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(54) REAL-TIME RADIO INTELLIGENT CONTROLLER

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G06F 8/656 (2018.01)

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

CPC ***H04B 7/04013*** (2023.05); ***G06F 8/656*** (2018.02)

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USPC 375/259–262, 265, 267; 370/235, 236, 370/253, 349, 350, 392; 709/201, 203
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2020/0213820 A1*	7/2020	Sim	....	H04L 61/4541
2020/0383115 A1*	12/2020	Kim	....	H04W 24/02
2021/0258969 A1*	8/2021	Yang	....	H04W 72/54
2021/0289385 A1*	9/2021	Roessler	....	G06F 9/5061
2022/0377615 A1*	11/2022	Radunovic	....	G06F 11/3428
2023/0209555 A1*	6/2023	Sosnin	....	H04L 5/0053 370/329

(Continued)

OTHER PUBLICATIONS

"Feasibility of Open-Source for 5G", Telecommunications Standards Development Society, India (TSDSI), Retrieved from the Internet: URL: https://tsdsi.in/wp-content/uploads/2020/09/Open-Source-White-Paper.pdf, Jul. 2021, 128 pages.

(Continued)

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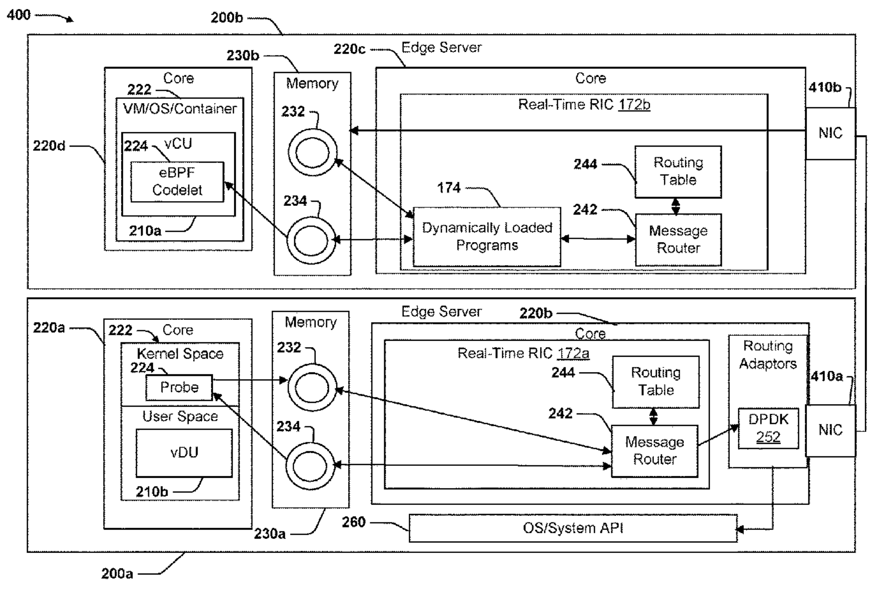
(57) ABSTRACT

A real-time radio intelligent controller (RIC) executes in parallel with one or more virtual radio access network functions to provide real-time analytics and control of the virtual radio access network functions. At least a first processor core is configured to execute a radio network virtual function. The radio network virtual function is configured with a codelet to output selected operational data to a first stream associated with a first stream ID and receive control information from a control stream associated with a second stream ID. At least a second processor core is configured to execute the real-time RIC isolated from the at least the first processor core. The real-time RIC includes one or more dynamically loaded programs configured to: access the first stream; perform processing on the operational data; and write commands for the radio network virtual function to the control stream.

23 Claims, 6 Drawing Sheets



(56) **References Cited**

U.S. PATENT DOCUMENTS

2023/0284301	A1*	9/2023	Cui	H04W 76/15 370/329
2023/0413111	A1*	12/2023	Kotaru	H04W 28/0858

OTHER PUBLICATIONS

Foukas, et al., "Taking 5G RAN Analytics and Control to a New Level", Retrieved from the Internet: URL: https://www.microsoft.com/en-us/research/uploads/prod/2022/12/JanusTechnicalReport.pdf, Dec. 12, 2022, 18 pages.
International Search Report and Written Opinion received for PCT Application No. PCT/US2024/032181, mailed on Sep. 25, 2024, 15 pages.

* cited by examiner

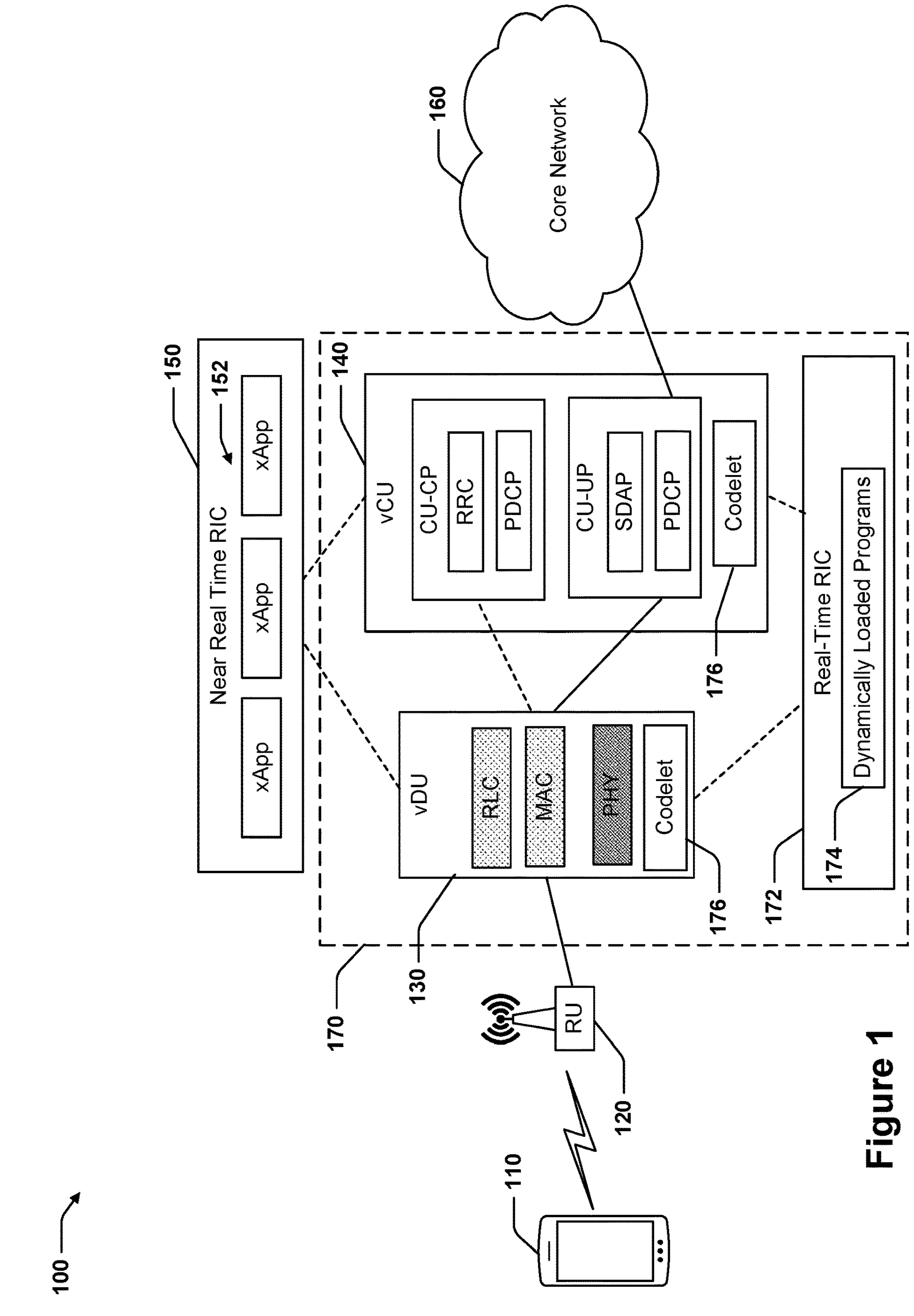

100
110
120
RU
130
vDU
RLC
MAC
PHY
Codelet
176
170
140
vCU
CU-CP
RRC
PDCP
CU-UP
SDAP
PDCP
Codelet
176
150
Near Real Time RIC
152
xApp
xApp
xApp
160
Core Network
172
Real-Time RIC
174
Dynamically Loaded Programs

