NFActor: A Resillient NFV System using the Distributed Actor Framework

Paper #44, xx pages

ABSTRACT

With the advent of Network Function Virtualization (NFV) paradigm, a few NFV management systems have been proposed, enabling NF service chaining, scaling, placement, load balancing, etc. Unfortunately, although failure resilience is of pivotal importance in practical NFV systems, it is mostly absent in existing systems. We identify the absence is mainly due to the challenge of patching source code of the existing NF software for extracting important NF states, a necessary step toward flow migration and replication. This paper proposes *NFActor*, a novel NFV system that uses the actor programming model to provide transparent resilience, easy scalability and high performance in network flow processing. In *NFActor*, a set of efficient APIs are provided for constructing NFs, with inherent support for scalability and resilience; a per-flow management principle is advocated - different from the existing systems - which provides dedicated service chain services for individual flows, enabling decentralized flow migration and scalable replication for each flow. Going beyond resilience, *NFActor* also enables several interesting applications, including live NF update, flow deduplication and reliable MPTCP subflow processing, which are not available in existing NFV systems due to the lack of decentralized flow migration. We implement *NFActor* on a real-world testbed and show that it achieves supreme scalability, prompt flow migration and failure recovery, ... **Chuan:** add more detailed results

1. INTRODUCTION

The recent paradigm of Network Function Virtualization (NFV) advocates moving Network Functions (NFs) out of dedicated hardware middleboxes and running them as virtualized applications on commodity servers [13]. With NFV, network operators no longer need to maintain complicated and costly hardware middleboxes. Instead, they may launch virtualized devices (virtual machines or containers) to run NFs on the fly, which drastically reduces the cost and complexity of deploying network services, usually consisting of a sequence of NFs such as "firewall→IDS→proxy", *i.e.*, a service chain.

A number of NFV management systems have been designed in recent years, *e.g.*, E2 [31], OpenBox [22], CoMb [36], xOMB [19], Stratos [23], OpenNetVM [26, 38], ClickOS [28]. They implement a broad range of NF management functionalities, including dynamic NF placement, elastic NF scaling, load balancing, etc., which facilitate network operators in operating NF service chains in virtualized environments. However, none of the existing systems enable failure tolerance [34, 37] and flow migration [24, 35, 27] capabilities simultaneously, both of which are of pivotal importance in practical NFV systems for resilience and scalability.

Failure resilience is crucial for stateful NFs. Many NFs maintain important per-flow states [20]. Intrusion detection systems such as Bro [3] parse different network/application protocols, and store and update protocol-related states for each flow to alert potential attacks. Firewalls [11] maintain TCP connection-related states by parsing TCP SYN/ACK/FIN packets for each flow. Some load-balancers [12] use a map between flow identifiers and the server address to modify the destination address in each flow packet. It is critical to ensure correct recovery of flow states in case of NF instance failures, such that the connections handled by the failed NF instances do not have to be reset. In practice, middlebox vendors strongly rejected the idea of simply resetting all active connections after failure as it disrupts users [37].

Flow migration is important for long-lived flows in various scaling cases. Existing NF management systems mostly assume dispatching new flows to newly created NF instances when existing instances are overloaded, or waiting for remaining flows to finish before shutting down a mostly idle instance, which is in fact only feasible in cases of short-lived flows. In real-world Internet systems, long-lived flows are common. Web applications usually multiplex application-level requests and responses in one TCP connection to improve performance. For example, a web browser uses one TCP connection to exchange many requests and responses with a web server [9]; video-streaming [7] and file-downloading [8] systems maintain long-lived TCP connection for fetching a large amount of data from CDN servers. When

NF instances handling long flows are overloaded, some flows need to be migrated to new NF instances, in order to mitigate overload of the existing ones in a timely manner [24]; when some NF instances are handling a few dangling long flows each, it is also more resource/-cost effective to migrate the flows to one NF instance while shutting the others down.

Given the importance of failure resilience and flow migration in an NFV system, why are they absent in the existing NF management systems? The reason is simple: implementing flow migration and fault tolerance has been a challenging task on the existing NFV software architectures. To provide resilience, important NF states must be correctly extracted from the NF software for transmitting to a new NF instance, needed both for flow migration and replication (for resilience). However, a separation between NF states and core processing logic is not enforced in the state-of-the-art implementation of NF software. Especially, important NF states may be scattered across the code base of the software, making extracting and serializing NF states a daunting task. Patch codes need to be manually added to the source code of different NFs to extract and serialize NF states [24][35]. This usually requires a huge amount of manual work to add up to thousands of lines of source code for one NF, *e.g.*, Gember-Jacobson *et al.* [24] report that it needs to add 3.3K LOC for Bro [3] and 7.8K LOC for Squid caching proxy [16]. Realizing this difficulty, Khalid *et al.* [27] use static program analysis technique to automate this process. However, applying static program analysis itself is a challenging task and the inaccuracy of static program analysis may prevent some important NF states from being correctly retrieved.

Even if NF states can be correctly acquired and NF replicas created, flows need to be redirected to the new NF instances in cases of NF load balancing and failure recovery. In the existing systems, this is usually handled by a centralized SDN controller, which initiates and coordinates the entire migration process for each flow. Aside from compromised scalability due to the centralized control, for lossless flow migration, the controller has to perform complicated migration protocols that involve multiple passes of messages among the SDN controller, switches, migration source and migration target [24], which adds delay to flow processing and limits packet processing throughput of the system.

In this paper, we propose a software framework for building resilient NFV systems, *NFActor*, exploiting the actor framework for programming distributed services [1, 15, 30]. Our main observation is that actor provides the unique benefits for light-weight, decentralized migration of network flow states, based on which we enable highly efficient flow migration and replication. *NFActor* tracks each flow's state with our high-performance flow actor, whose design transparently separates flow state from NF processing logic. *NFActor* provides service chain processing of flows using flow actors on carefully designed uniform runtime environment, and enables fast flow migration and replication without relying much on centralized control. *NFActor* achieves transparent resilience, easy scalability and high performance in network flow processing based on the following design highlights:

▷ *Clean separation between NF processing logic and resilience support.* Unlike existing work [24, 37] that patch functionalities for failure resilience into NF software, *NFActor* provides a clean separation between important NF states and core NF processing logic in each NF using a unique API, which makes extracting, serializing and transmitting important flow states an easy task. Based on this, the *NFActor* framework can transparently carry out flow migration and replication operations, those needed to enable failure resilience, regardless of the concrete network function to be replicated, *i.e.*, which we refer to as *transparent resilience*. Using *NFActor*, programmers implementing the NFs only need to focus on the core NF logic, and the framework provides the resilience support.

