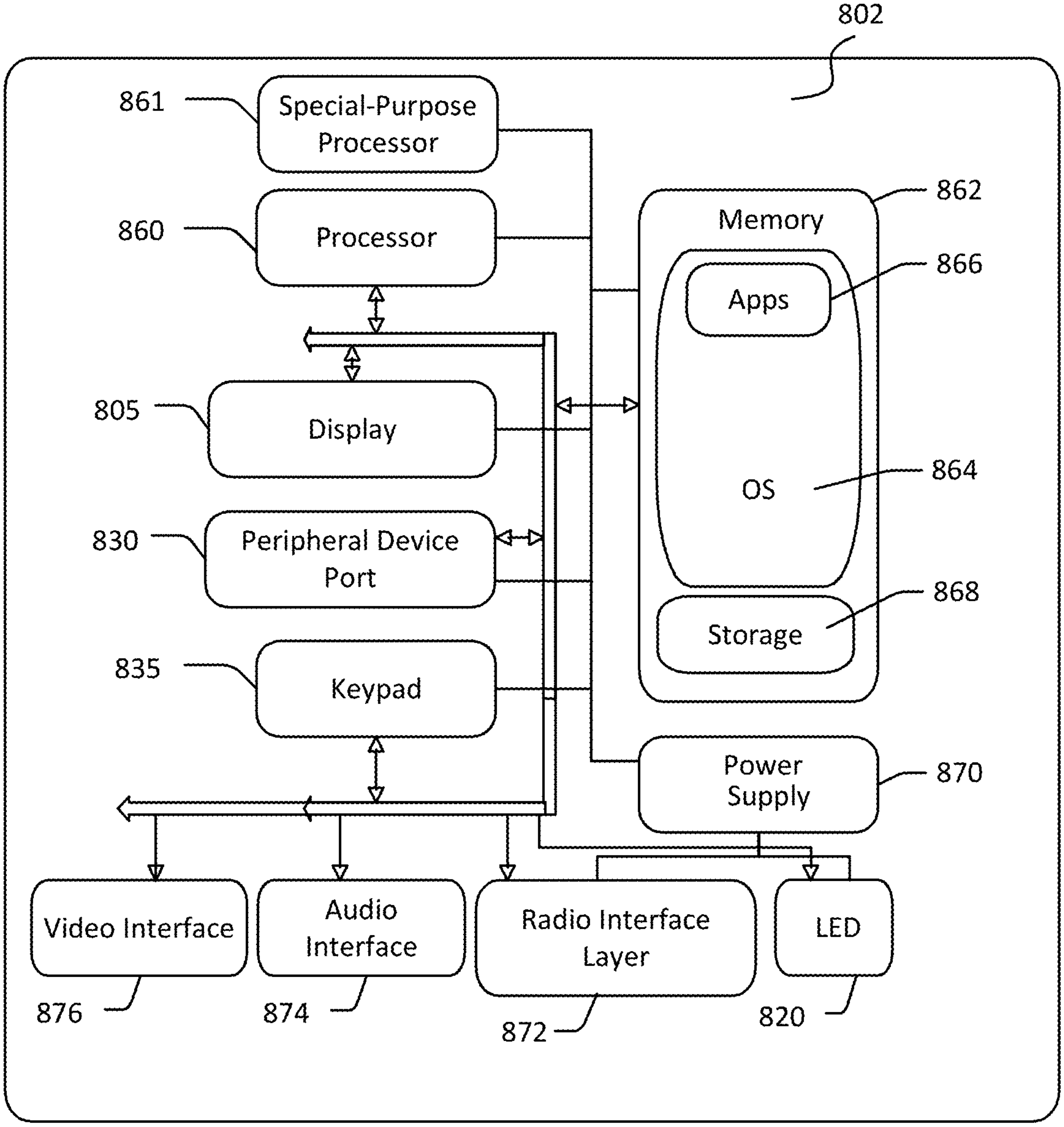
802
861
Special-Purpose Processor
860
Processor
805
Display
830
Peripheral Device Port
835
Keypad
Memory
862
Apps
866
OS
864
Storage
868
Power Supply
870
Video Interface
876
Audio Interface
874
Radio Interface Layer
872
LED
820

FIG. 8B

SWITCH-BASED WORKLOAD DISTRIBUTION FOR VIRTUALIZED RANs

BACKGROUND

Demand for integration between a cloud network and a radio access network (RAN) and/or a core network for wireless telecommunications has rapidly increased. The RAN provides wireless connectivity to mobile computing devices by converting data into data packets. The core network coordinates among various parts of the RAN and provides connectivity to a packet-based network (e.g., the Internet). Traditional wireless telecommunications deployed servers with hardware that was specialized to particular types of processing and was typically built with a capacity to accommodate an estimated peak load of the network traffic. Use of cloud network technology, particularly virtual server technologies, has enabled decoupling of at least some wireless data processing from specialized hardware onto general-purpose servers. The general-purpose servers, combined with accelerators and the virtualization technologies, are able to dynamically change resource usage based on network demands.

With the advent of 5G, which is a system of mobile communications that improved upon aspects of the previous 4G system (reduced latency, increased bandwidth, etc.), the scope of mobile networks has increased to provide a broad range of wireless services delivered across multiple platforms and multi-layer networks. 5G specifications outline a host of performance requirements related to bandwidth, peak data rate, energy efficiency, reliability, latency (both user-plane and control-plane latency), traffic capacity, etc. To meet these requirements, the RAN architecture has expanded. For instance, Multi-Access Edge Computing (MEC) brings applications from centralized datacenters to the network edge, closer to end users. MEC provides low latency, high bandwidth, and real-time access to RAN information. Distributing computing power enables the high volume of 5G devices and facilitates disaggregated, virtual RANs to create additional access points. Network Function Virtualization (NFV) replaces network functions like firewalls, load balancers, and routers with virtualized instances that run as software. Enhanced Common Public Radio Interface (eCPRI) can be used, for instance, for the fronthaul interface of a cloud RAN (e.g., for the real-time processing by the distributed unit (DU)).

As will be described further below, the cloud RAN for 5G comprises a distributed architecture including a Radio Unit (RU) at one or more cell towers and cloud servers at the network edge associated with one or more of a Distributed Unit (DU), a Central Unit (CU), and a RAN Intelligent Controller (RIC). The DU is associated with network switches and processes data in a series of operations associated with at least layer one (i.e., the “PHY” or physical layer) and layer two (the “MAC” or data link layer) of the Open Systems Interconnection (OSI) model. However, while there have been proposals to run PHY/MAC processing on multiple servers in the edge, it is still unclear how to distribute workloads (e.g., for processing IQ samples from cell towers) across servers. For instance, steering workloads in a correct and timely manner is critical in the RAN in various scenarios including load balancing, server failover, and maintenance.

It is with respect to these and other general considerations that the aspects disclosed herein have been made. Also, although relatively specific problems may be discussed, it should be understood that the examples should not be limited to solving the specific problems identified in the background or elsewhere in this disclosure.

SUMMARY

According to the present disclosure, the above and other issues are resolved by distributing workloads to virtual RANs (“vRANs”) via programmable switches at far-edge cloud datacenters. Traditionally, network traffic allocation is handled by dedicated servers running load-balancing software. However, rerouting RAN traffic to such servers increases both energy and capital costs, degrades the end-to-end performance, and requires additional physical space, all of which are undesirable or even infeasible for a RAN far-edge datacenter—particularly in view of the heightened 5G performance requirements.

As described further herein, since switches are located in the path of data traffic, real-time network information (e.g., queue length, server state) can be leveraged for real-time RAN workload balancing. By leveraging the proximity and programmability of the switches, steering decision policies can be quickly applied on the RAN workloads without incurring the performance, energy, and capital cost overheads of traditional systems. In particular, the steering decision policies can be designed to enable a switch to inspect packet headers of incoming traffic, evaluate real-time network information, determine available vRAN instances (or “workers”) to process the incoming traffic, and update the packet headers to steer the incoming traffic to the determined vRAN for processing—all essentially in real time. As network conditions change, the steering decision policies enable a programmable switch to dynamically redirect workloads to alternative vRANs for processing. As a result, with improved vRAN allocation, RAN processing efficiency and fault tolerance may improve—even in instances of changing network conditions and spikes in data traffic.