Figure 1

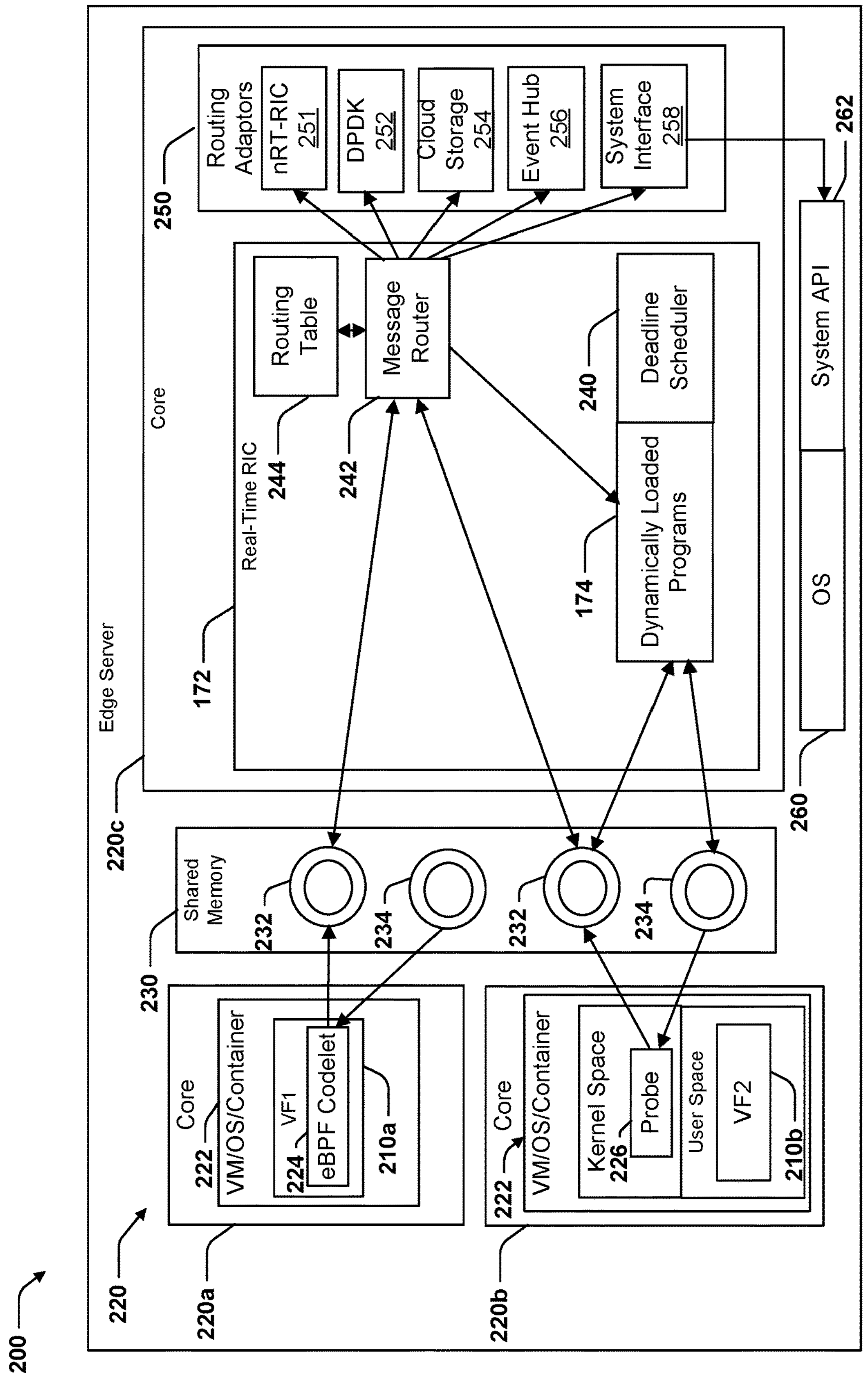
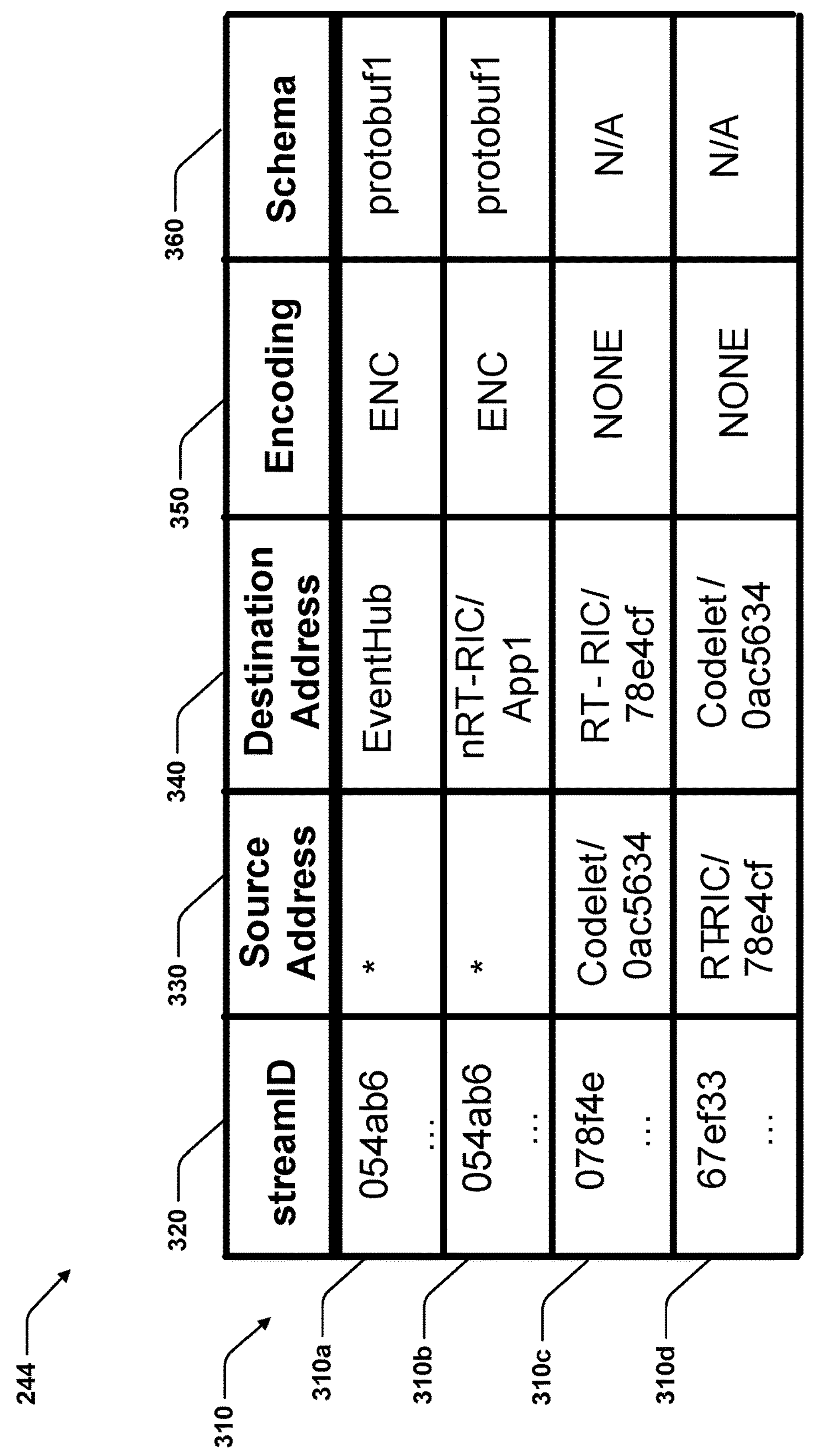

200
220
Edge Server
220a
Core
222
VM/OS/Container
VF1
224
eBPF Codelet
210a
220b
Core
222
VM/OS/Container
Kernel Space
226
Probe
User Space
VF2
210b
230
Shared Memory
232
234
232
234
220c
Core
172
Real-Time RIC
244
Routing Table
242
Message Router
174
Dynamically Loaded Programs
240
Deadline Scheduler
250
Routing Adaptors
nRT-RIC 251
DPDK 252
Cloud Storage 254
Event Hub 256
System Interface 258
262
System API
OS
260

Figure 2


244
310
320
330
340
350
360
310a
310b
310c
310d

streamID	Source Address	Destination Address	Encoding	Schema
054ab6 ...	*	EventHub	ENC	protobuf1
054ab6 ...	*	nRT-RIC/ App1	ENC	protobuf1
078f4e ...	Codelet/ 0ac5634	RT - RIC/ 78e4cf	NONE	N/A
67ef33 ...	RTRIC/ 78e4cf	Codelet / 0ac5634	NONE	N/A