▷ *Per-flow micro-management.* Fundamentally different from the existing systems, *NFActor* creates a micro execution context for each flow by providing a dedicated service chain on one actor for processing packets of this flow on the actor. This can be viewed as a micro (service chain) service dedicated to the flow. The micro execution context is constructed using actor framework, which has been proven to be a light-weight and scalable abstraction for building high-performance systems [30]. Scheduling actors to execute only incurs a small overhead, enabling *NFActor*to have a high packet processing throughput. The horizontal scalability of *NFActor*is also improved as actors can be scheduled to run on uniform runtime systems.

▷ *Largely decentralized implementation.* Based on decentralized message passing of the actor framework, flow migration and replication in *NFActor* are fully automated, achieved in a fully distributed fashion without continuous monitoring of a centralized controller, which distinguishes *NFActor* from the existing NFV systems [24]. The controller in *NFActor* is only used for controlling dynamic scaling and initiating flow migration and replication, thus light-weighted and failure resilient as the controller does not need to maintain complicated state generated by flow migration and can be easily replicated by storing its simple state on a reliable storage system like ZooKeeper [**?**]. In addition, *NFActor* is implemented on top of the high speed packet I/O library, DPDK [10], which further improves the performance of *NFActor*.

Going beyond resilience, our NFActor framework also

enables several interesting applications that the existing NFV systems are difficult to support, including live NF update, flow deduplication and reliable MPTCP subflow processing. These applications require individual NFs to initiate flow migration, which is hard to achieve (without significant overhead) in existing systems where flow migration is initiated and fully monitored by a centralized controller. In *NFActor*, these applications can utilize our decentralized and fast flow migration to achieve live NF update with almost no interruption to high-speed packet processing of the NF, best flow deduplication to conserve bandwidth, and correct MPTCP subflow processing, with ease.

We implement *NFActor* on a real-world testbed and opensource the project code [17] **Chuan:** improve the result discussion The result shows that the performance of the runtime system is desirable. The runtimes have almost linear scalbility. The flow migration is blazingly fast. The flow replication is scalable, achieves desirable throughput and recover fast. The dynamic scaling of NFActor framework is good with flow migration. The result of the applications are good and positive.

The rest of the paper is organized as follows. **Chuan:** to complete

2. BACKGROUND AND RELATED WORK

2.1 Network Function Virtualization

NFV was introduced by a 2012 white paper [18] by telecommunication operators that propose running virtualized network functions on commodity hardware. Since then, a broad range of NFV studies has been seen in the literature, including bridging the gap between specialized hardware and network functions [26, 25, 28, 32], scaling and managing NFV systems [23, 31], flow migration among different NF instances [35, 27, 24], NF replication [34, 37], and traffic steering [33]. In these systems, the NF instances are created as software modules running on standard VMs or containers. *NFActor* customizes a uniform runtime platform to run network functions, which enables transparent resilience support for all network functions/service chains in the runtimes. In addition, a dedicated service chain instance is provisioned for each flow, enabled by the actor framework, achieving failure tolerance and high packet processing throughput with ease. Even though modular design introduced by ClickOS [28] simplifies the way how NFs are constructed, advanced control functionalities, *e.g.*, that to enable flow migration, are still not easy to be integrated in NFs following the design.

A number of NFV systems [31, 22, 36, 19, 26, 38, 28, **?**] have been proposed to manage NF service chains or graphs in an effective and high-performance way. Among these work, Flurries [**?**] proposes to do fine-grained per-flow NF processing, and is able to dynamically assign a flow to a light-weight NF. While sharing some similarities, *NFActor* focuses on applying actor model to perform micro service chain processing for each flow, and uses actor model to provide transparent resilience. It is possible to expand the service chain processing in *NFActor* to service graph processing as in E2 [31] and OpenBox [22] because *NFActor* uses a run-to-completion scheduling strategy to process flow packets. But *NFActor* sticks to the service chain processing as it still represents the mainstream processing method [26, 28].

To achieve flow migration, existing work such as OpenNF [24] require direct modification of the core processing logic of NF software, which is tedious and difficult to achieve. In addition, existing NFV management [35] [24] systems mostly rely on a centralized SDN controllers to carry out the flow migration protocol, involving non-negligible message passing overhead that lowers packet processing speed of the system. *NFActor* overcomes these issues using a clean separation between NF processing logic and resilience support functionalities, as well as a system design based on the distributed actor framework. The actors can be migrated by communicating among themselves without the coordination from a centralized controller. A fast virtual switch is designed to achieve the functionality of a dedicated SDN switch. Only 3 rounds of request-response are needed for achieving flow migration, based on the actor framework and the customized virtual switch, enabling fast flow migration and high packet processing throughput.

Flow replication usually involves check-pointing the entire process image runing the NF software and creating a replica for the created process image [37] [34]. The checkpointing method, such as the one used by [37], may require temporary pause of an NF process, leading to flow packet losses. *NFActor* is able to checkpoint all states of a flow in a lightweight fashion without introducing large delay, due to that the clean separation between NF processing logic and NF flow state enables the actor to directly store all the flow states of the service chain and transmit the flow states at any time without interfering the normal execution of the NF, enabling transparent replication of NFs and service chains. Existing work [37] rely on automated tools to extract important state variables for replicating, which relies on static program analysis technique and may not accurately extract all the important state variables if the NF program is complicated and uses a new architecture.

2.2 Actor

The actor programming model has been used for constructing massive, distributed systems [1, 15, 30, 29]. Each actor is an independent execution unit, which can be viewed as a logical thread. In the simplest form, an actor contains an internal actor state (*e.g.*, statistic

counter, number of the out-going request), a mailbox for accepting incoming messages and several message handler functions. An actor can process incoming messages using its message handlers, send messages to other actors through the built-in message passing channel, and create new actors. Actors are well suited to implement state machine, that modify its internal state based on the received message, therefore facilitates distributed protocol implementation.In an actor system, actors are asynchronous entities that can receive and send messages as if they are running in their own threads, simplifying programmability of actors and eliminating potential race conditions which may cause the program to crash. The actors usually run on a powerful runtime system [6, 15, 4], which is a uniform platform to schedule actors to execute , enabling them to achieve network transparency, as actors could transparently communicate with remote actors running on different runtimes as they are all running on the same runtime. An actor could launch a remote actor and communicates with the remote actor to migrate/replicate all of its internal state. The remote actor could directly substitute the identity of the original actor whenever necessary. Therefore actor model provides a natural and unified way for migrating/replicating actors.

The actor model is a natural fit when building distributed NFV systems. We can create one actor as one flow processing unit (a NF or a service chain, while the later is our design choice in *NFActor*), and map flow packet processing to actor message processing. Meanwhile, flow migration and replication functions can be implemented as message handlers on the actors. Even though there exists this natural connection between the actor model and NF flow processing functions, we are not aware of any existing work that leverages the actor model to build an NFV system. To the best of our knowledge, we are the first to exploit the actor model in enabling resilient NFV systems and relevant applications, as well as to demonstrate the benefits of this actor-based approach.