This Summary is provided to introduce a selection of concepts in a simplified form, which is further described below in the Detailed Description. This Summary is not intended to identify key features or essential features of the claimed subject matter, nor is it intended to be used to limit the scope of the claimed subject matter. Additional aspects, features, and/or advantages of examples will be set forth in part in the following description and, in part, will be apparent from the description, or may be learned by practice of the disclosure.

BRIEF DESCRIPTIONS OF THE DRAWINGS

Non-limiting and non-exhaustive examples are described with reference to the following figures.

FIG. **1** illustrates an overview of an example system implementing a cloud RAN in accordance to aspects of the present disclosure.

FIGS. **2**A-B illustrate examples of a far-edge datacenter of a cloud RAN hosting virtual RAN instances in accordance with aspects of the present disclosure.

FIG. **3** illustrates a system depicting aspects of workload allocation to vRANs by a programmable switch associated with a far-edge datacenter of a cloud RAN in accordance with aspects of the present disclosure.

FIGS. **4**A-B illustrate a system depicting aspects of dynamic workload reallocation for server failover or maintenance by a programmable switch associated with a far-edge datacenter of a cloud RAN in accordance with aspects of the present disclosure.

FIGS. **5**A-B illustrate a system depicting aspects of dynamic workload reallocation for worker overload by a programmable switch associated with a far-edge datacenter of a cloud RAN in accordance with aspects of the present disclosure.

FIG. **6** illustrates an example method for dynamic workload allocation to vRANs by a programmable switch in accordance with aspects of the present disclosure.

FIG. **7** is a block diagram illustrating example physical components of a computing device with which aspects of the disclosure may be practiced.

FIG. **8**A is a simplified diagram of a mobile computing device with which aspects of the present disclosure may be practiced.

FIG. **8**B is another simplified block diagram of a mobile computing device with which aspects of the present disclosure may be practiced.

DETAILED DESCRIPTION

Various aspects of the disclosure are described more fully below with reference to the accompanying drawings, which form a part hereof, and which show specific example aspects. However, different aspects of the disclosure may be implemented in many different ways and should not be construed as limited to the aspects set forth herein; rather, these aspects are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the aspects to those skilled in the art. Practicing aspects may be as methods, systems, or devices. Accordingly, aspects may take the form of a hardware implementation, an entirely software implementation or an implementation combining software and hardware aspects. The following detailed description is, therefore, not to be taken in a limiting sense.

A mobile wireless telecommunication network may use a cloud service for implementing a RAN. In this case, the cloud service connects cell towers, with which mobile devices (e.g., smartphones) connect, to the public network (e.g., the Internet) and/or private networks. The cloud service provides virtual servers and other computing resources for dynamically scaling the computing capacity as needed based on the volume of data traffic. In aspects, a cloud RAN infrastructure represents an implementation of cloud services for the RAN. In contrast to a typical cloud service, the cloud RAN infrastructure includes geographical and physical constraints as well as latency constraints imposed by RAN standards. The cloud RAN infrastructure includes connection to at least one cell tower associated with a Radio Unit (RU) and cloud servers associated with one or more of a Distributed Unit (DU), a Central Unit (CU), and a RAN Intelligent Controller (RIC). The cell tower is in the field, where mobile devices connect over wireless cellular communications, and the RU of the cell tower connects to a DU of a RAN server at a far-edge datacenter. To enable real-time processing of RAN data traffic, the far-edge datacenter is relatively close (e.g., a few kilometers) to the cell tower.

As noted above, the DU is associated with network switches and processes data in a series of operations associated with at least layer one (i.e., the "PHY" or physical layer) and layer two (the "MAC" or data link layer) of the Open Systems Interconnection (OSI) model. The physical layer ("PHY") connects a data link layer device, e.g., "MAC" (medium access control), to a physical medium, e.g., optical fiber, copper cable. In aspects, a switch is a hardware device that connects devices on a digital network by using packet switching to receive and forward data to a destination device. Packet switching involves grouping the transmitted data into "packets." A "header" of each packet includes a "MAC address," which is a unique identifier used to direct the packet in the data link layer (layer two of the OSI model) to a destination device. A "payload" of each packet includes the transmitted data, which is ultimately extracted and used by application software. Some switches comprise application-specific integrated circuits (ASICs), which are integrated circuit chips programed for a specific use. These switches may also be referred to as "fixed-function" switches, which process packets according to fixed rules associated with a limited set of networking protocols. In contrast, programmable switches may be based on a protocol independent switch architecture (PISA), which enables developers to program each stage of packet processing. In this way, distinct treatment of different types of packets may be designed and implemented.

To meet 5G requirements, layers one and two need to be processed in essentially real time. In particular, steering workloads in a correct and timely manner is critical in the RAN in various scenarios including server failover and maintenance. However, while there have been proposals to run PHY/MAC processing on multiple servers in the edge, it is still unclear how to distribute workloads (e.g., for processing IQ samples from cell towers) across servers. Traditionally, network traffic allocation is handled by dedicated servers running load-balancing software. However, rerouting RAN traffic to such servers increases both energy and capital costs, degrades the end-to-end performance, and requires additional physical space, all of which are undesirable or even infeasible for a RAN far-edge datacenter—particularly in view of the heightened 5G performance requirements.

As discussed in more detail below, the present disclosure addresses the above and other issues by distributing workloads to virtual RANs ("vRANs") via programmable switches at far-edge cloud datacenters. Since switches are located in the path of data traffic, real-time network information (e.g., queue length, server state) can be leveraged for real-time RAN workload balancing. By leveraging the proximity and programmability of the switches, steering decision policies can be applied on the RAN workloads in real-time without incurring the performance, energy, and capital cost overheads of traditional systems. In particular, the steering decision policies can be designed to enable a switch to inspect packet headers of incoming traffic, evaluate real-time network information, determine available vRAN instances (or "workers") to process the incoming traffic, and update the packet headers to steer the incoming traffic to the determined vRAN for processing—all in essentially real time. As network conditions change, e.g., vRANs become overloaded (e.g., queue length increases), servers hosting the vRANs fail, power down (e.g., at night), or undergo maintenance, or the volume of data traffic fluctuates (e.g., during peak mobile usage periods), the steering decision policies enable a programmable switch to dynamically redirect workloads to alternative vRANs for processing. As a result, with improved vRAN allocation, RAN processing efficiency and fault tolerance may improve—even in instances of changing network conditions and spikes in data traffic.

FIG. **1** illustrates an overview of an example system **100** in which switch-based workload distribution may be implemented in accordance with the aspects of the present disclosure. Cell towers **102**A-C transmit and receive wireless communications with mobile computing devices (e.g., smartphones) over a radio access network (RAN). The example system **100** further includes far-edge datacenter **110** (switches, RAN servers), near-edge datacenter **130** (core network servers), and cloud datacenter **150** (cloud services). In aspects, the example system **100** corresponds to a cloud RAN infrastructure for a mobile wireless telecommunication network.

The far-edge datacenter **110** is a datacenter that is part of the cloud RAN, which includes distributed unit **112** (DU) and central unit **118** (CU). In aspects, the far-edge datacenter **110** enables cloud integration with a radio access network (RAN). The far-edge datacenter **110** includes a switch **114** and RAN servers **116** configured to host vRAN instances **120** for processing RAN data. A virtual RAN (or "vRAN") is a type of RAN in which networking functions (including the control and data planes) are separated from the hardware that hosts the vRAN (e.g., RAN server(s) **116**). In general, network function virtualization (NFV) involves enabling software to perform hardware-based functions, which enables increased responsiveness to network fluctuations and increased flexibility for enhancement since software can be upgraded or repaired more easily than hardware. In aspects, a vRAN instance **120** may be referred to as a "worker" for processing workflows.

The switch **114** and the RAN servers **116** process incoming data traffic and outgoing data traffic associated with layer one (the physical layer) **174** and at least a part of layer two (MAC) **176**. In aspects, the far-edge datacenter **110** is generally geographically remote from the cloud datacenters associated with the core network and cloud services. The remote site is in proximity to the cell towers **102**A-C. For example, the proximity in the present disclosure may be within a few kilometers or more. In aspects, the upstream data traffic corresponds to data flowing from the cell towers **102**A-C to servers **154** in the cloud datacenter **150** (service). Similarly, the downstream data traffic corresponds to data flowing from the cloud datacenter **150** (service) to the cell towers.