Figure 3

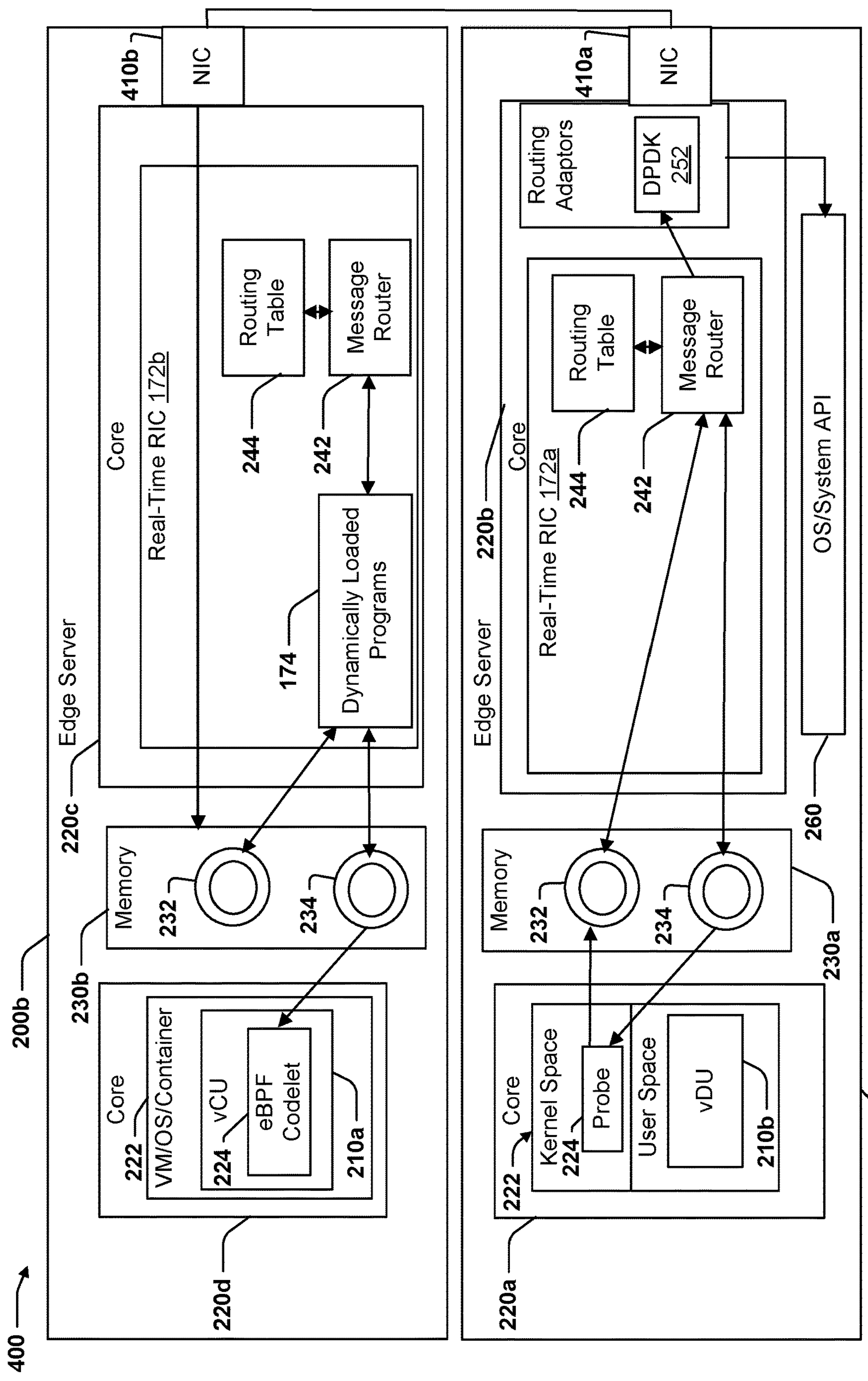

400
200b
Edge Server
NIC
410b
Core
220c
Real-Time RIC 172b
Routing Table
244
Message Router
242
Dynamically Loaded Programs
174
Memory
230b
232
234
Core
222
VM/OS/Container
vCU
224
eBPF Codelet
210a
220d
200a
Edge Server
NIC
410a
Core
220b
Real-Time RIC 172a
Routing Table
244
Message Router
242
Routing Adaptors
DPDK 252
OS/System API
260
Memory
230a
232
234
Core
222
Kernel Space
224
Probe
User Space
vDU
210b
220a

Figure 4

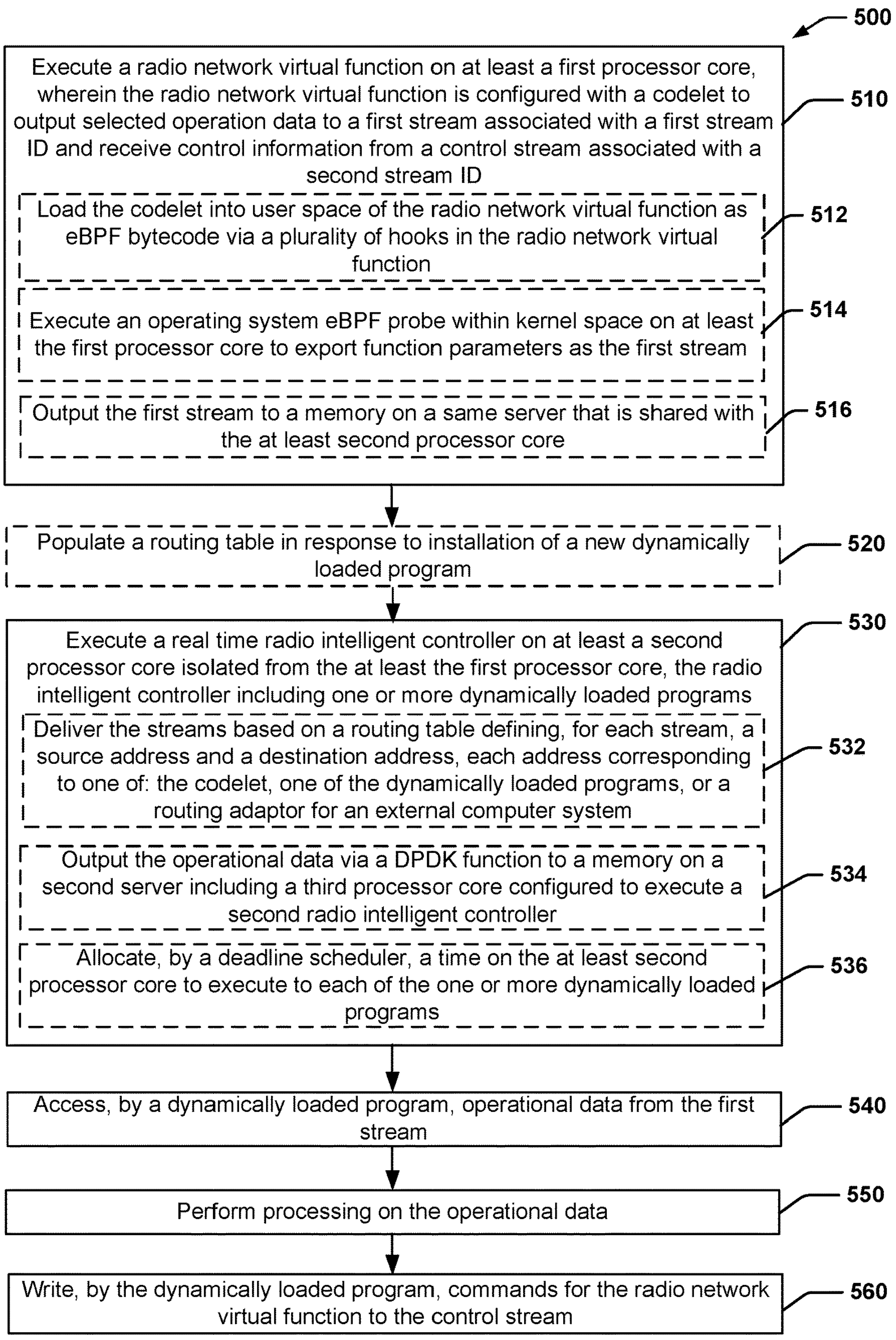

500
Execute a radio network virtual function on at least a first processor core, wherein the radio network virtual function is configured with a codelet to output selected operation data to a first stream associated with a first stream ID and receive control information from a control stream associated with a second stream ID
510
Load the codelet into user space of the radio network virtual function as eBPF bytecode via a plurality of hooks in the radio network virtual function
512
Execute an operating system eBPF probe within kernel space on at least the first processor core to export function parameters as the first stream
514
Output the first stream to a memory on a same server that is shared with the at least second processor core
516
Populate a routing table in response to installation of a new dynamically loaded program
520
Execute a real time radio intelligent controller on at least a second processor core isolated from the at least the first processor core, the radio intelligent controller including one or more dynamically loaded programs
530
Deliver the streams based on a routing table defining, for each stream, a source address and a destination address, each address corresponding to one of: the codelet, one of the dynamically loaded programs, or a routing adaptor for an external computer system
532
Output the operational data via a DPDK function to a memory on a second server including a third processor core configured to execute a second radio intelligent controller
534
Allocate, by a deadline scheduler, a time on the at least second processor core to execute to each of the one or more dynamically loaded programs
536
Access, by a dynamically loaded program, operational data from the first stream
540
Perform processing on the operational data
550
Write, by the dynamically loaded program, commands for the radio network virtual function to the control stream
560