There are several popular actor frameworks, *e.g.*, Scala Akka [15], Erlang [6], Orleans [14] and C++ Actor Framework [4]. These frameworks have been used to build a broad range of distributed applications. For example, Blizzard (a famous PC game producer) and Groupon/Amazon/eBay (famous e-commerce websites) all use Akka in their production environment [15]. However, none of these frameworks are optimized for building NFV systems. In our initial prototype implementation, we built *NFActor*on top of the C++ Actor Framework [4], but the message-passing performance of that prototype turned out to be non-satisfactory , due mainly to that C++ Actor Framework uses kernel networking stack to transmit actor messages and the context switching overhead is intolerable in NFV system [28].

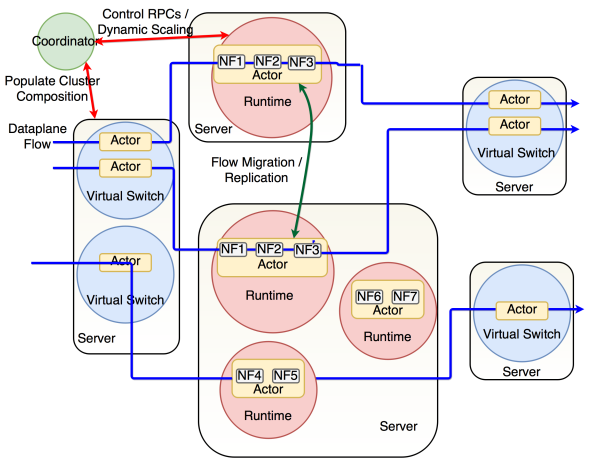


Figure 1: An overview of *NFActor*.

This inspires us to create a customized actor framework for *NFActor* with significantly improved performance.

3. THE NFACTOR SYSTEM

We present the design and key modules of *NFActor* in this section.

3.1 Overview

NFActor includes three key modules: (i) runtime systems that enable flow processing using actors; (ii) virtual switches for distributing and balancing flows to runtime systems; and (iii) a light-weight coordinator for basic system management. An illustration of the architecture of *NFActor* is given in Fig. 1.

A runtime system, referred to as *runtime* for short, is the execution environment of NFs and service chains. A runtime is running on a container, for quick launching and rebooting in cases of scaling up and failure recovery. There can be multiple runtimes (containers) running on the same physical server. In *NFActor*, the virtual switches are running in the same environments (containers) as those runtimes and run actors for flow distribution, *i.e.*, a virtual switch can be regarded as a special runtime that runs a load balancer function. Runtimes and virtual switches are inter-connected through a L2 network.

The virtual switch is configured with an entry IP address and the coordinator sets up corresponding flow rules to direct the dataplane flow to the virtual switch,which dispatches it to a runtime hosting the NF service chain that the flow is to traverse (Sec. 3.4). When a runtime receives a new flow, it creates a new flow actor to process the flow. Our runtime design follows the one-actor-one flow principle (Sec. 3.2): the flow actor loads all the required NFs of the service chain, and passes the received packets of the flow to these NFs in sequence. Once a packet has been processed by all NFs in the service chain, the runtime sends the packet to another virtual

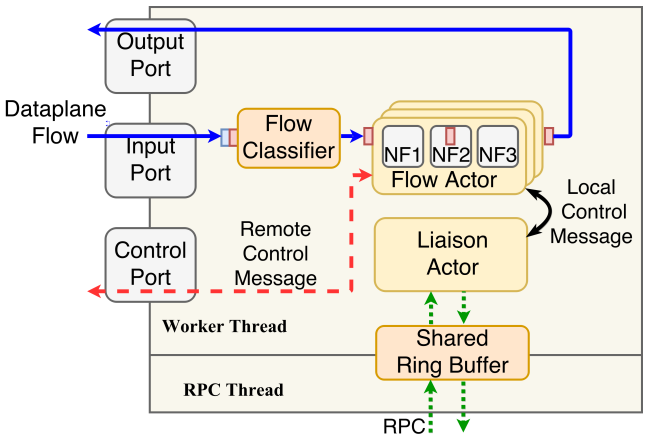


Figure 2: The internal structure of a runtime in *NFActor*.

switch, where the packet is forwarded to its destination (the packet will be forwarded out by the replica flow actor when the failure resilience mechanism is in place Sec. 4.1).

The coordinator in *NFActor* is responsible for basic cluster management (Sec. **??**), *e.g.*, updating latest cluster composition to the virtual switches and runtimes, monitoring workload of runtimes, control dynamic scaling. As compared to SDN controllers used in the existing NFV management systems [24, 35], the coordinator is much lightweight, without involving in the entire flow migration and replication process.Instead, flow migration and replication are handled in fully distributed fashion among flow actors, and only exploit the coordinator in the initialization phase.

The design of *NFActor* targets the following goals.

1. Transparent Resilience. Flow actor should be able to transparently perform resilience operations, including flow migration and replication, regardless of the service chain that is configured for it.

2. High Scalability. The runtime should have good horizontal scalability so that *NFActor* could easily scale-up by launching additional runtimes.

3. Low Overhead. High speed packet processing must be achieved by *NFActor* framework to suit the requirement of modern NFV system.

3.2 Runtime

The concept of a uniform runtime system, as a basic flow processing and scaling unit in *NFActor*, does not appear in most existing work [21, 23, 31]. In existing NFV systems, the basic flow processing and scaling unit is an NF instance, which is a virtual machine or container hosting an instance of a NF. The primary reason that we design such a runtime is to enable NFs/service chains to achieve failure resilience automatically without coordinator intervention, as the runtime provides a uniform communication channel to exchange messages among each other, which are crucial for flow migration and replication. Especially, in a runtime, we adopt the simple yet powerful design to create a micro execution context for each flow, and encapsulate packet processing of a flow over its entire service chain inside the micro execution context. Then we can enable failure resilience on the basis of each micro execution context (Sec. 4.1).

In *NFActor*, we exploit the actor programming model to implement the micro execution context. Each micro execution context is a flow actor. Flow processing by NFs in the service chain, flow migration and replication functionalities are all implemented as message handlers of the flow actor. The runtime provides the basic runtime environment for all the flow actors that it has created.

Fig. 2 shows the internal structure of a runtime. The input and output ports are used for receiving and sending flow packets from and to virtual switches. The control port, as well as input and output ports, are used for transmitting and receiving remote actor messages exchanged among actors running on different runtimes, which are directly encapsulated inside L2 packets. Input packets of dataplane traffic are first sent to a flow classifier, which uses the classical 5-tuple of a flow (*i.e.*, source IP address, destination IP address, transport-layer protocol, source port and destination port) to identify packets belonging to the same flow. One flow actor is created for each new flow. Upon creation, the flow actor loads NFs of the service chain configured in the runtime. All packets of the same flow are sent to the same flow actor, which processes them in sequence by passing them through NFs in the service chain.