The near-edge datacenter **130** (e.g., hosting the core network) includes a central unit **132** (CU) and RAN intelligent controller **136** (RIC) (near real-time processing, which may be less strictly time-sensitive than real-time processing). As illustrated, CU **132** is associated with servers **134** and RIC **136** is associated with servers **138**. In aspects, the near-edge datacenter **130** is at a regional site of a private cloud service. For example, the regional site may be about tens of kilometers from the cell towers.

The cloud datacenter **150** (service) includes RIC **152** (non-real-time processing) associated with servers **154**. For example, RIC **152** processes non-real-time service operations. In aspects, the cloud datacenter **150** may be at a central location in a cloud RAN infrastructure. For example, the central locations may be hundreds of kilometers from the cell towers.

In aspects, the far-edge datacenter **110**, which is closer to the cell towers **102**A-C than the cloud datacenter **150**, provides real-time processing. In contrast, the cloud datacenter **150**, which is the furthest from the cell towers **102**A-C in the cloud RAN infrastructure, provides processing in a non-real-time manner.

The operational partitions **170** illustrate various operational segments for processing data traffic in the RAN. For example, the operational partitions **182-191** may correspond to layer one **174** processing and operational partitions **192-195** may correspond to layer two **176** processing of the OSI seven-layer model.

In aspects, conversion of data associated with a radio frequency **172** (RF) occurs prior to processing data at layer one **174**. For radio frequency **172** (RF) data processing, the radio front-end partition receives and sends data through the cell towers **102**A-C to mobile computing devices over wireless communications. The A/D **181**A converts analog data from the radio front-end to digital data for the upstream data traffic. The D/A **181**B converts digital data into analog data for the downstream data traffic. In aspects, the interface between DU and RU in a cloud RAN is referred to as "Fronthaul." The Fronthaul defines a number of "planes" of operations, including the "c-plane" (control plane), the "u-plane" (user plane), the "s-plane" (synchronization plane), and the "m-plane" (management plane). In general, c-plane data is directed to scheduling and coordination of data transmission, u-plane data is directed to efficient data transfer (e.g., defined by 5G specifications), s-plane data is directed to timing and synchronization of data transmission between RU and DU, and m-plane data relates to managing the RU. Packets having data payloads related to the different planes of operation comprise corresponding header information, e.g. a "c-plane header," "u-plane header," etc.

Partitions in layer one **174** (physical layer) may be associated with operations for converting coded symbols associated with a bit stream into a physical signal for transmission using communication media (e.g., a physical wire or radio). In aspects, the operational partitions for processing upstream data traffic of the physical layer may include, CP **182**A, FFT **183**A, Demap **184**A, Channel **185**A, Eq **186**A, Demod **187**A, Descram **188**A, Rate **189**A, Decoding **190**A, and CRC **191**A. The operational partitions for processing downstream data traffic in the physical layer may include, CRC **191**B, Coding **190**A, Rate **189**B, Scram **188**B, Mod **187**B, Layer **186**B, Precode **185**B, Map **184**B, iFFT **183**B, and CP **182**B.

Partitions in layer two **176** (media access control—MAC) may be associated with operations for transferring data frames between network hosts over a physical link. In aspects, partitions in layer two correspond to the data link layer in the OSI seven-layer model. Low-MAC **192** is the lowest partition in the layer two **176**. Other partitions above the Low-MAC **192** include, an ascending sequence of layers, High-MAC **193**, Low-Radio Link Control (RLC) **194**, and High-RLC **195**.

Partitions in the layer three **178** may be associated with operations for forwarding data packets through routers. In aspects, layer three **178** corresponds to the network layer in the OSI seven-layer model. The partitions in layer three **178** may be associated with protocol-governed operations such as Packet Data Convergence Protocol **196** (PDCP), Radio Resource Control **197**A (RRC) and Service Data Adaptation Protocol **197**B (SDAP).

In aspects, a combination of DU **112** and CU **118** in the far-edge datacenter **110** may process partitions associated with layer one **174**, layer two **176**, and at least a part of layer three **178**. In particular, respective servers of RAN servers **116** include central processors (CPUs) and a variety of accelerators for processing data associated with one or more partitions of the operational partitions **170**.

As previously noted, to meet 5G requirements, layers one and two need to be processed in essentially real time. In particular, steering workloads in a correct and timely manner is critical in the RAN in various scenarios including server failover and maintenance. For example, RAN workloads may include processing IQ samples from cell towers. Quadrature signals, also called IQ signals, IQ data or IQ samples, are often used in radio frequency (RF) applications, such as a RAN. IQ samples form the basis of complex RF signal modulation and demodulation, both in hardware and in software, as well as in complex signal analysis. To facilitate transmission of this type of data, IQ samples are often compressed and are transmitted via u-plane data packets with corresponding u-plane headers. Again, this type of RAN data requires real-time processing to meet latency and other performance metrics of 5G.

Traditionally, network traffic allocation is handled by dedicated servers running load-balancing software. However, rerouting RAN traffic to such servers increases both energy and capital costs, degrades the end-to-end performance, and requires additional physical space, all of which are undesirable or even infeasible for a RAN far-edge datacenter. The present disclosure addresses this issue by distributing workloads to vRAN instances **120** via programmable switches **114** at the far-edge datacenter **110**. As illustrated by FIG. **1**, switch **114** is located in the path of data traffic at the interface between the RU and DU cloud infrastructure components.

In aspects, since switch **114** is in the path of the data traffic, switch **114** is able to gather real-time packet, network, and resource information. By leveraging programmability of switch **114**, steering decision policies (or "workflow allocation policies") can be applied on the RAN workloads without incurring the performance, energy, and capital cost overheads of traditional server-based systems. The workflow allocation policies may be customized for the RAN infrastructure. For instance, the policies may programmatically enable the switch **114** to recognize different types of RAN data based on inspecting packet headers. That is, whereas data packets associated with different operational planes may be interleved within a transmission stream, switch **114** may be programmed identify packets in the u-plane from packets in the c-plane by inspecting a plane field in the packet header. Furthermore, switch **114** may be programmed to process packets in different planes differently—giving preference to packets requiring real-time processing over packets with less stringent processing requirements. Additionally or alternatively, the switch **114** may recognize RAN data originating from a particular cell tower (e.g., based on a cell ID, subcarrier ID, etc.), for instance. In this way, by modifying packet headers originating at the particular cell tower, the corresponding RAN data may be directed to a particular vRAN destination.

Switch **114** may also be programmed to take different actions based on network or resource conditions. For instance, policies may enable switch **114** to recognize when a vRAN is becoming overloaded (e.g., based on queue length) or when a server has failed, powered down or is ungoing maintenance. Switch **114** may redirect data traffic to an available vRAN by revising a destination address in the packet header of a redirected packet (or packets). Since the switch **114** is in the path of the upstream and downstream traffic, fluctuations in the volume of data traffic may also be observed and addressed by switch **114**. In some cases, the switch **114** may enable deployment of additional vRANs and/or reduce the number of vRANs allocated for RAN workload processing. As a result, with improved vRAN allocation, RAN processing efficiency and fault tolerance may improve—even in instances of changing network conditions or resources and spikes in data traffic.

As will be appreciated, the various methods, devices, applications, features, etc., described with respect to FIG. **1** are not intended to limit the system **100** to being performed by the particular applications and features described. Accordingly, additional controller configurations may be used to practice the methods and systems herein and/or features and applications described may be excluded without departing from the methods and systems disclosed herein.