Figure 5

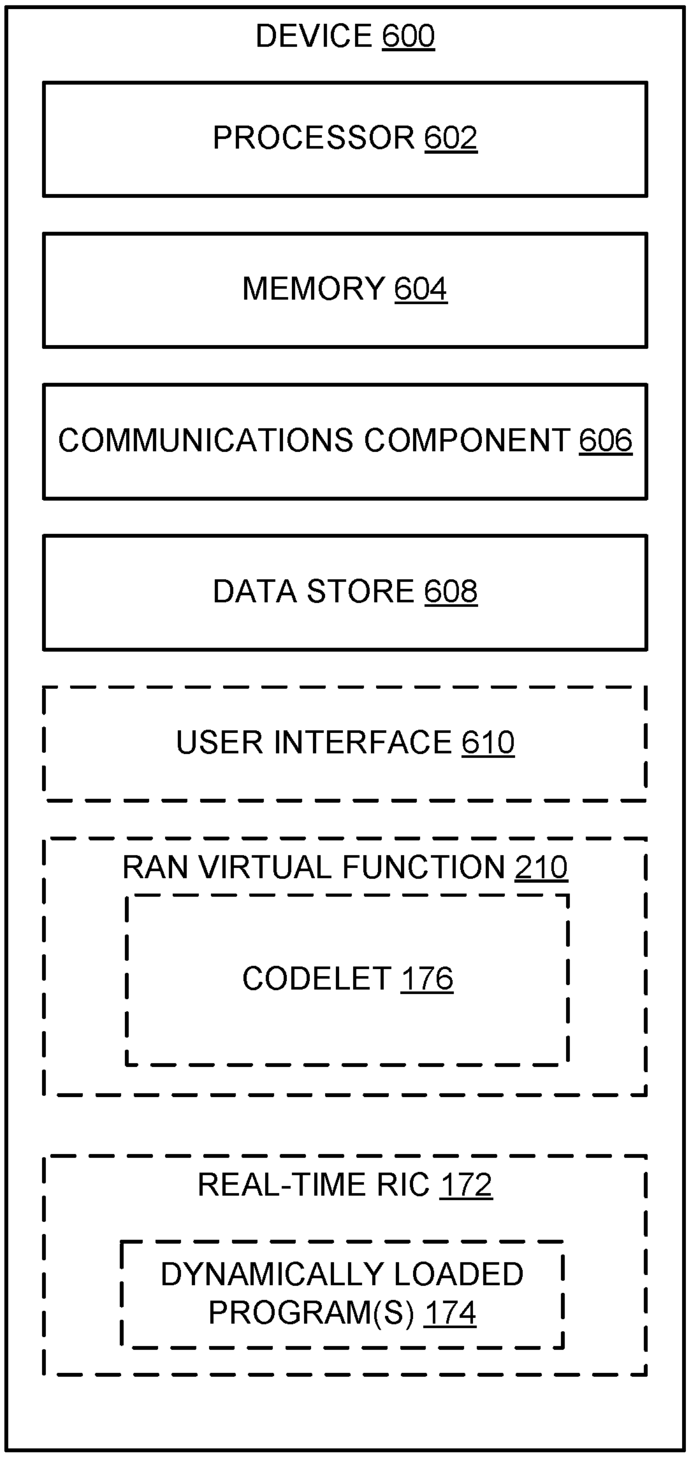

DEVICE 600
PROCESSOR 602
MEMORY 604
COMMUNICATIONS COMPONENT 606
DATA STORE 608
USER INTERFACE 610
RAN VIRTUAL FUNCTION 210
CODELET 176
REAL-TIME RIC 172
DYNAMICALLY LOADED PROGRAM(S) 174

Figure 6

REAL-TIME RADIO INTELLIGENT CONTROLLER

BACKGROUND

A radio access network (RAN) may provide multiple user devices with wireless access to a network. The user devices may wirelessly communicate with a base station, which forwards the communications towards a core network. Conventionally, a base station in the RAN is implemented by dedicated processing hardware (e.g., an embedded system) located close to a radio unit including antennas. The base station may perform lower layer processing including physical (PHY) layer and media access control (MAC) layer processing for one or more cells. There may be costs associated with deploying dedicated processing hardware for each base station in a RAN, particularly for a RAN including small cells with relatively small coverage areas. Additionally, the dedicated processing hardware may be a single point of failure for the cell.

A virtualized radio access network may utilize an edge data center with generic computing resources for performing RAN processing for one or more cells. That is, instead of performing PHY and MAC layer processing locally on dedicated hardware, a virtualized radio access network may forward radio signals from the radio units to the edge data center for processing and similarly forward signals from the edge data center to the radio units for wireless transmission. In one specific example, cloud-computing environments can be used to provide mobile edge computing (MEC) where certain functions of a mobile network can be provided as workloads on nodes in the cloud-computing environment. In MEC, a centralized unit (CU) can be implemented in a back-end node, one or more distributed units (DUs) can be implemented in intermediate nodes, and various remote units (RU), which can provide at least PHY and/or MAC layers of a base station or other RAN node of the mobile network, can be deployed at edge servers. The RUs can communicate with the CU via one or more DUs. In an example, the DUs can provide higher network layer functionality for the RAN, such as radio link control (RLC) or packet data convergence protocol (PDCP) layer functions. The RUs can facilitate access to the CU for various downstream devices, such as user equipment (UE), Internet-of-Things (IoT) devices, etc.

Because the edge data center utilizes generic computing resources, a virtualized RAN may provide scalability and fault tolerance for base station processing. For example, the edge data center may assign a variable number of computing resources (e.g., servers) to perform PHY layer processing for the radio units associated with the edge data center based on a workload. Further, a virtualized RAN may implement multiple layers of RAN processing at a data center, enabling collection of multiple data feeds.

SUMMARY

The following presents a simplified summary of one or more aspects in order to provide a basic understanding of such aspects. This summary is not an extensive overview of all contemplated aspects, and is intended to neither identify key or critical elements of all aspects nor delineate the scope of any or all aspects. Its sole purpose is to present some concepts of one or more aspects in a simplified form as a prelude to the more detailed description that is presented later.

In some aspects, the techniques described herein relate to a computing system including: at least a first processor core configured to execute a radio network virtual function, wherein the radio network virtual function is configured with a codelet to output selected operational data to a first stream associated with a first stream ID and receive control information from a control stream associated with a second stream ID; at least a second processor core configured to execute a real time radio intelligent controller isolated from the at least the first processor core, the radio intelligent controller including one or more dynamically loaded programs configured to: subscribe to the first stream; perform processing on the operational data; and write commands for the radio network virtual function to the control stream.

In some aspects, the techniques described herein relate to a method including: executing a radio network virtual function on at least a first processor core, wherein the radio network virtual function is configured with a codelet to output selected operational data to a first stream associated with a first stream ID and receive control information from a control stream associated with a second stream ID; executing a real time radio intelligent controller on at least a second processor core isolated from the at least the first processor core, the radio intelligent controller including one or more dynamically loaded programs; accessing, by a dynamically loaded program, operational data from the first stream; performing processing on the operational data; and writing, by the dynamically loaded program, commands for the radio network virtual function to the control stream.

In some aspects, the techniques described herein relate to a method, wherein executing the radio network virtual function includes loading the codelet into user space of the radio network virtual function as extended Berkeley Packet Filter (eBPF) bytecode via a plurality of hooks in the radio network virtual function.

To the accomplishment of the foregoing and related ends, the one or more aspects comprise the features hereinafter fully described and particularly pointed out in the claims. The following description and the annexed drawings set forth in detail certain illustrative features of the one or more aspects. These features are indicative, however, of but a few of the various ways in which the principles of various aspects may be employed, and this description is intended to include all such aspects and their equivalents.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a diagram of an example virtualized radio access network (vRAN) connecting a user equipment (UE) to a core network.

FIG. **2** is a diagram of an example edge server configured to execute virtual functions and a real-time radio intelligent controller (RIC).

FIG. **3** is an example of a routing table for the real-time RIC.

FIG. **4** is a diagram of an example server rack implementing a real-time RIC over multiple servers.

FIG. **5** is a flow diagram of an example of a method for executing applications using operational data of a radio access network virtual function in a real-time RIC.

FIG. **6** illustrates an example of a device including additional optional component details as those shown in FIGS. **2** and **4**.

DETAILED DESCRIPTION

The detailed description set forth below in connection with the appended drawings is intended as a description of various configurations and is not intended to represent the only configurations in which the concepts described herein may be practiced. The detailed description includes specific details for the purpose of providing a thorough understanding of various concepts. However, it will be apparent to those skilled in the art that these concepts may be practiced without these specific details. In some instances, well-known components are shown in block diagram form in order to avoid obscuring such concepts.

This disclosure describes various examples related to a real-time radio intelligent controller (RIC). The real-time RIC analyzes operational data of one or more radio access network (RAN) virtual functions. The real-time RIC controls the one or more RAN virtual functions by writing to a control stream. The RAN virtual functions may have tight timing controls, for example, on the order of microseconds (u) in order to meet the slot and mini-slot timing of RAN transmissions.

A key transformation of the Radio Access Network (RAN) in 5G is the migration to an Open RAN architecture, that sees the 5G RAN virtualized and disaggregated across multiple open interfaces. This approach fosters innovation by allowing multiple vendors to come up with unique solutions for different components at a faster pace. Furthermore, a new component introduced in the Open RAN architecture called a Radio Intelligent Controller (RIC) allows third parties to build new, vendor-agnostic monitoring and optimization use cases over interfaces standardized by O-RAN.

Despite this compelling vision, the opportunity for innovation still largely remains untapped because of two main challenges. The first challenge is related to the flexible data collection for monitoring and telemetry applications. The RAN functions can generate huge volumes of telemetry data at a high frequency (e.g., gigabytes per second). Collecting, transferring, and processing this data can put a strain on compute and network capacity. A conventional approach, standardized by the 3rd generation partnership project (3GPP), defines a small set of aggregate cell key performance indicators (KPIs) collected every few seconds or minutes. The O-RAN RIC extends this idea by providing new KPIs at a finer time granularity. The O-RAN RIC may be classified as a near real-time RIC. Each KPI is defined through a service model (a form of API), most of them standardized by O-RAN. However, this approach is slow to evolve and does not scale well because of a limited number of initial use cases and a need to standardize new proposals. The second challenge is due to the real-time nature of many RAN control and data plane operations. Any new functionality added to these operations, in order to support a new service model, must be completed within a deadline, typically ranging from microseconds (μs) to a few milliseconds (ms). A deadline violation may cause performance degradation or even crash a vRAN. Any changes on these critical paths can create substantial design challenges and make RAN vendors reluctant to add new features.