Each runtime is configured with a specific service chain by the coordinator during its booting phase. The runtime installs and initializes all the NFs of the service chain upon booting. When a flow actor is created, it loads these NFs and a number of carefully defined NF APIs, as given in Table 1 in Sec. 3.3, to allocate flow states for each NF and process packets across all the NFs. Using its own execution context, the flow actor can execute distributed flow migration and replication by itself, in response to certain actor messages.

When multiple flow actors are concurrently running on one runtime, they are scheduled by a worker thread using a customized flow actor scheduler (Sec. 6.2), which schedules a flow actor to run whenever a flow packet belonging to the flow actor or an actor message sent to the flow actor is received by the runtime. In addition, our design of the NF modules in the next section will show that passing packets to a NF for processing in a flow actor is essentially just a function call; only one copy of each NF software needs to be loaded in a runtime, while the flow actors can all make use of it.

The runtime also consists of a RPC thread for re-

Table 1: APIs to be Implemented by NFs in *NFActor*.

API	Usage
nf.allocate_new_fs()	Create a new flow state object for a new flow actor, to be used for storing flow state
nf.deallocate_fs(fs)	Deallocate the flow state object when the flow actor expires
nf.process_pkt(input_pkt, fs)	Process the input packet using the current flow state

ceiving RPC requests from the coordinator (for flow migration, replication, etc.) and responding to them. The RPC thread and the worker thread share a ring buffer, used for relaying RPC requests received by the RPC thread to a liaison actor in the worker thread. We use a high-speed shared ring buffer to achieve fast inter-thread communication [10] . The liaison actor is responsible for coordinating with flow actors to execute the RPC requests from the coordinator.

Discussions on Runtime Design Choices. The design of supporting only one service chain in one runtime significantly reduces the overhead of installing many NFs and avoids service chain selection in one runtime, for higher packet processing efficiency (speed) and management simplicity. Our one-actor-one-flow design is useful for facilitating fast flow migration (Sec. 4.1), which migrates a flow by performing a flow actor migration.There are a few possible alternatives to our one-actor-one-flow design: (1) *One flow actor handles multiple flows.* It compromises the efficiency of flow migration, especially when multiple flows come from different virtual switch actors. In this case, the flow actor must synchronize the responses sent from different virtual switch actors after their destination runtimes are changed to ensure loss-avoidance migration (Sec. 4.1), adding overhead to flow migration process. (2) *One flow actor runs one NF.* Additional overhead is needed for chaining multiple flow actors to constitute a service chain, lowering packet processing speed. Instead of using multiple worker threads in a runtime, the single-worker-thread design guarantees a sequential execution order of flow actors, thereby completely eliminating the need to protect message passing among flow actors by locks , and achieving higher efficiency.

3.3 NF APIs

To achieve transparent resilience together with the micro execution environments provided by runtimes in *NFActor*, an important step is to separate useful NF states from the core processing logic of each NF. With this separation, a flow actor can retrieve NF states for transmission whenever needed, without interfering with packet processing of the NF. In *NFActor*, we achieve this separation by designing a set of APIs that NF implementation should follow in *NFActor*.

The APIs are given in Table 1, provided as three public methods for each NF to implement. When a new flow actor is created to handle a new flow, it first calls $nf.allocate\_new\_fs()$ to create a flow state object. The actor then stores the flow state object in its internal storage. Whenever the actor receives a new packet, the actor passes the received packet and the flow state object to $nf.process\_pkt(input\_pkt, fs)$, for processing by the NFs, in sequence of the service chain. Any changes to the flow state when an NF has processed the packet is immediately visible to the flow actor. When the flow terminates, the flow actor expires and it calls $nf.deallocate\_fs(fs)$ to deallocate the flow state object. Using these three APIs, the flow actor always has direct access to the latest flow state, enabling it to transmit the flow state during flow migration and replication processes without disturbing packet processing of the NFs.

To implement an NF in *NFActor*, core processing logic of the NF needs to be implemented following the actor model and the APIs in Table 1. Nevertheless, porting the core processing logic of an existing NF software is relatively straightforward. We have implemented a broad range of NFs in *NFActor*and will present details in Sec. 7.

3.4 Virtual Switch

A virtual switch in *NFActor* is a special runtime where the actors do not run a service chain but only a load balancer function. Following the one-actor-one-flow principle, a virtual switch can create multiple actors each to dispatch packets belonging to one flow. We refer to a flow dispatching actor in a virtual switch as a *virtual switch actor*.

Each virtual switch receives information of the runtimes that it can dispatch flows to from the coordinator, through RPC requests its liaison actor receives, including MAC addresses of the input ports of the runtimes. A virtual switch actor selects one of the runtimes to forward its flow in a round-robin fashion, upon creation of this actor. We choose a simple round-robin approach because the virtual switch must run very fast and a round-robin algorithm introduces the smallest amount of overhead while providing satisfactory load balancing performance. Whenever a virtual switch actor receives an incoming packet, it replaces the destination MAC address of the packet to MAC address of input port of the chosen runtime, modifies the source MAC address of the packet to MAC address of output port of the virtual switch, and then sends the packet out from the output port.

The architectural consistency of virtual switches and runtimes in *NFActor* facilitates flow migration and replication. The flow actor on a runtime can analyze the source MAC address of the incoming packets and determine which virtual switch this packet comes from. Then the flow actor can contact the virtual switch during flow migration and replication processes, to indicate

change of the runtime that the respective virtual switch actor should dispatch packets to. This is done through sending a remote actor message to the virtual switch actor, which is further explained in Sec. 4.1.

The virtual switch is also used as a relay-point to the final destination of the dataplane traffic flows. By connecting the output ports of runtimes with the input port of a virtual switch and configuring proper SDN rules on the output port of the virtual switch, the virtual switch is able to forwards all the outgoing packets from the runtime to their final destination.

Existing NFV management systems either rely on SDN switches [23, 24] to route flows from one NF to the next, or build a customized data-plane for interconnecting different NF instances [31]. In comparison, our virtual switch is lightweight, only to dispatch flows to runtimes, but not route flows through individual NFs.

3.5 Coordinator

The *NFActor*'s coordinator is responsible for launching new virtual switches and runtimes, monitoring the load on each runtime and executing dynamic scaling. Due to our distributed flow actor design, the coordinator only needs to participate in the initiation phase of flow migration and replication (Sec. 4.1). This differentiates *NFActor*'s coordinator with the controllers in existing NFV systems [24][35], which need to fully coordinate the entire flow migration process. The design of the coordinator is simplified (a single thread module) and the failure resilience of the system is improved, as the coordinator does not need to maintain complicated states associated with flow migration.