FIG. **2**A illustrates a first example of a far-edge datacenter **210** of RAN environment **200**. The far-edge datacenter **210** includes at least a switch **212**, vRAN instances **214**A-C, and RAN server **216**. The switch **212** connects the cell towers (e.g., the cell towers **102**A-C, as shown in FIG. **1**) with RAN server **216**, which hosts vRAN instances (or "vRANs") **214**A-C, at far-edge datacenter **210**. As illustrated, vRAN instances **214**A-C of FIG. **2**A are hosted by a single server **216**. Similarly, FIG. **2**B illustrates a second example of far-edge datacenter **210**. In this case, far-edge datacenter **210** includes a switch **212**, vRAN instances **214**A-C, and RAN servers **220**, **222**, and **224**. In the case of FIG. **2**B, the switch **212** connects the cell towers (e.g., the cell towers **102**A-C, as shown in FIG. **1**) with RAN server **220** (which hosts vRAN instance **214**A), RAN server **222** (which hosts vRAN instance **214**B), and RAN server **224** (which hosts vRAN instance **214**C), at far-edge datacenter **210**. As illustrated, vRAN instances **214**A-C of FIG. **2**B are hosted by multiple servers **220**, **222**, **224**.

In aspects, the switch **212** is a programmable switch. Since switch **212** is located in the path of RAN data traffic **218**, real-time network information (e.g., queue length, server state) can be leveraged for RAN workload balancing. By leveraging the programmability of switch **212**, policies can be applied on the RAN workloads without incurring the performance, energy, and capital cost overheads of traditional systems (e.g., systems using allocated servers implementing software-based load balancing). In particular, one or more programs encoding workflow allocation policies can be designed to enable switch **212** to inspect packet headers of incoming RAN data traffic **218**, evaluate real-time network information, determine available vRAN instances **214**A-C (or "workers") to process the incoming RAN data traffic **218**, and update packet headers to steer the incoming RAN data traffic **218** to the determined vRAN for processing. In some cases, the policies enable switch **212** to prioritize some workloads for real-time processing, whereas other workloads may be identified for near real-time processing or even higher latency processing. As network conditions change, e.g., one or more of vRAN instances **214**A-C become overloaded (e.g., queue length increases), one or more of the servers fail or undergo maintenance (e.g., servers **216**, **220**, **222**, **224** hosting the vRANs **214**A-C), or the volume of RAN data traffic **218** fluctuates (e.g., during peak mobile usage periods), the workflow allocation policies enable switch **212** to dynamically redirect workloads to alternative vRANs for processing. As a result, with improved vRAN allocation, RAN processing efficiency and fault tolerance may improve—even in instances of changing network conditions and spikes in RAN data traffic **218**.

FIG. **3** illustrates a system **300** depicting aspects of workload allocation to vRANs by a programmable switch **306** associated with a far-edge datacenter **316** of a cloud RAN. As illustrated, system **300** comprises cell towers **302**A-C, gateway router **304**, and far-edge data center **316**. The gateway router **304** may be at the interface between cell towers **302** and an internet service provider (ISP). In aspects, gateway router **304** may detect a level of incoming data traffic to the ISP. In examples, the ISP may host a private cloud network including far-edge data center **316**. Far-edge data center **316** comprises switch **306** and RAN servers **312** and **314**. In this configuration, RAN server **312** hosts vRAN instance **310**A and RAN server **314** hosts vRAN instances **310**B-C.

Switch **306** may be a programmable "top-of-rack" (ToR) switch. In aspects, switches can be incorporated with servers in multiple configurations. Two common infrastructure designs are Top of Rack (ToR) and End of Row (EoR). In the ToR design, servers **312**, **314** may connect to switch **306** installed in the rack of servers, which provides the benefit of maintaining all copper cabling between the server and the switch within the rack itself. Switch **306** then links the rack to the far-edge datacenter **316** network at a common aggregation point. In this example, each rack can be treated as a modular unit. In an EoR design, each of servers **312**, **314** in a rack are connected to a common aggregation switch directly without connecting to individual switches on each rack. Racks are typically lined up in a row and EoR switch(es) are provided at the end of the row so, in this example, each row acts as a unit.

As described above, switch **306** may be loaded with one or more programs encoding workflow allocation policies that are designed to enable switch **306** to inspect packet headers of incoming RAN data traffic, evaluate real-time network information, determine available vRAN instances **310**A-C (or "workers") to process the incoming RAN data traffic, and update packet packet headers to steer the incoming RAN data traffic to the determined vRAN for processing. In some cases, the policies enable switch **306** to prioritize some workloads for real-time processing, whereas other workloads may be identified for near real-time processing or even higher latency processing. As network conditions change, e.g., one or more of vRAN instances **310**A-C become overloaded (e.g., queue length increases), one or more of the servers fail or undergo maintenance (e.g., servers **312**, **314** hosting the vRANs **310**A-C), or the volume of RAN data traffic fluctuates (e.g., during peak mobile usage periods), the workflow allocation policies enable switch **306** to dynamically redirect workloads to alternative vRANs for processing.

It will be appreciated that while system **300** is illustrated as comprising two servers **312** and **314**, and three vRAN instances **310**A-C, any number of servers or vRAN instances may be used.

FIGS. **4**A-B illustrate a system **400** depicting aspects of dynamic workload reallocation for server failover or maintenance by a programmable switch associated with a far-edge datacenter of a cloud RAN. As illustrated by FIG. **4**A, system **400** comprises cell towers **402**A-C and far-edge data center **416**. Far-edge data center **416** comprises switch **406** (e.g., a ToR switch) and workers **410**A-C, where each worker may correspond to a vRAN instance. While any combination of one or more RAN servers may host workers **410**A-C, the RAN servers are not depicted in FIG. **4**A.

Switch **406** may be a programmable switch, as described above, and may execute one or more policies for monitoring and keeping track of load information, making traffic steering decisions, and implementing the traffic steering decisions. For instance, the switch **406** may monitor a "system load" of data traffic based on a level of ingress data traffic at an ingress port and/or a level of egress data traffic at an egress port of switch. The switch **406** may further detect an availability of resources, such as vRAN instances, based on a "worker traffic allocation," which refers to a volume of data traffic directed to each worker from the switch. To determine whether a worker is becoming overloaded, the switch **406** may monitor a queue length for each worker **410**A-C, where the queue length corresponds to a "worker load" or "workload" for each worker. Increased queue length may signal that the worker **410**A-C is becoming overloaded, which may be due to the worker traffic allocation being too high and/or the processing of workflows by the worker **410**A-C being too slow. In aspects, the switch **406** may also be able to detect resource conditions, such as a "server state" of one or more servers hosting the workers **410**A-C. In aspects, server states may include "running state," "failure state," "offline state," and the like. When a server transitions from a running state to a failure state (e.g., when the server is experiencing a hardware or software failure) or an offline state (e.g., when the server is offline to undergo maintenance or powered-down for resource conservation), workers hosted by the server may become unavailable for processing workflows.

Switch **406** may further be configured, based on the policies, to make traffic steering decisions based on the system load, the worker load, and/or resource conditions (e.g., server state). For instance, switch **406** may map traffic from a particular cell tower to a particular worker. In response to making the traffic steering decisions (e.g., the cell-worker mapping), switch **406** may implement the traffic steering decision by altering packet headers of data traffic from the particular cell tower to specify the particular worker as the destination of the data traffic. In an example, switch **406** may determine that worker **410**A is available and may make a decision to direct RAN data traffic from cell tower **402**A to worker **410**A for processing. In response to the decision, as illustrated by dashed arrow **418**, switch **406** may inspect RAN-specific packet headers (e.g., cell ID, subcarrier ID, etc.) to identify data traffic from cell tower **402**A and may modify the packet headers to specify worker **410**A as the destination. A workload performed by worker **410**A may comprise layer one (PHY) processing of the RAN data traffic from cell tower **402**A. In aspects, it may be necessary for worker **410**A to perform the layer one (PHY) processing in real-time. In contrast, worker **410**C may perform layer two (MAC) processing on RAN data and may direct the processed RAN data traffic back to switch **406**, as illustrated by arrow **420**.

Similar to FIG. **4**A, FIG. **4**B illustrates system **400** including cell towers **402**A-C and far-edge data center **416**. Far-edge data center **416** comprises switch **406** (e.g., a ToR switch) and workers **410**A-C, where each worker may correspond to a vRAN instance. In this case, switch **406** has detected that worker **410**A has become unavailable, as illustrated by fault symbol **422**. For instance, it may be detected that a server (not shown) hosting worker **410**A has transitioned to a failure state or an offline state and no longer supports worker **410**A.