In an aspect, the present disclosure describes a computing system for hosting both RAN virtual functions and a real-time RIC. For example, the computing system may be an edge server or an edge server rack including multiple edge servers. The RAN virtual functions are protected by isolation from the real-time RIC. For example, each RAN virtual function may be executed on a separate processor core from the real-time RIC. The processor core(s) executing the RAN virtual functions are configured with a codelet that outputs selected operational data to a first stream. The codelet is further configured to receive control information from a control stream. The real-time RIC includes one or more dynamically loaded programs that execute in parallel with the RAN virtual functions. The dynamically loaded programs are configured to access the first stream, perform processing on the operational data, and write commands for the RAN virtual functions to the control stream.

The real-time RIC provides great flexibility for the dynamically loaded programs while requiring little modification of the RAN virtual functions by the RAN vendors. For example, the dynamically loaded programs may include complex machine-learning models. Because the dynamically loaded programs are isolated from the RAN virtual functions, timing delays of the dynamically loaded programs will not crash the RAN virtual functions. Further, the codelets for accessing the RAN virtual functions are less intrusive and demanding than conventional service models. For example, a RAN vendor may configure a RAN virtual function with various hook points to allow execution of a codelet including extended Berkeley packet filter (eBPF) bytecode, which can be statically verified prior to loading. As another example, the codelet may be an operating system eBPF probe that executes in kernel space to access function parameters. The operating system eBPF probe can be configured using function calls within the RAN virtual function without modifying the RAN virtual function.

Turning now to FIGS. **1-6**, examples are depicted with reference to one or more components and one or more methods that may perform the actions or operations described herein, where components and/or actions/operations in dashed line may be optional. Although the operations described below in FIG. **5** are presented in a particular order and/or as being performed by an example component, the ordering of the actions and the components performing the actions may be varied, in some examples, depending on the implementation. Moreover, in some examples, one or more of the actions, functions, and/or described components may be performed by a specially-programmed processor, a processor executing specially-programmed software or computer-readable media, or by any other combination of a hardware component and a software component capable of performing the described actions or functions.

FIG. **1** is a diagram of an example vRAN **100** connecting a user equipment (UE) **110** to a core network **160**. The vRAN **100** may include radio units **120** that transmit and receive wireless signals with the UE **110**. The vRAN **100** may include a virtual distributed unit (vDU) **130** that performs processing, for example, at the physical (PHY) layer, media access control (MAC) layer, and radio link control (RLC) layer. The vRAN **100** may include a virtual central unit (vCU) **140** that performs processing at higher layers of the wireless protocol stack. The vRAN **100** may include a RAN intelligent control (RIC) that performs autonomous configuration and optimization of the vRAN **100**.

The division of functionality between the vDU **130** and the vCU **140** may depend on a functional split architecture. The vCU **140** may be divided into a central unit control plane (CU-CP) and central unit user plane (CU-UP). CU-UP may include the packet data convergence protocol (PDCP) layer and the service data adaptation (SDAP) layer, and the radio resource control (RRC) layer. Different components or layers may have different latency and throughput requirements. For example, the PHY layer may have latency requirements between 125 μs and 1 ms and a throughput requirement greater than 1 Gbps, the MAC and RLC layers may have latency requirements between 125 μs and 1 ms and a throughput requirement greater than 100 Mbps, and the higher layers at the vCU may have latency requirements greater than 125 μs and a throughput requirement greater than 100 Mbps.

Programmability in Open RAN components may be facilitated through a near real-time RIC **150**. A network operator can install applications (Apps **152**, e.g., xApps in Open RAN) on top of the near real-time RIC **150**, which may collect detailed telemetry and may leverage the telemetry to optimize network performance or report issues in near real-time (e.g., >10 ms to seconds). The data collection and control of the vRAN components may be facilitated through service models that must be embedded in the vRAN functions by vendors. The service models may explicitly define the type and frequency of data reporting for each App **152**, as well as a list of control policies that the RIC can use to modify the RAN behavior. Each App **152** may specify its own service model, requiring the collection of different telemetry data.

The initial xApps proposed for standardization by Open RAN focus on optimizing handovers, self-organizing network (SON) functionality, anomaly detection, and coarse grained radio resource allocation. In these use cases, significant network events occur at a low rate (100s of ms to seconds). The volume of generated telemetry data is low, and all the data are transported to the RIC. This allows Apps **152** to have a full insight into the domain and tune the vRAN functions through a pre-determined set of control policies. Unfortunately, this approach does not scale to many other use cases of RAN monitoring and control for two main reasons.

Firstly, for many lower layer applications (e.g., PHY and MAC), it is inefficient to transport all the data to the near real-time RIC **150** due to the sheer volume of data. For example, applications like localization, channel estimation, interference detection, and beamforming may require uplink IQ samples from the physical layer. Transporting all IQ samples to the RIC requires more than 5 Gbps per cell for 100 MHZ 4×4 MIMO. The standard near real-time RIC design overcomes this problem by specifying in the service model of each App the data required in terms of type and frequency (e.g., in a raw or a pre-processed format). The form of pre-processing (e.g., sub-sampling, averages, or subsets of data) greatly depends on the service model, posing a serious limitation to interoperability because vRAN vendors must implement and support each proprietary service model.

Secondly, many real-time control loops (e.g., packet scheduling and power control), have very tight time constraints (<10 ms). Such time constraints cannot be met by the standard near real-time RIC design that has an expected latency in the order of hundreds of milliseconds. As in the case of telemetry, the App choice of control policy is limited by a set of (standardized) policies that the appropriate service model of the RIC provides. vRAN vendors must implement and integrate such algorithms in their stack, while ensuring that they do not affect the run time performance of the vRAN component. This framework of services models implanted by the vRAN vendor makes it very difficult to practically implement new custom variants of tight control loops.

In an aspect, the present disclosure provides for a real-time RIC **172** that is executed on the same resources **170** (e.g., server or server rack) as the virtual radio functions (e.g., vDU **130** and vCU **140**). The resources **170** include multiple processor cores, and the real-time RIC **172** is isolated from the virtual radio functions and executed on different processor core(s). The virtual radio functions are

configured with codelets **176** to output selected operational data to streams and receive control information from a control stream. The real-time RIC **172** includes one or more dynamically loaded programs **174** that access the streams of operational data. For example, the dynamically loaded programs **174** may include WebAssembly (Wasm) programs, which allow flexibility for machine-learning models while also providing control over run time. The real-time RIC **172** may be configured to execute other dynamically loaded programs, which may, for example, be implemented as bytecode, containers, or virtual machines. At least one of the dynamically loaded programs **174** subscribes to a stream, performs processing on the operational data, and writes commands to the control stream. For instance, the dynamically loaded programs **174** may include applications configured to analyze the operational data. In some cases, the dynamically loaded programs **174** may make decisions for the virtual network functions, for example, by writing a command to the control stream.

FIG. **2** is a diagram of an example edge server **200** configured to execute virtual functions **210** and a real-time RIC **172**. The edge server **200** may correspond to resources **170**. The edge server **200** includes a plurality of processor cores **220** and may be considered a multi-core system.

A multi-core system may take advantage of multi-threaded parallel processing capabilities of multiple processor cores **220**. For example, a multi-core system may include a central processing unit (CPU) such as a server grade X86 processor. The multi-core system may have one or more physical chips that provide a plurality of virtual CPUs (vCPUs). Each vCPU may be able to handle a thread of execution in parallel with the other vCPUs. In a general purpose multi-core system, an operating system may use context switching to assign different threads of execution to vCPUs as needed. In some implementations, a multi-core system may lock one or more vCPUs to certain threads of execution for virtual functions. For instance, in an implementation, a plurality of the processor cores **220** (e.g., vCPUs) may be locked to a virtual function thread of execution using a pull mode driver that occupies the processor core **220** at all times. Locking a thread of execution to a processor core **220** may reduce the overhead of context switching among threads and improve performance of the virtual function. For instance, a virtual function **210** may execute on a respective processor core **220** without interruption.

In some implementations, a virtual function **210** is executed on a core **220** within a virtual machine **222**. For example, the virtual machine **222** may be referred to as a VM, operating system (OS), or container. The virtual machine **222** may include a kernel space and a user space. The virtual function **210** may execute within the user space. In an aspect, the virtual function **210** may be a proprietary third-party application provided by, for example, a vRAN vendor. Accordingly, the functionality of the virtual function **210** may be fixed with some functionality exposed via the pre-determined set of control policies and service models. In order to export operational data from a virtual function **210** or input controls to the virtual function **210**, the virtual function **210** may be configured with a codelet **176**. The codelet **176** is verified code that is allowed to execute within another application.

In a first implementation, the codelet **176** is an extended Berkeley packet filter (eBPF) codelet **224**. The eBPF codelet **224** executes within the user space of the radio network virtual function **210***a*. the eBPF codelet **224** may be referred to as a user-space Berkeley packet filter (uBPF) codelet. The radio network virtual function **210** may be configured with a plurality of hooks to load eBPF bytecode to output a stream to a shared memory **230**. For instance, the vRAN vendor may configure the plurality of hooks in the radio network virtual function **210***a*.