To deploy a service chain in *NFActor*, the system administrator first specifies composition of the service chain to the coordinator, as well as several rules to match the input flows to service chains. The coordinator then launches a new virtual switch and a new runtime, configures the runtime with this service chain and installs several SDN rules that forward the input flows using the service chain to the virtual switch. Each runtime or virtual switch is assigned a global unique ID to ease management. In *NFActor*, a virtual switch is responsible for dispatching flows using the same service chain, to runtimes installed with this service chain. The virtual switches and runtimes handling the same service chain are referred to as a *cluster* in *NFActor*. Flow migration and replication occur within a cluster. These design choices are made since it simplifies cluster management and improves the packet processing throughput of both virtual switches and runtimes, as they do not need to perform an extra service chain selection for each flow.

The controller constantly polls load information from all the runtimes. When the coordinator detects that a runtime is overloaded, it scales up the cluster by launching a new runtime and configures the service chain on that runtime (Sec. **??**). The coordinator does not take care of the scaling of virtual switches. The scaling of virtual switch is offloaded to NIC hardware using Receiver Side Scaling (RSS) [**?**, **?**], which is a static scaling method that requires the controller to configure a fixed number of virtual switches to match the number of the receiver queues of the NIC.

Table 2: Control RPCs Exposed at Each Runtime

Control RPC	Functionality
PollWorkload()	Poll the load information from a runtime.
NotifyClusterCfg(cfg)	Notify a runtime the current cluster view.
SetMigrationTarget(runtime_id, migration_number)	Initiate flow migration. It tells the runtime to migrate migration_num of flows to the runtime with runtime_id.
SetReplica(runtime_id)	Set the runtime with runtime_id as the replica.
Recover(runtime_id)	Recover all the flows replicated from runtime with runtime_id.

The coordinator communicates with runtimes via a series of control RPCs exposed by each runtime, as summarized in Table 2. It uses $PollWorkload()$ to acquire the current load on a runtime, to produce scaling decision. The coordinator maintains the composition of the system, which includes the mac addresses of input/output/control ports and the IDs of all runtimes and virtual switches of all clusters (handling different service chains). The coordinator updates the cluster composition to all the runtimes and virtual switches using $NotifyClusterCfg(cfg)$. The last three RPCs are used to initiate flow migration and replication. After issuing these three calls, migration and replication are automatically executed without further involving the coordinator. The use of RPC for coordinator to runtime communication decouples the execution of runtimes from the controller, therefore simplifying controller design.

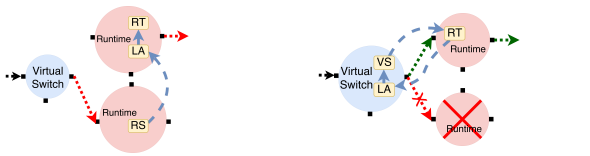
4. MAJOR SYSTEM MANAGEMENT OPERATIONS

4.1 Fault Tolerance

We next introduce the fault tolerance mechanisms in *NFActor*, for the coordinator, the virtual switches and the runtimes, respectively. Depending on the nature of these three components, we carefully design lightweight replication mechanisms, targeting robustness and little impact on performance of their normal operations.

4.1.1 Replicating Coordinator

Since the coordinator is a single-threaded module that mainly maintains composition of clusters in the system, we persistently log and replicate such information



(a) Flow replication. **(b)** Flow recover when the original runtime has failed.

Figure 3: Flow replication and recovery: **RT** - replication target actor, **RS** - Replication source actor, **LA** - liaison actor, **VS** - virtual switch actor; **dotted line** - flow packets, **dashed line** - actor messages.)

Chuan: where do you replicate the information to?. The liveness of the coordinator is monitored by a guard process and the coordinator is restarted immediately in case of failure. On a reboot, the coordinator reconstructs the system view by replaying logs. Each runtime or runtime monitors the connection status with the coordinator and reconnects to the coordinator in case of a connection failure **Chuan:** clarify whether the address of coordinator remains the same such that virtual switch and runtime knows how to reconnect.

4.1.2 *Replicating Virtual Switches*

Chuan: update the following paragraph on how virtual switch is to be replicated The most important state of the virtual switch process is its switching hash table in memory. In order to replicate the virtual switch for failure resilience, we constantly check-point the container memory image of the virtual switch using CRIU [5], a popular tool for checkpointing/restoring Linux processes. One main technical challenge is that CRIU has to stop a process before checkpointing it, which may hurt the availability of the virtual switch. We tackle this challenge by letting the virtual switch call a fork() periodically (by default, one minute), and then we use CRIU to checkpoint the child process. Therefore, the virtual switch can proceed without affecting the system performance.

4.1.3 *Replicating Runtimes*

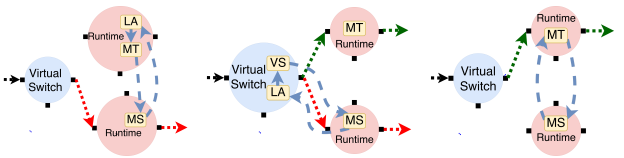
To perform lightweight runtime replication, we leverage the actor abstraction and state separation to create a lightweight flow replication strategy. In a runtime, important flow states associated with a flow is owned by a unique flow actor. The runtime can replicate each flow actor independently without check-pointing the entire container image [37, 34]. The biggest difference between *NFActor*'s replication strategy and the existing work (*e.g.*, [37]) is that *NFActor* replicates individual flows, not NFs, and the replication is transparent to the NFs. Each flow actor replicates itself on another runtime in the same cluster, without the need of dedicated back-up servers [37], achieving very good scalability. Meanwhile, this fine-grained replication strategy provides the same output-commit property as indicated in [37] with a desirable replication throughput and fast recovery time.

The detailed flow replication process is illustrated in Fig. 3. When a runtime is launched, the coordinator sends a list of runtimes in the same cluster (desirably running on different physical servers from the server hosting this runtime) to its liaison actor via RPC *SetReplica*(*runtime_id*) **Chuan:** revise this RPC to set multiple replica runtimes. The coordinator launches new runtimes if there are no available replication target runtimes in a cluster. When a flow actor is created on the runtime, it acquires its replication target runtime by sending a local actor message to liaison actor. The liason actor sends back the ID of the replica runtime, selected in the round-robin fashion among all available runtimes received from the coordinator.