In this example, switch **406** may determine that worker **410**B is available and may make a decision to redirect the RAN data traffic from cell tower **402**A to worker **410**B for processing. In response to the decision, as illustrated by dashed arrow **424**, switch **406** may inspect RAN-specific packet headers (e.g., cell ID, subcarrier ID, etc.) to identify data traffic from cell tower **402**A and may modify the packet headers to specify worker **410**B as the destination. The workload performed by worker **410**B may also comprise layer one (PHY) processing of the RAN data traffic from cell tower **402**A. In aspects, it may be necessary for worker **410**B to perform the layer one (PHY) processing in real-time. Similar to FIG. **4**A, worker **410**C may perform layer two (MAC) processing on RAN data and may direct the processed RAN data traffic back to switch **406**, as illustrated by arrow **420**.

FIGS. **5**A-B illustrate a system **400** depicting aspects of dynamic workload reallocation for worker overload by a programmable switch associated with a far-edge datacenter of a cloud RAN. As illustrated by FIG. **5**A, system **500** comprises cell towers **502**A-C and far-edge data center **516**. Far-edge data center **516** comprises switch **506** (e.g., a ToR switch) and workers **510**A-C, where each worker may correspond to a vRAN instance. As illustrated, each worker **510**A-C may be associated with a queue **512**A-C, respectively. While any combination of one or more RAN servers may host workers **510**A-C, the RAN servers are not depicted in FIG. **5**A.

Switch **506** may be a programmable switch, as described above, and may execute one or more policies for monitoring and keeping track of load information, making traffic steering decisions, and implementing the traffic steering decisions. For instance, the switch **506** may monitor a "system load" of data traffic based on a level of ingress data traffic at an ingress port and/or a level of egress data traffic at an egress port of switch. The switch **506** may further detect an availability of resources, such as vRAN instances, based on a "worker traffic allocation," which refers to a volume of data traffic directed to each worker from the switch. To determine whether a worker is becoming overloaded, the switch **506** may monitor a queue length for each worker **510**A-C, where the queue length corresponds to a "worker load" or "workload" for each worker. Increased queue length may signal that the worker **510**A-C is becoming overloaded, which may be due to the worker traffic allocation being too high and/or the processing of workflows by the worker **510**A-C being too slow. In aspects, the switch **506** may also be able to detect resource conditions, such as a "server state" of one or more servers hosting the workers **510**A-C. In aspects, server states may include "running state," "failure state," "offline state," and the like. When a server transitions from a running state to a failure state (e.g., when the server is experiencing a hardware or software failure) or an offline state (e.g., when the server is offline to undergo maintenance or powered-down for resource conservation), workers hosted by the server may become unavailable for processing workflows.

Switch **506** may further be configured, based on the policies, to make traffic steering decisions based on the system load, the worker load, and/or resource conditions (e.g., server state). For instance, switch **506** may map traffic from a particular cell tower to a particular worker. In response to making the traffic steering decisions (e.g., the cell-worker mapping), switch **506** may implement the traffic steering decision by altering packet headers of data traffic from the particular cell tower to specify the particular worker as the destination of the data traffic. In an example, switch **506** may determine that worker **510**A is available and may make a decision to direct RAN data traffic from cell towers **502**A and **502**B to worker **510**A for processing. In response to the decision, switch **506** may inspect RAN-specific packet headers (e.g., cell ID, subcarrier ID, etc.) to identify data traffic from cell towers **502**A and **502**B and may modify the packet headers to specify worker **510**A as the destination (as illustrated by dashed arrows **518** and **520**, respectively). A workload performed by worker **510**A may comprise layer one (PHY) processing of the RAN data traffic from cell towers **502**A and **502**B. In aspects, it may be necessary for worker **510**A to perform the layer one (PHY) processing in real-time. In contrast, worker **510**C may perform layer two (MAC) processing on RAN data and may direct the processed RAN data traffic back to switch **406**, as illustrated by arrow **522**. As illustrated, a first queue length of queue **512**A is greater than a second queue length of queue **512**B and a third queue length of queue **512**C. In aspects, the first queue length may be nearing a maximum queue length and worker **510**A may be overloaded.

Similar to FIG. **5**A, FIG. **5**B illustrates system **500** including cell towers **502**A-C and far-edge data center **516**. Far-edge data center **516** comprises switch **506** (e.g., a ToR switch) and workers **510**A-C, where each worker may correspond to a vRAN instance. In this case, switch **506** has detected that worker **510**A has become overloaded (e.g., based on the first queue length of queue **512**A illustrated by FIG. **5**A). In aspects, worker **510**A may be overloaded due to a workload allocation that was too high or workload processing that was too slow.

In this example, switch **506** may determine that worker **510**B is available (e.g., based on the second queue length of queue **512**B) and may make a decision to redirect the RAN data traffic from cell tower **502**B to worker **510**B for processing. In response to the decision, as illustrated by dashed arrow **524**, switch **506** may inspect RAN-specific packet headers (e.g., cell ID, subcarrier ID, etc.) to identify data traffic from cell tower **502**B and may modify the packet headers to specify worker **510**B as the destination. The workload performed by worker **510**B may also comprise layer one (PHY) processing of the RAN data traffic from cell tower **502**B. In aspects, it may be necessary for worker **510**B to perform the layer one (PHY) processing in real-time. Similar to FIG. **5**A, worker **510**C may perform layer two (MAC) processing on RAN data and may direct the processed RAN data traffic back to switch **506**, as illustrated by arrow **522**. After redirecting the data traffic, the first queue length of queue **512**A has decreased and is substantially similar to the second queue length of queue **512**B and the third queue length of queue **512**C. As a result, the system load has been balanced by switch **506** across workers **510**A-C of system **500**.

FIG. **6** illustrates an example method for dynamic workload allocation to vRANs by a programmable switch. A general order of the operations for the method **600** is shown in FIG. **6**. Generally, the method **600** begins with start operation **602** and ends with end operation **618**. The method **600** may include more or fewer steps or may arrange the order of the steps differently than those shown in FIG. **6**. The method **600** can be executed as a set of computer-executable instructions executed by a computer system and encoded or stored on a computer readable medium. Further, the method **600** can be performed by gates or circuits associated with a processor, an ASIC, an FPGA, a SOC or other hardware device. Hereinafter, the method **600** shall be explained with reference to the systems, components, devices, modules, software, data structures, data characteristic representations, signaling diagrams, methods, etc., described in conjunction with FIGS. **1**-**5**B, **7**, and **8**A-B. For example, aspects of method **600** may be performed by a programmable switch, such as switch **114** of FIG. **1**, switch **212** of FIGS. **2**A-B, switch **306** of FIG. **3**, switch **406** of FIGS. **4**A-B and switch **506** of FIGS. **5**A-B.

Following start operation **602**, at execute operation **604**, a programmable switch associated with a far-edge datacenter of a cloud RAN may execute workflow allocation policies. Since switches are located in the path of data traffic, real-time network information (e.g., queue length, server state) can be leveraged for real-time RAN workload balancing. By leveraging the proximity and programmability of the switches, workflow allocation policies can be designed and applied on the RAN workloads in real-time without incurring the performance, energy, and capital cost overheads of traditional systems. In particular, the workflow allocation policies can be designed to enable a switch to inspect packet headers of incoming traffic, evaluate real-time network information, determine available vRAN instances to process the incoming traffic, and update the packet headers to steer the incoming traffic to the determined vRAN instances for processing—all in essentially real time. As network conditions change, e.g., vRANs become overloaded (e.g., queue length increases), servers hosting the vRANs fail, power down (e.g., at night), or undergo maintenance, or the volume of data traffic fluctuates (e.g., during peak mobile usage periods), the workflow allocation policies enable a programmable switch to dynamically redirect workloads to alternative vRANs for processing.