In a second implementation, the codelet **176** may be configured as an operating system eBPF probe **226** that executes in kernel space on the processor core **220***b* and exports function parameters as a stream to the shared memory **230**. The operating system eBPF probe **226** may be, for example, a Linux eBPF uProbe. The operating system eBPF probe **226** may not require hooks within the virtual function **210***b*. Instead, the operating system eBPF probe **226** may be configured with function calls of the virtual function **210***b* and access the function parameters from the kernel space. Accordingly, a vRAN vendor may allow access to the operational data without modifying the virtual function **210***b* by providing information about the function calls.

The shared memory **230** may include one or more computer memories (e.g., RAM). The shared memory **230** may be shared between the processor cores **220** including the processor cores **220***a* and **220***b* that are assigned to the virtual functions and the processor core **220***c* that is configured to execute the real-time RIC **172**. The codelet **176** executing on processor core **220***a* or **220***b* may write a stream **232** to the shared memory **230**. The real-time RIC **172** or a dynamically loaded program **174** may write a control stream **234** to the shared memory **230**. In some implementations, the shared memory **230** is configured to store streams **232**, **234** in a lockless ring buffer. Accordingly, either the codelet **176** or the real-time RIC **172** may access the lockless ring buffer.

The real-time RIC **172** includes the one or more dynamically loaded programs **174**. The dynamically loaded programs **174** are configured to access a stream, perform processing on the operational data, and write commands for the respective radio network virtual function to the control stream. In some implementations, a dynamically loaded program **174** may be configured to directly access the shared memory **230** to read or write to a stream **232**, **234**. In some implementations, the real-time RIC **172** includes a deadline scheduler **240** configured to allocate a time on the processor core **220***c* to execute to each of the one or more dynamically loaded programs **174**. When multiple dynamically loaded programs **174** are executed within the real-time RIC **172** on the same processor core **220***c*, a dynamically loaded program **174** may exhibit blocking behavior that prevents another dynamically loaded program **174** from satisfying a latency requirement. The deadline scheduler **240** may configure each dynamically loaded program **174** with a deadline, at which point, context switching may occur to allow the other dynamically loaded program **174** to execute. Accordingly, the dynamically loaded programs **174** may satisfy latency requirements if they can complete execution within the allocated time. In some implementations, the deadline scheduler **240** may also apply to a message router **242** or other applications executed by the real-time RIC **172**.

In some implementations, the real-time RIC **172** may include a message router **242** that is configured to access the shared memory **230** to read a stream **232**, **234** and forward a message to another entity. The dynamically loaded programs may subscribe to a stream **232**, **234** via the message router **242**. The message router **242** may provide access to the operational data of the virtual functions **210** or results of the dynamically loaded programs **174** to entities that are not on the resources **170**. For example, referring back to FIG. **1**,

the message router **242** may communicate with the near real-time RIC **150** and/or the core network **160**. In some implementations, the message router **242** is configured with a routing table **244** that defines, for each stream, a source address and a destination address. Each address may corresponding to one of: the codelet **176**, one of the dynamically loaded programs **174**, or a routing adaptor **250** for an external computer system. Further details of the routing table **244** are discussed below with respect to FIG. **3**.

The routing adaptors **250** may convert internal messages compatible with the codelet **176** to formats or protocols usable with external systems. In an implementation, the routing adaptors **250** include one or more of: a near rea-time RIC (nRT-RIC) adaptor **251**, a data plane development kit (DPDK) adaptor **252**, a cloud storage adaptor **254**, an event hub adaptor **256**, and a system interface adaptor **258**. The nRT-RIC adaptor **251** may communicate with the near real-time RIC **150**. The DPDK adaptor **252** may allow the real-time RIC **172** to send messages to another real-time RIC or associated codelet or dynamically loaded program in real time (e.g., to satisfy latency requirements). In some implementations, the DPDK adaptor **252** is configured to output operational data to a memory on a second server that is connected to the edge server **200** via a single hop network link using a DPDK function. The cloud storage adaptor **254** and the event hub adaptor **256** may communicate with cloud network applications. The system interface adaptor **258** may communicate with the operating system **260** of the edge server **200** or a system API **262**. For instance, the system interface adaptor **258** may allow the real-time RIC **172** to set a CPU frequency or execute eBPF codelets.

FIG. **3** is an example of a routing table **244**. The routing table **244** includes a plurality of entries **310** each corresponding to a stream with a stream ID **320**. For each entry **310**, the routing table **244** defines a source address **330**, destination address **340**, encoding field **350**, and schema field **360**. The source address **330** and destination address **340** may include one or more of: a codelet **176**, one of the dynamically loaded programs **174**, or a routing adaptor **250**. In some implementations, the source address may be any source (*). For example, the entries **310***a* and **310***b* may be for the same stream ID, may apply to any source, and may have different destination addresses (e.g., an event hub via event hub adaptor **256** and an App **152** on near real time RIC **150** via nRT-RIC adaptor **251**). Such entries may support multicast of operational data and/or events. For example, a codelet **176** may write to the stream ID to export operational data to multiple external systems. The encoding field **350** may indicate whether the stream is to be encoded, decoded, or neither. For example, the codelet **176** may write to the stream using a protobuf encoder defined by a protobuf schema. The encoding field **350** for entries **310***a* and **310***b* may indicate that the stream is encoded with a schema named "protobuf1" as indicated by the schema field **360**. The message router **242** and/or routing adaptor **250** may use the encoding field **350** and schema field **360** to format the message for the destination. The entry **310***c* may define a stream from a codelet **176** to a dynamically loaded program **174** on the real-time RIC **172**. For instance, the entry **310***c* may correspond to an output stream **232**. The entry **310***d* may define a steam from the dynamically loaded program **174** to the codelet **176**. Accordingly, the entry **310***d* may correspond to a control stream **234**.

FIG. **4** is a diagram of an example server rack **400** implementing a real-time RIC **172** over multiple servers **200**. In the example implementation, a first server **200***a* executes a first virtual function **210** (e.g., a vDU) and the second server **200***b* executes a second virtual function **210** (e.g., a vCU). Each server **200** may execute an instance of the real-time RIC **172***a*, **172***b* on a separate core (e.g., processor cores **220***b*, **220***c*). Each server **200***a*, **200***b* may include a respective memory **230***a*. **230***b*. In an implementation, the first server includes a network interface controller (NIC) **410***a* and the second server **200***b* includes a NIC **410***b*. The NIC **410***a* and NIC **410***b* may be connected by a direct single hop network link (e.g., Ethernet).

The second server **200***b* may include a dynamically loaded program **174** executing on a processor core **220***d* for controlling the second virtual function **210** based on operational data from the first virtual function **210**. The dynamically loaded program **174** does not have direct access to the output stream **232** on memory **230***a* of the first server **200***a*. Instead, the message router **242** may read the stream **232** and forward a message from the stream **232** to the memory **230***b* via the DPDK adaptor **252**. The DPDK adaptor **252** may invoke a DPDK function that allows the NIC **410***b* to write directly to the memory **230***b* (for example, to a copy of output stream **232**). The dynamically loaded program **174** may then read the output stream **232** and write to a control stream **234** on memory **230***b*. Accordingly, the server rack **400** may support real-time RIC operations across multiple servers. Such an implementation may provide greater scaling and/or flexibility for allocating resources.

FIG. **5** is a flow diagram of an example of a method **500** for executing applications using operational data of a radio access network virtual function in a real-time RIC. For example, the method **500** can be performed by a server **200**, server rack **400** and/or one or more components thereof to execute a dynamically loaded program **174** to control a virtual function **210**.

At block **510**, the method **500** includes executing a radio network virtual function on at least a first processor core. In an example, a edge server **200**, e.g., in conjunction with one or more processor cores **220**, memory **230**, and a virtual machine **222**, can execute a radio network virtual function **210** on at least a first processor core **220**. The radio network virtual function **210** is configured with a codelet **176** (e.g., eBPF codelet **224** or probe **226**) to output selected operational data to a first stream **232** associated with a first stream ID and receive control information from a control stream **234** associated with a second stream ID. In some implementations, at sub-block **512**, the block **510** may optionally include loading the codelet **176** (e.g., eBPF codelet **224**) into user space of the radio network virtual function **210** as eBPF bytecode via a plurality of hooks in the radio network virtual function **210**. For example, the radio network virtual function **210** including the plurality of hooks may be provided by a third-party vRAN vendor and an operator of the server **200** may configure the radio network virtual function **210** by loading the eBPF codelet **224** onto one or more hooks to export desired operational data. In some implementations, at sub-block **514**, the block **510** may optionally include execute an operating system eBPF probe **226** within kernel space on at least the first processor core **220** to export function parameters as the first stream **232**. For example, the eBPF probe **226** may be executed within the kernel space of the virtual machine **222** and may reference functions of the radio network virtual function **210**. In some implementations, at sub-block **516**, the block **510** may optionally include outputting the first stream **232** to a memory **230** on a same server that is shared with the at least second processor core (e.g., processor core **220***c*).

At block **520**, the method **500** may optionally populating a routing table in response to installation of a new dynamically loaded program. In an example, the real-time RIC **172**. e.g., in conjunction with processor core **220***c*, memory **230**, and operating system **260**, can populating the routing table **244** in response to installation of a new dynamically loaded program **174**. For example, the real-time RIC **172** may add one or more new entries **310** to the routing table **244**, for example, to define a source stream and a control stream for the new dynamically loaded program **174**.