When a flow actor has processed a flow packet, it sends a replication actor message, containing the current flow states and the packet, directly to the liaison actor on the replication target runtime. The liaison actor checks whether there exists a replica flow actor on this replication target runtime using the 5-tuple of the packet. If not, it creates a new replica flow actor using the same 5-tuple and forwards all subsequent replication messages that share the same 5-tuple to that replica flow actor. A replica flow actor is created as a special flow actor, which processes received replication messages, stores latest flow states contained, and then directly sends the packets contained out from the output port of the replication target runtime. Though configured with the service chain of the flow, it does not invoke NFs, and will only do so after it becomes the primary flow actor for processing the flow, when the runtime hosting the original flow actor has failed.

As shown in Fig. 3(a), when the runtime replication mechanism is in place, the path of dataplane flows in *NFActor* is as follows: virtual switch → runtime hosting flow actor to process the flow → runtime hosting replica flow actor → virtual switch → final flow destination. This design guarantees the same output-commit property as in [37]: only one copy of the output packet is sent out from the system even when the replica is in place **Chuan:** check if this is what you meant by 'output-commit'.

When a runtime fails, the coordinator sends recovery RPC requests *Recover*(*runtime_id*) to all the runtimes that it forwarded earlier to the failed runtime as candidates to store flow replicas. When a runtime R receives this RPC, it checks if it indeed stores flow replicas of the failed runtime. If so, each replica flow actor on runtime R sends a request to the virtual switch responsible for forwarding the respective flow to the failed runtime, which further identifies the virtual switch actor in charge, and asks it to change the destination run-



(a) 1st req-rep. **(b)** 2nd req-rep. **(c)** 3rd req-rep.

Figure 4: The flow migration process that migrates migration source actor running on migration source runtime to migration target runtime. (**MT**: Migration target actor. **MS**: Migration source actor. **CO**: liaison actor. **VS**: Virtual switch actor. **Dotted line**: Dataplane flow packets. **Dashed line**: Actor messages.)

time to runtime R. After the acknowledge message from the virtual switch is received by the replica flow actor, packets of the flow start to arrive at the replica flow actor, and the flow is successfully restored on runtime R (Fig. 3(b)). Immediately after the replica flow actor becomes the primary one to handle the flow, it seeks another runtime to replicate itself, following the same procedure as described above.

Our primary-backup replication approach can tolerate the failure of one runtime (between runtimes that the actor and its replica are residing in). We consider this guarantee sufficient because the chance for both runtimes (on two servers) failing at the same time is very low. An alternative design is to restart the failed runtime, copy back replicated flows states, and rerun the flow actors on the recovered runtime. In comparison, our design avoids the addition delay for relaunching flow actors and minimize interruption to consecutive flow processing. When a replica runtime becomes overloaded, our scaling control takes over and moves out some of the flow actors (Sec. 5). Even if routing an output packet to the replica flow actor before sending it out incurs more inter-server communication, our experiments show that the impact is very small.

4.2 Flow Migration

We next present the lightweight, distributed flow migration mechanism in *NFActor*. Flow migration functionalities as built as message handlers of the actors, and transparent to NF processing logic. Based on the actor model, flow migration can be regarded as a transaction between a source flow actor and a target flow actor, where the source flow actor delivers its entire state and processing tasks to the target flow actor. Flow migration is successful once the target actor has completely taken over packet processing of the flow. In case of unsuccessful flow migration, the source flow actor can fallback to regular packet processing and instruct to destroy the target flow actor.

Flow migration is initiated by the flow actor that processes the flow. The runtime that the flow actor resides on checks the received cluster view (from the coordinator) to obtain the contact address and load information of other runtimes, and selects an appropriate target for migration its flow to **Chuan:** describe more clearly how the decision is made based on load of runtimes, and whether the runtime or the flow actor makes the decision.

Flow migration in *NFActor* only involves 3 passed of request-response messages in sequence, as illustrated in Fig. 4.

1st req-rep: The source flow actor sends 5-tuple of its flow to the liaison actor on the migration target runtime. The liaison actor creates a migration target actor using the 5-tuple, and sends a response back to the migration source actor. During the first request-response process, migration source actor continues to process packets as usual.

2nd req-rep: The source flow actor sends the 5-tuple of its flow and the ID of the migration target runtime to the liaison actor on the virtual switch responsible for forwarding the flow to it. The liaison actor uses the 5-tuple to identify the virtual switch actor in charge and notifies it to change the destination runtime to the migration target runtime. After this change, the virtual switch actor sends a response back to the source actor, and the migration target actor starts to receive packets. Instead of processing the packets, the target actor buffers all the received packets until it receives the third request from the source actor. The migration source actor keeps processing received flow packets until it receives the response from the virtual switch.

3rd req-rep: The source flow actor then sends its flow state to the migration target actor. After receiving the flow states, the migration target actor saves them, sends a response to the source actor and then immediately start processing all the buffered packets. The migration source actor expires when it receives the response from the target actor.

Besides being fully distributed, the flow migration also guarantees two properties that (i) except for the migration target side buffer overflow or network packet reordering (which rarely happens in *NFActor*), no flow packets are dropped by the flow migration protocol, which we refer to as **loss-avoidance** property (this is slightly weaker that the loss-free property in OpenNF [24]) and (ii) the same **order-preserving** property as in OpenNF [24]. There has been a long understanding that providing good properties for flow migration would compromise the performance of flow migration [24]. *NFActor* breaks this misunderstanding using the novel distributed flow migration.

The Loss-Avoidance Property. Before the migration target actor receives the third request, it needs to buffer input packets indefinitely, which might lead to a buffer overflow if the third request takes a long time to arrive. *NFActor* simply drops additional flow packets

after buffer overflow because *NFActor* needs to process packet at a high throughput rate and does not want to grow buffer indifinitely. In *NFActor*, a large collective buffer is used to buffer the packets for different migration target actors and the distributed flow migration process is extremely fast, so the buffer overflow rarely happens, even when migrating a huge number of flows. This is demonstrated in the evaluation section **??**.

Besides buffer overflow, the only step that might incur potential packet drop is in the third request-response. When the second response is received by the migration source actor, it must immediately send its flow state in the third request to the migration target actor. After sending the third request, there might be pending flow packets continuing to arrive at migration source actor. These pending packets are are sent out by the virtual switch actor before the destination runtime is changed. If this happens, the migration source actor has to discard these pending flow packets because it has already sent out the third request. Continuing to process these packets may generate inconsistent output packets.

If the network doesn't reorder packet, which is a common case because *NFActor* is deployed over a L2 network, *NFActor*'s flow migration can eliminate the second cause of packet drop by transmitting second response in a network packet over the same network path as the data plane packets that are sent to the migration source actor. Recall that in Figure 2, the remote messages could be sent over input/output port of a runtime. The second response is encapsulated in a raw packet **??**, sent by the output port of the virtual switch and received by the input port of the migration source runtime, therefore sharing the same network path as the data plane packets that are sent to the migration source actor.