At monitor operation **606**, based on the workflow allocation policies, the programmable switch can be programmed to monitor data traffic and resource availability. For instance, the switch may monitor a "system load" of data traffic based on a level of ingress data traffic at an ingress port and/or a level of egress data traffic at an egress port of switch. The switch may further detect an availability of resources, such as vRAN instances, based on a "worker traffic allocation," which refers to a volume of data traffic directed to each vRAN instance from the switch. To determine whether a worker is becoming overloaded, the switch may monitor a queue length for each vRAN instance, where the queue length corresponds to a "worker load" or "workload" for each vRAN instance. Increased queue length may signal that the vRAN instance is becoming overloaded, which may be due to the worker traffic allocation being too high and/or the processing of workflows by the vRAN instance being too slow. In aspects, the switch may also be able to detect resource conditions, such as a "server state" of one or more servers hosting the vRAN instances. In aspects, server states may include "running state," "failure state," "offline state," and the like. When a server transitions from a running state to a failure state (e.g., when the server is experiencing a hardware or software failure) or an offline state (e.g., when the server is offline to undergo maintenance or powered-down for resource conservation), vRAN instances hosted by the server may become unavailable for processing workflows.

At determine operation **608**, the programmable switch may determine that a first vRAN instance is available to process a first workflow associated with RAN data. For example, the programmable switch may evaluate a plurality of vRAN instances to determine one or more vRAN instances are available for processing a first workflow associated with RAN data. In aspects the first workflow may be associated with layer one (PHY) processing or layer two (MAC) processing of RAN data. It may be determined that a vRAN instance available for processing is not overloaded, e.g., a vRAN instance that comprises a queue length that is not within a threshold of a maximum queue length. In some cases, it may be further determined that an available vRAN instance comprises a stable queue length (e.g., that is not increasing toward the threshold). It may also be determined that an available vRAN instance is not associated with a server having a server state of failure or offline. In response to evaluating the plurality of vRAN instances, the programmable switch may determine that the first vRAN instance is available to process a first workflow associated with RAN data.

At inspect operation **610**, the programmable switch may inspect packet headers of incoming data traffic to identify RAN-specific headers. As described above, RAN workloads may include processing IQ samples from cell towers. To facilitate transmission of this type of data, IQ samples are often compressed and are transmitted via u-plane data packets with corresponding u-plane headers. In aspects, the workflow allocation policies may enable the programmable switch to recognize different types of RAN data based on inspecting RAN-specific packet headers. That is, although data packets associated with different operational planes may be interleved within a transmission stream, the switch may be programmed identify packets in the u-plane from packets in the c-plane by inspecting the RAN-specific fields of packet headers. Additionally or alternatively, the switch may be programmed to recognize RAN data originating from a particular cell tower (e.g., based on a cell ID, subcarrier ID, etc.).

At modify operation **612**, the switch may modify a subset of the RAN-specific packet headers. For example, the switch may be programmed to process packets in different planes differently—giving preference to packets requiring real-time processing over packets with less stringent processing requirements. The switch may further be programmed to direct RAN data from a particular cell tower to an available RAN instance for processing. In aspects, the subset of RAN-specific packet headers may be modified to specify the first RAN instance as the destination so as to direct the subset of corresponding RAN data packets to the first RAN instance.

At determine operation **614**, the programmable switch may determine that the first RAN instance is not available to process a second workflow associated RAN data. In aspects the second workflow may be associated with layer one (PHY) processing or layer two (MAC) processing of RAN data. It may be determined that the first vRAN instance is not available for processing when the first vRAN is overloaded, e.g., a queue length associated with the first vRAN instance is within a threshold of a maximum queue length. Additionally or alternatively, it may be determined that the first vRAN instance is associated with a server having a server state of failure or offline.

At determine operation **616**, the programmable switch may determine that a second vRAN instance is available to process the second workflow associated with RAN data. For instance, it may be determined that the second vRAN instance is not overloaded, e.g., a queue length associated with the second vRAN instance is not within a threshold of a maximum queue length. Additionally, it may be determined that the second vRAN instance is not associated with a server having a server state of failure or offline.

At modify operation **618**, the switch may modify the subset of the RAN-specific packet headers. In aspects, the subset of RAN-specific packet headers may be modified to specify the second RAN instance as the destination so as to direct the subset of corresponding RAN data packets to the second RAN instance.

An arrow is illustrated from operation **618** to operation **604** to indicate that flow may loop between operations **604**-**618**, thereby dynamically allocating and reallocating RAN workflows based on techniques described herein. As should be appreciated, operations **602**-**618** are described for purposes of illustrating the present methods and systems and are not intended to limit the disclosure to a particular sequence of steps, e.g., steps may be performed in different order, additional steps may be performed, and disclosed steps may be excluded without departing from the present disclosure.

FIG. **7** is a block diagram illustrating physical components (e.g., hardware) of a computing device **700** (e.g., a programmable switch) with which aspects of the disclosure may be practiced. The computing device components described below may have computer executable instructions for implementing workflow policies **720** on a computing device (e.g., switch **114**), including computer executable instructions for the workflow policies **720** that can be executed to implement the methods disclosed herein. In a basic configuration, the computing device **700** may include at least one processing unit **702** and a system memory **704**. Depending on the configuration and type of computing device, the system memory **704** may comprise, but is not limited to, volatile storage (e.g., random access memory), non-volatile storage (e.g., read-only memory), flash memory, or any combination of such memories. The system memory **704** may include an operating system **705** and one or more program modules **706** suitable for running workflow policies **720**, such as one or more components and, in particular, traffic/resource monitor **711**, vRAN identifier **713**, packet inspector **715**, and/or packet manipulator **717**.

The operating system **705**, for example, may be suitable for controlling the operation of the computing device **700**. Furthermore, embodiments of the disclosure may be practiced in conjunction with a graphics library, other operating systems, or any other application program and is not limited to any particular application or system. This basic configuration is illustrated in FIG. **7** by those components within a dashed line **708**. The computing device **700** may have additional features or functionality. For example, the computing device **700** may also include additional data storage devices (removable and/or non-removable) such as, for example, magnetic disks, optical disks, or tape. Such additional storage is illustrated in FIG. **7** by a removable storage device **709** and a non-removable storage device **710**.

As stated above, a number of program modules and data files may be stored in the system memory **704**. While executing on the processing unit **702**, the program modules **706** (e.g., workflow policies **720**) may perform processes including, but not limited to, the aspects, as described herein. Other program modules that may be used in accordance with aspects of the present disclosure, and in particular for allocating workflows to vRAN instances, may include traffic/resource monitor **711**, vRAN identifier **713**, packet inspector **715**, and/or packet manipulator **717**, etc.

Furthermore, embodiments of the disclosure may be practiced in an electrical circuit comprising discrete electronic elements, packaged or integrated electronic chips containing logic gates, a circuit utilizing a microprocessor, or on a single chip containing electronic elements or microprocessors. For example, embodiments of the disclosure may be practiced via a system-on-a-chip (SOC) where each or many of the components illustrated in FIG. **7** may be integrated onto a single integrated circuit. Such an SOC device may include one or more processing units, graphics units, communications units, system virtualization units and various application functionality all of which are integrated (or "burned") onto the chip substrate as a single integrated circuit. When operating via an SOC, the functionality, described herein, with respect to the capability of client to switch protocols may be operated via application-specific logic integrated with other components of the computing device **700** on the single integrated circuit (chip). Embodiments of the disclosure may also be practiced using other technologies capable of performing logical operations such as, for example, AND, OR, and NOT, including but not limited to mechanical, optical, fluidic, and quantum technologies. In addition, embodiments of the disclosure may be practiced within a general-purpose computer or in any other circuits or systems.

The computing device **700** may also have one or more input device(s) **712** such as a keyboard, a mouse, a pen, a sound or voice input device, a touch or swipe input device, etc. The output device(s) **714** such as a display, speakers, a printer, etc. may also be included. The aforementioned devices are examples and others may be used. The computing device **700** may include one or more communication connections **716** allowing communications with other computing devices **750**. Examples of suitable communication connections **716** include, but are not limited to, radio frequency (RF) transmitter, receiver, and/or transceiver circuitry; universal serial bus (USB), parallel, and/or serial ports.

The term computer readable media as used herein may include computer storage media. Computer storage media may include volatile and nonvolatile, removable and non-removable media implemented in any method or technology for storage of information, such as computer readable instructions, data structures, or program modules. The system memory **704**, the removable storage device **709**, and the non-removable storage device **710** are all computer storage media examples (e.g., memory storage). Computer storage media may include RAM, ROM, electrically erasable read-only memory (EEPROM), flash memory or other memory technology, CD-ROM, digital versatile disks (DVD) or other optical storage, magnetic cassettes, magnetic tape, magnetic disk storage or other magnetic storage devices, or any other article of manufacture which can be used to store information and which can be accessed by the computing device **700**. Any such computer storage media may be part of the computing device **700**. Computer storage media does not include a carrier wave or other propagated or modulated data signal.