At block **530**, the method **500** includes executing a real time radio intelligent controller on at least a second processor core isolated from the at least the first processor core, the radio intelligent controller including one or more dynamically loaded programs. In an example, the server **200**, e.g., in conjunction with processor core **220***c*, memory **230**, and operating system **260**, can execute the real-time RIC **172** on at least a second processor core (e.g. processor core **220***c*) isolated from the at least the first processor core (e.g., processor core **220***a* or **220***b*). The real-time RIC **172** includes one or more dynamically loaded programs **174**. In some implementations, at sub-block **532**, the block **530** may optionally include delivering the streams **232** based on a routing table **244** defining, for each stream, a source address **330** and a destination address **340**, each address **330**, **340** corresponding to one or more of: the codelet **176**, one of the dynamically loaded programs **174**, or a routing adaptor **250** for an external computer system. For example, the message router may deliver the stream **232** based on the routing table **244**. In some implementations, the routing table **244** further defines a protobuf encoding or decoding (e.g., encoding field **350**) and schema (e.g., schema field **360**) for a routing adaptor **250**. In some implementations, at sub-block **534**, the block **530** may optionally include outputting the operational data via a DPDK function to a memory **230***b* on a second server **200***b* including a third processor core **220***c* configured to execute a second real-time RIC **172***b*. For example, the message router **242** may copy the stream **232** via a DPDK function over NICs **410***a* and **410***b* to memory **230***b*. In some implementations, at sub-block **536**, the block **530** may optionally include allocating, by a deadline scheduler **240**, a time on the at least second processor core **220***c* to execute to each of the one or more dynamically loaded programs **174**.

At block **540**, the method **500** includes accessing, by a dynamically loaded program, operational data from the first stream. In an example, the server **200** executing the dynamically loaded program **174** within the real-time RIC **172**, e.g., in conjunction with processor core **220***c*, memory **230**, and operating system **260**, can access operational data from the first stream **232**.

At block **550**, the method **500** includes performing processing on the operational data. In an example, the server **200** executing the dynamically loaded program **174** within the real-time RIC **172**, e.g., in conjunction with processor core **220***c*, memory **230**, and operating system **260**, can perform processing on the operational data. For instance, the processing may include relatively complicated processing that cannot be written in eBPF bytecode for execution within the virtual functions **210**. In an example, the processing may include applying the operational data to a trained machine-learning model.

At block **560**, the method **500** includes writing, by the dynamically loaded program, commands for the radio network virtual function to the control stream. In an example, the server **200** executing the dynamically loaded program **174** within the real-time RIC **172**, e.g., in conjunction with processor core **220***c*, memory **230**, and operating system **260**, can write commands for the radio network virtual function **210** to the control stream **234**. In some implementations, the dynamically loaded program **174** may write the commands directly to the shared memory **230**. In some implementations, writing the commands may be via the message router **242**, which may, for example, apply encoding or decoding as defined in the routing table **244**.

FIG. **6** illustrates an example of a device **600** including additional optional component details as those shown in FIGS. **2** and **4**. In one aspect, device **600** may include one or more processors **602**, which may be similar to processor cores **220** for carrying out processing functions associated with one or more of components and functions described herein. Processor(s) **602** can include a single or multiple set of processors or multi-core processors. Moreover, processor (s) **602** can be implemented as an integrated processing system and/or a distributed processing system.

Device **600** may further include one or more memory/memories **604**, which may be similar to memory **230** such as for storing local versions of operating systems (or components thereof) and/or applications being executed by processor(s) **602**, such as RAN virtual functions **210** and real-time RIC **172**, etc. Memory/memories **604** can include a type of memory usable by a computer, such as random access memory (RAM), read only memory (ROM), tapes, magnetic discs, optical discs, volatile memory, non-volatile memory, and any combination thereof.

Further, device **600** may include a communications component **606** that provides for establishing and maintaining communications with one or more other devices, parties, entities, etc. utilizing hardware, software, and services as described herein. Communications component **606** may carry communications between components on device **600**, as well as between device **600** and external devices, such as devices located across a communications network and/or devices serially or locally connected to device **600**. For example, communications component **606** may include one or more buses, and may further include transmit chain components and receive chain components associated with a wireless or wired transmitter and receiver, respectively, operable for interfacing with external devices.

Additionally, device **600** may include a data store **608**, which can be any suitable combination of hardware and/or software, that provides for mass storage of information, databases, and programs employed in connection with aspects described herein. For example, data store **608** may be or may include a data repository for operating systems (or components thereof), applications, related parameters, etc. not currently being executed by processor(s) **602**. In addition, data store **608** may be a data repository for doorway RAN virtual functions **210**, real-time RIC **172**, and/or one or more other components of the device **600**.

Device **600** may optionally include a user interface component **610** operable to receive inputs from a user of device **600** and further operable to generate outputs for presentation to the user. User interface component **610** may include one or more input devices, including but not limited to a keyboard, a number pad, a mouse, a touch-sensitive display, a navigation key, a function key, a microphone, a voice recognition component, a gesture recognition component, a depth sensor, a gaze tracking sensor, a switch/button, any other mechanism capable of receiving an input from a user, or any combination thereof. Further, user interface component **610** may include one or more output devices, including but not limited to a display, a speaker, a haptic feedback mechanism, a printer, any other mechanism capable of presenting an output to a user, or any combination thereof.

Device **600** may additionally include the RAN virtual function **210** configured with the codelet **176** and the real-time RIC **172** for executing dynamically loaded program(s) **174**, as described herein.

The following numbered clauses provide an overview of aspects of the present disclosure:

Clause 1. A computing system comprising: at least a first processor core configured to execute a radio network virtual function, wherein the radio network virtual function is configured with a codelet to output selected operational data to a first stream associated with a first stream ID and receive control information from a control stream associated with a second stream ID; and at least a second processor core configured to execute a real-time radio intelligent controller isolated from the at least the first processor core, the real-time radio intelligent controller including one or more dynamically loaded programs configured to: access the first stream; perform processing on the operational data; and write commands for the radio network virtual function to the control stream.

Clause 2. The computing system of clause 1, wherein the radio network virtual function is configured with a plurality of hooks to load the codelet into user space of the radio network virtual function as extended Berkeley Packet Filter (eBPF) bytecode to output the first stream.

Clause 3. The computing system of clause 1 or 2, wherein the radio network virtual function is configured with an operating system eBPF probe that executes in kernel space on at least the first processor core and exports function parameters as the first stream.

Clause 4. The computing system of any of clauses 1-3, wherein the codelet is configured to output the first stream to a memory on a same server that is shared with the at least second processor core.

Clause 5. The computing system of clause 4, wherein at least one of the dynamically loaded programs is configured to route a message of the first stream to a second server, the codelet, or another one of the dynamically loaded programs.

Clause 6. The computing system of clause 4 or 5, wherein the memory stores the stream as a lockless ring buffer.

Clause 7. The computing system of any of clauses 1-6, wherein the real-time radio intelligent controller includes a message router configured to deliver the streams based on a routing table defining, for each stream, a source address and a destination address, each address corresponding to one or more of: the codelet, one of the dynamically loaded programs, or a routing adaptor for an external computer system.

Clause 8. The computing system of clause 7, wherein the message router is configured to output the operational data to a memory on a second server including a third processor core configured to execute a second radio intelligent controller, wherein the second server is connected to a first server including the first processor core via a single hop network link and the output is via a data plane development kit (DPDK) function.

Clause 9. The computing system of clause 7 or 8, wherein the routing table further defines a protobuf encoding or decoding and schema for a routing adaptor.

Clause 10. The computing system of any of clauses 7-9, wherein the real-time radio intelligent controller is configured to populate the routing table in response to installation of a new dynamically loaded program.

Clause 11. The computing system of any of clauses 1-10, wherein the real-time radio intelligent controller includes a deadline scheduler configured to allocate a time on the at least second processor core to execute to each of the one or more dynamically loaded programs.

Clause 12. A method comprising: executing a radio network virtual function on at least a first processor core, wherein the radio network virtual function is configured with a codelet to output selected operational data to a first stream associated with a first stream ID and receive control information from a control stream associated with a second stream ID; executing a real time radio intelligent controller on at least a second processor core isolated from the at least the first processor core, the radio intelligent controller including one or more dynamically loaded programs; accessing, by a dynamically loaded program, operational data from the first stream; performing processing on the operational data; and writing, by the dynamically loaded program, commands for the radio network virtual function to the control stream.

Clause 13. The method of clause 12, wherein executing the radio network virtual function comprises loading the codelet into user space of the radio network virtual function as extended Berkeley Packet Filter (eBPF) bytecode via a plurality of hooks in the radio network virtual function.

Clause 14. The method of clause 12 or 13, wherein executing the radio network virtual function comprises executing an operating system eBPF probe within in kernel space on at least the first processor core to export function parameters as the first stream.

Clause 15. The method of any of clauses 12-14, wherein executing the radio network virtual function comprises outputting the first stream to a memory on a same server that is shared with the at least second processor core.

Clause 16. The method of clause 15, further comprising forwarding, by one of the dynamically loaded programs, a message of the first stream to a second server.