Because the second response are sent after the destination runtime of the virtual switch actor is changed and share the same network path as the data plane packets that are sent to the migration source actor, it also becomes a strong indication that no more input packets will be sent to the migration source actor. This is verified in our evaluation **??**.

Order-preserving Property. Since the second request-response eliminate the packet drop if the network doesn't reorder packets, flow packets could always be processed in the order that they are sent out from the virtual switch. The order-preserving property is therefore guaranteed.

Error Handling. The three request-responses may not always be successfully executed. In case of request timeout, the migration source actor is responsible for restoring the destination runtime of the virtual switch actor (if it is changed) and resumes normal packet processing. The migration target actor is automatically deleted after a timeout.

5. DYNAMIC SCALING

The dynamic scaling algorithm used by the controller is shown in Algorithm 1. The algorithm fully exploits the fast and scalable distributed flow migration to quickly resolve hot spot during scale-up and immediately shutdown idle runtime during scale-in.

The algorithm starts (line 2 in Algorithm 1) by polling the workload statistics from all the runtimes, containing the number of dropped packets on the input port, the current packet processing throughput and the current active flow number.

Since each runtime has a polling worker thread that keeps the CPU usage to 100% all the time, the controller can not decide whether the runtime is overloaded simply by reading the CPU usage. Instead, the controller uses the total number of dropped packets on the input port to determine overloaded. This is a very effective indicator in *NFActor* because when the runtime is not overloaded, it can not timely polls the all the packets from the input port, therefore increasing the number of the dropped packets. The controller keeps recording the maximum throughput during the previous overload for each runtime and uses that to identify idleness. If the current throughput is smaller than half of maximum throughput, then the controller identifies the runtime as idle.

Then algorithm decides whether to scale-out or scale-in (line 3-9 in Algorithm 1) and executes corresponding operations. To scale-up (line 10-15 in Algorithm 1), the runtime launches a new runtime and keeps migrating 500 flows from each overloaded runtimes, until all the hotspots are resolved. If the new runtime is overloaded during the migration, the algorithm continues to scale-up. To scale-in (line 16-20), the runtime selects a runtime with smallest packet throughput and migrate its flows to the rest of the runtime.

The algorithm uses 500 flows as the basic migration number, which is a tunable value in *NFActor*. We use this value because 500 flows could be migrated within one millisecond in *NFActor*and the controller could gradually increases the workload during migration to evenly balance the workload.

6. IMPLEMENTATION

NFActor framework is implemented in C++. The core functionality of NFActor framework contains around 8500 lines of code. We use BESS [2][**?**] as the dataplane inter-connection tool to connect different runtimes and virtual switches. The three ports that are assigned to each runtime are zero-copy VPort in BESS, which is a high-speed virtual port for transmitting raw packets. BESS could build a virtual L2 ethernet inside a server and connect this virtual ethernet to the physical L2 ethernet. By connecting the virtual L2 ethernet with the ports of runtimes, We can connect different runtimes

Algorithm 1: The dynamic scaling algorithm used by *NFActor*'s controller.

```
1  while True do
2      get the workload statistics of all the runtimes;
3      state = null;
4      if at least one runtime is overloaded then
5          state = scale-out;
6      else if the current throughput of all runtimes are
       smaller than half of the maximum throughput then
7          state = scale-in;
8      else
9          state = null;
10     if state == scale-out then
11         launch a new runtime;
12         while the new runtime is not overloaded &&
           the hotspots in overloaded runtimes are not
           resolved do
13             foreach overloaded runtime do
14                 migrate 500 flows to the new runtime;
15             update the workload statistics of all the
               runtimes;
16     if state == scale-in then
17         select a runtime with the smallest throughput
           to scale-in;
18         notify the virtual switch to stop sending new
           flows to the selected runtime;
19         while active flows on selected runtime is larger
           than 0 do
20             migrate 500 flows to other runtimes in a
               round-robin way;
```

running on different servers together.

6.1 Reuse BEES Module System

The runtime needs to poll packets from the input port, schedule flow actors to run and transmit remote actor messages. To schedule these tasks efficiently, we decide to reuse BESS module systems. BESS module system is specifically designed to schedule packet processing pipelines in high-speed NFV systems, which is a perfect suit to NFActor runtime architecture. We port the BESS module system and BESS module scheduler to the runtime and implement all the actor processing tasks as BESS modules. These modules are connected into the following 5 pipelines.

- The first/second pipeline polls packets from the input/output port, runs actor scheduler on these packets and sends the packets out from the output/input port.
- The third pipeline polls packets from control ports, reconstruct packet stream into remote actor messages and send the actor messages to the receiver actors. (The first/second pipeline also carries out this processing because remote messages are also sent to input/output port **??**).
- The fourth pipeline schedules coordinator actor to execute RPC requests sent from the controller. In particular, coordinator actor updates the configuration information of other runtimes in the cluster and dispatches flow migration initiation messages to active flow actors in the runtime.
- When processing the previous four pipelines, the actors may send remote actor messages. These messages are placed into ring buffers **??**. The fifth pipeline fetches remote actor messages from these ring buffers and sends remote actor messages out from corresponding ports.

The runtime uses BESS scheduler to schedule these 5 pipelines in a round-rubin manner to simulate a time-sharing scheduling.

6.2 Customized Actor Library

To minimize the overhead of actor programming, we choose to implement our own actor library. In this actor library, due to the single-worker-thread design, local actor message transmission is directly implemented as a function call, therefore eliminating the overhead of enqueuing and dequeuing messages from an actor mailbox []. For remote actor message passing, we assign a unique ID to each runtime and each actor. The sender actor only needs to specify the receiver actor's ID and runtime ID, then the reliable transmission module **??** could deliver the remote actor message to the receiver actor.

To schedule flow actors, we directly run a flow actor scheduler in the first three pipelines. The flow actor scheduler redirects both input flow packets and remote actor messages to corresponding flow actors, by looking up the flow actors using the flow identifier.

Even though the functionality implemented by our customized actor library is very simple compared with other mature actor libraries [15] [4], the simple architecture of our actor library decreases overhead associated with actor processing, enabling *NFActor*to satisfy the high-speed packet processing requirement of mordern NFV system.

6.3 Reliable Message Passing Module

To reliably deliver remote actor messages, we build a customized reliable message passing module for NFActor framework. Unlike user-level TCP stack, where messages are inserted into a reliable byte stream and transmitted to the other end, the reliable message passing encodes messages into reliable packet streams.

The reliable message passing module creates one ring buffer for each remote runtime. When an actor sends a remote actor message, the reliable transmission module allocates a packet, copy the content of the message into the packet and then enqueue the packet into the ring

buffer. A message may be splitted into several packets and different messages do not share packets. When the fifth pipeline is scheduled to run, the packets containing remote messages are dequeued from the ring buffer. These packets are configured with a sequential number, appended with a special header to differentiate them from normal data plane packets and sent to their corresponding remote runtimes. The remote runtime sends back acknowledgement packets. Retransmission is fired up in case that the acknowledgement for a packet is not received after a configurable timeout (10 times of the RTT).