Communication media may be embodied by computer readable instructions, data structures, program modules, or other data in a modulated data signal, such as a carrier wave or other transport mechanism, and includes any information delivery media. The term "modulated data signal" may describe a signal that has one or more characteristics set or changed in such a manner as to encode information in the signal. By way of example, and not limitation, communication media may include wired media such as a wired network or direct-wired connection, and wireless media such as acoustic, radio frequency (RF), infrared, and other wireless media.

FIGS. **8**A and **8**B illustrate a mobile computing device **800**, for example, a mobile telephone, a smart phone, wearable computer (such as a smart watch), a tablet computer, a laptop computer, and the like, with which embodiments of the disclosure may be practiced. In some aspects, the client may be a mobile computing device. With reference to FIG. **8**A, one aspect of a mobile computing device **800** for implementing the aspects is illustrated. In a basic configuration, the mobile computing device **800** is a handheld computer having both input elements and output elements. The mobile computing device **800** typically includes a display **805** and one or more input buttons **810** that allow the user to enter information into the mobile computing device **800**. The display **805** of the mobile computing device **800** may also function as an input device (e.g., a touch screen display). If included, an optional side input element **815** allows further user input. The side input element **815** may be a rotary switch, a button, or any other type of manual input element. In alternative aspects, mobile computing device **800** may incorporate more or less input elements. For example, the display **805** may not be a touch screen in some embodiments. In yet another alternative embodiment, the mobile computing device **800** is a portable phone system, such as a cellular phone. The mobile computing device **800** may also include an optional keypad **835**. Optional keypad **835** may be a physical keypad or a "soft" keypad generated on the touch screen display. In various embodiments, the output elements include the display **805** for showing a graphical user interface (GUI), a visual indicator **820** (e.g., a light emitting diode), and/or an audio transducer **825** (e.g., a speaker). In some aspects, the mobile computing device **800** incorporates a vibration transducer for providing the user with tactile feedback. In yet another aspect, the mobile computing device **800** incorporates input and/or output ports, such as an audio input (e.g., a microphone jack), an audio output (e.g., a headphone jack), and a video output (e.g., a HDMI port) for sending signals to or receiving signals from an external device.

FIG. **8**B is a block diagram illustrating the architecture of one aspect of a mobile computing device. That is, the mobile computing device **800** can incorporate a system (e.g., an architecture) **802** to implement some aspects. In one embodiment, the system **802** is implemented as a "smart phone" capable of running one or more applications (e.g., browser, e-mail, calendaring, contact managers, messaging clients, games, and media clients/players). In some aspects, the system **802** is integrated as a computing device, such as an integrated personal digital assistant (PDA) and wireless phone.

One or more application programs **866** may be loaded into the memory **862** and run on or in association with the operating system **864**. Examples of the application programs include phone dialer programs, e-mail programs, personal information management (PIM) programs, word processing programs, spreadsheet programs, Internet browser programs, messaging programs, and so forth. The system **802** also includes a non-volatile storage area **868** within the memory **862**. The non-volatile storage area **868** may be used to store persistent information that should not be lost if the system **802** is powered down. The application programs **866** may use and store information in the non-volatile storage area **868**, such as email or other messages used by an email application, and the like. A synchronization application (not shown) also resides on the system **802** and is programmed to interact with a corresponding synchronization application resident on a host computer to keep the information stored in the non-volatile storage area **868** synchronized with corresponding information stored at the host computer. As should be appreciated, other applications may be loaded into the memory **862** and run on the mobile computing device **800**, including the instructions for implementing workflow policies as described herein (e.g., traffic/resource monitor, vRAN identifier, packet inspector, and/or packet manipulator, etc.).

The system **802** has a power supply **870**, which may be implemented as one or more batteries. The power supply **870** may further include an external power source, such as an AC adapter or a powered docking cradle that supplements or recharges the batteries.

The system **802** may also include a radio interface layer **872** that performs the function of transmitting and receiving radio frequency communications. The radio interface layer **872** facilitates wireless connectivity between the system **802** and the "outside world," via a communications carrier or service provider. Transmissions to and from the radio interface layer **872** are conducted under control of the operating system **864**. In other words, communications received by the radio interface layer **872** may be disseminated to the application programs **866** via the operating system **864**, and vice versa.

The visual indicator **820** may be used to provide visual notifications, and/or an audio interface **874** may be used for producing audible notifications via an audio transducer **825** (e.g., audio transducer **825** illustrated in FIG. **8**A). In the illustrated embodiment, the visual indicator **820** is a light emitting diode (LED) and the audio transducer **825** may be a speaker. These devices may be directly coupled to the power supply **870** so that when activated, they remain on for a duration dictated by the notification mechanism even though the processor **860** and other components might shut down for conserving battery power. The LED may be programmed to remain on indefinitely until the user takes action to indicate the powered-on status of the device. The audio interface **874** is used to provide audible signals to and receive audible signals from the user. For example, in addition to being coupled to the audio transducer **825**, the audio interface **874** may also be coupled to a microphone to receive audible input, such as to facilitate a telephone conversation. In accordance with embodiments of the present disclosure, the microphone may also serve as an audio sensor to facilitate control of notifications, as will be described below. The system **802** may further include a video interface **876** that enables an operation of peripheral device **830** (e.g., on-board camera) to record still images, video stream, and the like.

A mobile computing device **800** implementing the system **802** may have additional features or functionality. For example, the mobile computing device **800** may also include additional data storage devices (removable and/or non-removable) such as, magnetic disks, optical disks, or tape. Such additional storage is illustrated in FIG. **8**B by the non-volatile storage area **868**.

Data/information generated or captured by the mobile computing device **800** and stored via the system **802** may be stored locally on the mobile computing device **800**, as described above, or the data may be stored on any number of storage media that may be accessed by the device via the radio interface layer **872** or via a wired connection between the mobile computing device **800** and a separate computing device associated with the mobile computing device **800**, for example, a server computer in a distributed computing network, such as the Internet. As should be appreciated such data/information may be accessed via the mobile computing device **800** via the radio interface layer **872** or via a distributed computing network. Similarly, such data/information may be readily transferred between computing devices for storage and use according to well-known data/information transfer and storage means, including electronic mail and collaborative data/information sharing systems.

As should be appreciated, FIGS. **8**A and **8**B are described for purposes of illustrating the present methods and systems and is not intended to limit the disclosure to a particular sequence of steps or a particular combination of hardware or software components.

The description and illustration of one or more aspects provided in this application are not intended to limit or restrict the scope of the disclosure as claimed in any way. The claimed disclosure should not be construed as being limited to any aspect, for example, or detail provided in this application. Regardless of whether shown and described in combination or separately, the various features (both structural and methodological) are intended to be selectively included or omitted to produce an embodiment with a particular set of features. Having been provided with the description and illustration of the present application, one skilled in the art may envision variations, modifications, and alternate aspects falling within the spirit of the broader aspects of the general inventive concept embodied in this application that do not depart from the broader scope of the claimed disclosure.

The present disclosure relates to systems and methods for RAN resource allocation using reinforcement learning according to at least the examples provided in the sections below.

In an aspect, a system is provided. The system includes at least one processor and a memory storing instructions that, when executed by the at least one processor, cause the system to perform a set of operations. The set of operations include executing, by a programmable switch of a far-edge datacenter, workflow allocation policies and, based on the workflow allocation policies, monitoring a volume of data traffic and an availability of a plurality of virtual RAN (vRAN) instances, where the plurality of vRAN instances are hosted by one or more RAN servers at the far-edge datacenter. The operations further include determining that a first vRAN instance of the plurality of vRAN instances is available to process a first workflow associated with RAN data. Additionally, the operations include inspecting packet headers of the data traffic to identify RAN-specific packet headers and modifying a subset of the RAN-specific packet headers to direct a subset of the RAN data to the first vRAN instance for processing the first workflow.