Clause 17. The method of clause 15 or 16, wherein the memory stores the stream as a lockless ring buffer.

Clause 18. The method of any of clauses 12-17, wherein executing the real time radio intelligent controller comprises delivering the streams based on a routing table defining, for each stream, a source address and a destination address, each address corresponding to one of: the codelet, one of the dynamically loaded programs, or a routing adaptor for an external computer system.

Clause 19. The method of clause 18, wherein executing the real time radio intelligent controller comprises outputting the operational data via a data plane development kit (DPDK) function to a memory on a second server including a third processor core configured to execute a second radio intelligent controller, wherein the second server is connected to a first server including the first processor core via a single hop network link.

Clause 20. The method of clause 18 or 19, wherein the routing table further defines a protobuf encoding or decoding and schema for a routing adaptor.

Clause 21. The method of any of clauses 18-20, further comprising populating the routing table in response to installation of a new dynamically loaded program.

Clause 22. The method of any of clauses 12-21, further comprising allocating, by a deadline scheduler, a time on the at least second processor core to execute to each of the one or more dynamically loaded programs.

One or more non-transitory computer-readable media having stored thereon compute-executable instructions that when executed by one or more processors, individually or in combination, cause the one or more processors to perform the method of any of clauses 12-22.

By way of example, an element, or any portion of an element, or any combination of elements may be implemented with a "processing system" that includes one or more processors. Examples of processors include microprocessors, microcontrollers, digital signal processors (DSPs), field programmable gate arrays (FPGAs), programmable logic devices (PLDs), state machines, gated logic, discrete hardware circuits, and other suitable hardware configured to perform the various functionality described throughout this disclosure. One or more processors in the processing system may execute software. Software shall be construed broadly to mean instructions, instruction sets, code, code segments, program code, programs, subprograms, software modules, applications, software applications, software packages, routines, subroutines, objects, executables, threads of execution, procedures, functions, etc., whether referred to as software, firmware, middleware, microcode, hardware description language, or otherwise.

Accordingly, in one or more aspects, one or more of the functions described may be implemented in hardware, software, firmware, or any combination thereof. If implemented in software, the functions may be stored on or encoded as one or more instructions or code on a computer-readable medium. Computer-readable media includes computer storage media. Storage media may be any available media that can be accessed by a computer. By way of example, and not limitation, such computer-readable media can comprise RAM, ROM, EEPROM, CD-ROM or other optical disk storage, magnetic disk storage or other magnetic storage devices, or any other medium that can be used to carry or store desired program code in the form of instructions or data structures and that can be accessed by a computer. Disk and disc, as used herein, includes compact disc (CD), laser disc, optical disc, digital versatile disc (DVD), and floppy disk where disks usually reproduce data magnetically, while discs reproduce data optically with lasers. Combinations of the above should also be included within the scope of computer-readable media. Non-transitory computer readable media specifically exclude transitory signals.

The previous description is provided to enable any person skilled in the art to practice the various aspects described herein. Various modifications to these aspects will be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other aspects. Thus, the claims are not intended to be limited to the aspects shown herein, but are to be accorded the full scope consistent with the claim language. Reference to an element in the singular is not intended to mean "one and only one" unless specifically so stated, but rather "one or more." Unless specifically stated otherwise, the term "some" refers to one or more. Moreover, the term "or" is intended to mean an inclusive "or" rather than an exclusive "or." That is, unless specified otherwise, or clear from the context, the phrase "X employs A or B" is intended to mean any of the natural inclusive permutations. That is, the phrase "X employs A or B" is satisfied by any of the following instances: X employs A; X employs B; or X employs both A and B. In addition, the articles "a" and "an" as used in this application and the appended claims should generally be construed to mean "one or more" unless specified otherwise or clear from the context to be directed to a singular form. Moreover, nothing disclosed herein is intended to be dedicated to the public regardless of whether such disclosure is explicitly recited in the claims. No claim element is to be construed as a means plus function unless the element is expressly recited using the phrase "means for".

What is claimed is:

1. A computing system comprising:

at least a first processor core configured to execute a radio network virtual function, wherein the radio network virtual function is configured with a codelet to output selected operational data to a first stream associated with a first stream ID and receive control information from a control stream associated with a second stream ID; and

at least a second processor core configured to execute a real-time radio intelligent controller isolated from the at least first processor core, the real-time radio intelligent controller including one or more dynamically loaded programs, wherein the at least second processor core is configured to:

access the selected operational data from the first stream;

perform processing on the selected operational data; and

write commands for the radio network virtual function to the control stream.

2. The computing system of claim **1**, wherein the radio network virtual function is configured with a plurality of hooks to load the codelet into user space of the radio network virtual function as extended Berkeley Packet Filter (eBPF) bytecode.

3. The computing system of claim **1**, wherein the radio network virtual function is configured with an operating system eBPF probe that exports function parameters.

4. The computing system of claim **1**, wherein the radio network virtual function is configured to output the first stream including the selected operational data to a memory on a same first server, wherein the memory is shared with the at least second processor core.

5. The computing system of claim **4**, wherein at least one of the one or more dynamically loaded programs is configured to route a message to a second server, the codelet, or another one of the dynamically loaded programs, wherein the second server is different than the first server.

6. The computing system of claim **4**, wherein the memory stores the selected operational data to the first stream at a lockless ring buffer.

7. The computing system of claim **1**, wherein the real-time radio intelligent controller includes a message router configured to deliver the first stream and the control stream based on a routing table defining, for each of a plurality of streams, a source address and a destination address, each address corresponding to one or more of: the codelet, one of the one or more dynamically loaded programs, or a routing adaptor for an external computer system.

8. The computing system of claim **7**, wherein the message router is configured to output the selected operational data to a memory on a second server including a third processor core configured to execute a second radio intelligent controller, wherein the second server is connected to a first server including the at least first processor core via a single hop network link, and wherein the output of the selected operational data is via a data plane development kit (DPDK) function.

9. The computing system of claim **7**, wherein the routing table further defines a protobuf encoding or decoding and schema for the routing adaptor.

10. The computing system of claim **7**, wherein the real-time radio intelligent controller is configured to populate the routing table in response to installation of a new dynamically loaded program.

11. The computing system of claim **1**, wherein the real-time radio intelligent controller includes a deadline scheduler configured to allocate a time on the at least second processor core to execute to each of the one or more dynamically loaded programs.

12. A method comprising:

executing a radio network virtual function on at least a first processor core, wherein the radio network virtual function is configured with a codelet to output selected operational data to a first stream associated with a first stream ID and receive control information from a control stream associated with a second stream ID;

executing a real-time radio intelligent controller on at least a second processor core isolated from the at least first processor core, the real-time radio intelligent controller including one or more dynamically loaded programs;

accessing, by a dynamically loaded program, the selected operational data from the first stream;

performing processing on the selected operational data; and

writing, by the dynamically loaded program, commands for the radio network virtual function to the control stream.

13. The method of claim **12**, wherein executing the radio network virtual function comprises loading the codelet into user space of the radio network virtual function as extended Berkeley Packet Filter (eBPF) bytecode via a plurality of hooks in the radio network virtual function.

14. The method of claim **12**, wherein executing the radio network virtual function comprises executing an operating system eBPF probe within kernel space on the at least first processor core to export function parameters.

15. The method of claim **12**, wherein executing the radio network virtual function comprises outputting the first stream including the selected operational data to a memory on a same first server, wherein the memory is shared with the at least second processor core.

16. The method of claim **15**, further comprising forwarding, by one of the one or more dynamically loaded programs, a message to a second server, wherein the second server is different than the first server.

17. The method of claim **15**, wherein the memory stores the selected operational data of the first stream at a lockless ring buffer.

18. The method of claim **12**, wherein executing the real-time radio intelligent controller comprises delivering the first stream and the control stream based on a routing table defining, for each of a plurality of streams, a source address and a destination address, each address corresponding to one of: the codelet, one of the one or more dynamically loaded programs, or a routing adaptor for an external computer system.

19. The method of claim **18**, wherein executing the real-time radio intelligent controller comprises outputting the selected operational data via a data plane development kit (DPDK) function to a memory on a second server including a third processor core configured to execute a second radio intelligent controller, wherein the second server is connected to a first server including the at least first processor core via a single hop network link.

20. The method of claim **18**, wherein the routing table further defines a protobuf encoding or decoding and schema for the routing adaptor.

21. The method of claim **18**, further comprising populating the routing table in response to installation of a new dynamically loaded program.

22. The method of claim **12**, further comprising allocating, by a deadline scheduler, a time on the at least second processor core to execute to each of the one or more dynamically loaded programs.

23. One or more non-transitory computer-readable media having stored thereon compute-executable instructions that when executed by one or more processors, individually or in combination, cause the one or more processors to:

execute a radio network virtual function on at least a first processor core, wherein the radio network virtual function is configured with a codelet to output selected operational data to a first stream associated with a first stream ID and receive control information from a control stream associated with a second stream ID;

execute a real-time radio intelligent controller on at least a second processor core isolated from the at least first processor core, the real-time radio intelligent controller including one or more dynamically loaded programs;

access, by a dynamically loaded program, the selected operational data from the first stream;

perform processing on the selected operational data; and

write, by the dynamically loaded program, commands for the radio network virtual function to the control stream.

* * * * *