In another aspect, a method for dynamically allocating workflows to one or more virtual radio access network (vRAN) instances is provided. The method includes executing, by a programmable switch, workflow allocation policies and, based on the workflow allocation policies, monitoring a volume of data traffic and an availability of a plurality of vRAN instances. The plurality of vRAN instances may be hosted by one or more RAN servers at a far-edge datacenter, where the availability of the plurality of vRAN instances is determined based on one of a workload associated with each vRAN instance or a server state associated with a RAN server hosting each vRAN instance. The method further includes determining that a first vRAN instance of the plurality of vRAN instances is available to process a first workflow associated with RAN data. Additionally, the method includes inspecting packet headers of the data traffic to identify RAN-specific packet headers and modifying a subset of the RAN-specific packet headers to direct a subset of RAN data to the first vRAN instance for processing the first workflow.

In yet another aspect, a method for allocating workflows at a far-edge datacenter is provided. The method includes executing, by a programmable switch of the far-edge datacenter, workflow allocation policies and, based on the workflow allocation policies, monitoring a volume of data traffic and an availability of a plurality of virtual RAN (vRAN) instances, where the plurality of vRAN instances are hosted by one or more RAN servers at the far-edge datacenter. The method further includes determining that a first vRAN instance of the plurality of vRAN instances is available to process a first workflow associated with RAN data. Additionally, the method includes inspecting packet headers of the data traffic to identify RAN-specific packet headers, where a subset of RAN-specific packet headers are associated with RAN data originating at a cell tower of a plurality of cell towers, and modifying the subset of the RAN-specific packet headers to cause the subset of RAN data from the cell tower to be directed to the first vRAN instance for processing the first workflow.

Any of the one or more above aspects in combination with any other of the one or more aspect. Any of the one or more aspects as described herein.

What is claimed is:

1. A system comprising:

at least one processor; and

memory storing instructions that, when executed by the at least one processor, cause the system to perform a set of operations, the set of operations comprising:

executing, by a programmable switch of a far-edge datacenter as a radio access network (RAN) server, workflow allocation policies;

based on the workflow allocation policies, monitoring a volume of data traffic and an availability of a plurality of virtual radio access network (vRAN) instances, wherein the plurality of vRAN instances is hosted by one or more RAN servers at the far-edge datacenter, and a vRAN instance represents a network function virtualization for processing control of the RAN;

determining that a first vRAN instance of the plurality of vRAN instances is available to process a first workflow associated with RAN data;

determining that the first vRAN instance is not available to process a second workflow associated with RAN data;

determining that a second vRAN instance is available to process the second workflow associated with RAN data;

inspecting packet headers of the data traffic to identify RAN-specific packet headers;

modifying, by the programmable switch of the far-edge datacenter, a subset of the RAN-specific packet headers to direct a subset of the RAN data to the first vRAN instance for processing the first workflow; and

modifying the subset of the RAN-specific packet headers to redirect the subset of the RAN data to the second vRAN instance for processing the second workflow.

2. The system of claim **1**, wherein the inspecting packet headers further comprises inspecting layer one data of the data traffic according to the Open System Interconnection model, and the availability of the plurality of vRAN instances is determined based on a data traffic allocation associated with each vRAN instance and a workload associated with each vRAN instance.

3. The system of claim **2**, wherein the workload associated with each vRAN instance is determined based on a queue length for each vRAN instance.

4. The system of claim **1**, wherein the availability of the plurality of vRAN instances is determined based on a server state associated with a RAN server hosting each vRAN instance.

5. The system of claim **1**, wherein the subset of the RAN-specific packet headers is associated with a cell tower of a plurality of cell towers, and wherein modifying the subset of the RAN-specific packet headers causes the subset of the RAN data from the cell tower to be directed to the first vRAN instance.

6. The system of claim **1**, wherein determining that the first vRAN instance is not available to process the second workflow comprises determining that the first vRAN instance is overloaded.

7. The system of claim **1**, wherein determining that the first vRAN instance is not available to process the second workflow comprises determining that a RAN server hosting the first vRAN instance is associated with one of a failure state or an offline state.

8. The system of claim **1**, wherein determining that the first vRAN instance is overloaded is based on examining a queue length of the first vRAN instance.

9. The system of claim **1**, wherein the RAN data comprises one or more IQ samples, and wherein the first workflow comprises processing the one or more IQ samples.

10. The system of claim **9**, wherein the processing of the one or more IQ samples is performed in real time.

11. The system of claim **1**, wherein the programmable switch executes the workflow allocation policies on data traffic originating from one or more first cell towers, and wherein the set of operations further comprises:

executing in parallel, by a second programmable switch of the far-edge datacenter, the workflow allocation policies on data traffic originating from one or more second cell towers.

12. A method for dynamically allocating workflows to one or more virtual radio access network (vRAN) instances, comprising:

executing, by a programmable switch of a far-edge datacenter as a radio access network (RAN) server, workflow allocation policies;

based on the workflow allocation policies, monitoring a volume of data traffic and an availability of a plurality of vRAN instances, wherein the plurality of vRAN instances is hosted by one or more RAN servers at the far-edge datacenter, wherein a vRAN instance represents a network function virtualization for processing control of the RAN, and wherein the availability of the plurality of vRAN instances is determined based on one of a workload associated with each vRAN instance or a server state associated With a RAN server hosting each vRAN instance;

determining that a first vRAN instance of the plurality of vRAN instances is available to process a first workflow associated with RAN data;

determining that the first vRAN instance is not available to process a second workflow associated with RAN data;

determining that a second vRAN instance is available to process the second workflow associated with RAN data;

inspecting packet headers of the data traffic to identify RAN-specific packet headers;

modifying, by the programmable switch of the far-edge datacenter, a subset of the RAN-specific packet headers to direct a subset of RAN data to the first vRAN instance for processing the first workflow; and

modifying the subset of the RAN-specific packet headers to redirect the subset of RAN data to the second vRAN instance for processing the second workflow.

13. The method of claim **12**, wherein the inspecting packet headers further comprises inspecting layer one data of the data traffic according to the Open System Interconnection model, and the workload associated with each vRAN instance is determined based on a queue length for each vRAN instance.

14. The method of claim **12**, wherein determining that the first vRAN instance is not available to process the second workflow comprises determining that the first vRAN instance is overloaded.

15. The method of claim **12**, wherein determining that the first vRAN instance is not available to process the second workflow comprises determining that a RAN server hosting the first vRAN instance is associated with one of a failure state or an offline state.

16. The method of claim **12**, wherein the RAN data comprises one or more IQ samples, and wherein the first workflow comprises processing the one or more IQ samples.

17. A method for allocating workflows at a far-edge datacenter, the method comprising:

executing, by a programmable switch of the far-edge datacenter as a radio access network (RAN) server, workflow allocation policies;

based on the workflow allocation policies, monitoring a volume of data traffic and an availability of a plurality of virtual radio access network (vRAN) instances, wherein the plurality of vRAN instances is hosted by one or more RAN servers at the far-edge datacenter, and a vRAN instance represents a network function virtualization for processing control of the RAN;

determining that a first vRAN instance of the plurality of vRAN instances is available to process a first workflow associated with RAN data;

determining that the first vRAN instance is not available to process a second workflow associated with RAN data;

determining that a second vRAN instance is available to process the second workflow associated with RAN data;

inspecting packet headers of the data traffic to identify RAN-specific packet headers, wherein a subset of the RAN-specific packet headers is associated with a subset of RAN data originating at a cell tower of a plurality of cell towers;

modifying, by the programmable switch of the far-edge datacenter, the subset of the RAN-specific packet headers to cause the subset of RAN data from the cell tower to be directed to the first vRAN instance for processing the first workflow; and

modifying the subset of the RAN-specific packet headers to cause the RAN data from the cell tower to be redirected to the second vRAN instance for processing the second workflow.

18. The method of claim **17**, wherein the first workflow and the second workflow comprise real-time processing of layer one data of the RAN data according to the Open System Interconnection model.

19. The method of claim **17**, wherein the inspecting packet headers further comprises inspecting layer one data of the data traffic, and the availability of the plurality of vRAN instances is determined based on a data traffic allocation associated with each vRAN instance and a workload associated with each vRAN instance.

20. The method of claim **17**, wherein determining that the first vRAN instance is not available to process the second workflow comprises determining that the first vRAN instance is overloaded.

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