We do not use user-level TCP like [**?**] to implement the reliable message passing module. Because compared with our simple goal of reliably transmitting remote actor messages over an inter-connected L2 network, using a user-level TCP imposes too much processing overhead for reconstructing byte stream into messages. The packet-based reliable message passing provides additional benefits during flow management tasks. For instance, because the second response in the flow migration protocol is sent as a packet on the same path with the dataplane flow packet, it enables us to implement loss-avoidance migration with ease **??**. Also, during flow replication, we can directly send the output packet as a message to the replica, without the need to do additional packet copy.

6.4 Dedicated RPC Thread

As mentioned in **??**, the runtime has a dedicated RPC thread for receiving RPC request sent from the controller. In *NFActor*, the RPC are implemented with GRPC [**?**] and the RPC requests are sent over a reliable TCP connection. To avoid context switches, *NFActor*uses a dedicated RPC thread to receive the initial RPC requests and forward these requests to the worker thread through a shared ring buffer. This improves the performance of the worker thread by eliminating potential context switches caused by using kernel networking stack.

6.5 New Applications

Asides from NF processing, we build several new applications that is inspired by our light-weight and distributed flow migration. These applications use flow migration to achieve useful practical functionalities, including live NF update, reduce output bandwidth for deduplication NF and ensure reliable and safe MPTCP processing. We evaluate and demonstrate these new applications in our evaluation.

The first application is live NF update. In this application, *NFActor*dynamically updates NF module on a runtime (*i.e.* update NF modules version, update important NF module configuration files) without interfering active flows running on that runtime. *NFActor*achieves this by dynamically migrating the flows out to a backup runtime, perform update and migrate the flows back. We show in the evaluation **??** that the dynamic update ensures no active flows are dropped during the update.

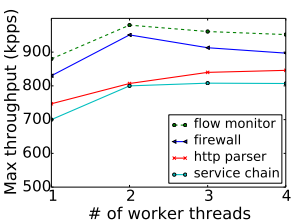
The second application is enable reliable MPTCP [] sub-flow processing. MPTCP sub-flows belonging to the same MPTCP flow may be sent to different runtimes because they have different flow-5-tuple and appear as different flows on the virtual switch. We add a MPTCP sub-flow detection function to each flow actor, such that when the flow actor finishes processing a packet of a MPTCP subflow, it can check which MPTCP flow it belongs to. Then the flow actor performs a consistent hashing using the MPTCP header to select a consistent migration target runtime in the current cluster configuration. Then the flow actor initiates the migration to the migration target actor. This application guarantees that different sub-flows belonging to the same MPTCP flow are always processed by the service chain. This is hard to achieve in existing NFV systems because flows can not initiate active migration request by themselves.

The final application is similar with MPTCP application, which reduces the output bandwidth for deduplication. When the runtime receives a flow, it checks for duplicated content contained in the flow packet. In case it finds out the duplication, the flow actor initiates a migration to migrate itself to a specific runtime. In this way, duplicated flows could be processed on the same runtime, therefore eliminating the output bandwidth on each runtime.

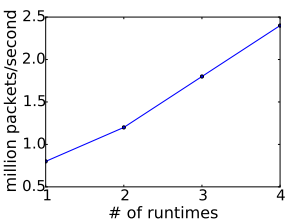
7. EVALUATION

We evaluate *NFActor*framework using a Dell R430 Linux server, containing 20 logical cores, 48GB memory and 2 Intel X710 10Gb NIC. In our evaluation, we run the controller process, helper deamon process, virtual switch container and runtime containers on the same server.

To evaluate the performance of *NFActor*, we implement 3 customized NF modules using the API provided by *NFActor* framework, the 3 NF modules are flow monitor, firewall and HTTP parser. The flow monitor updates an internal counter when it receives a packet. The firewall maintains several firewall rules and checks each received packet against the rule. If the packet matches the rule, a tag in the flow state is flipped and later packets are automatically dropped. The firewall also records the connection status of a flow in the flow state. For the HTTP parser, it parses the received packets for the HTTP request and responses. The requests, responses and the HTTP method are saved in the flow state. Throughout the evaluation, we use a service chain consisting of "flow monitor→firewall→http parser" as the service chain. We generate evaluation traffic using the BESS's FlowGen module and we directly connect

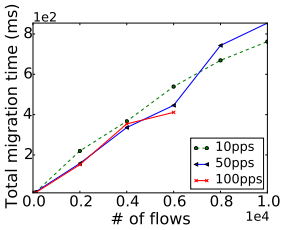


(a) Packet processing capacity of a single *NFActor* runtime system running with different number of worker threads.

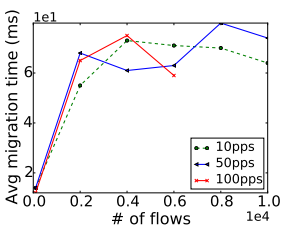


(b) Aggregate packet processing capacity of several *NFActor* runtimes.

Figure 5: The performance and scalability of *NFActor* runtime, without enabling flow migration



(a) The total time to migrate different numbers of flows.



(b) The average flow migration time of a single flow when migrating different number of flows.

Figure 6: The flow migration performance of *NFActor*

the FlowGen module to the external input port of the virtual switch.

The rest of the section tries to answer the following questions. *First,* what is the packet processing capacity of *NFActor* framework? (Sec. 7.1) *Second,* how well is *NFActor* scales, both in terms of the number of worker threads used by a runtime and the number of runtimes running inside the system? (Sec. 7.1) *Third,* how good is the flow migration performance of *NFActor* framework when compared with existing works like OpenNF? (Sec. 7.2) *Fourth,* what is the performance overhead of flow state replication and does the replication scale well? (Sec. 7.3)

7.1 Packet Processing Capacity

Figure 5 illustrates the normal case performance of running *NFActor* framework. Each flow in the generated traffic has a 10 pps (packet per second) per-flow packet rate. We vary the number of concurrently generated flows to produce varying input traffics. In this evaluation, we gradually increase the input packet rate to the *NFActor* cluster and find out the maximum packet rate that the *NFActor* cluster can support without dropping packets. In figure 5a, the performance of different NF modules and the service chain composed of the 3 NF modules are shown. Only one *NFActor* runtime is launched in the cluster. It is configured with different number of worker threads. In figure 5b, we create different number of *NFActor* runtimes and configure each runtime with 2 worker threads. Then we test the performance using the entire service chain.

From figure 5a, we can learn that the packet throughput decreases when the length of the service chain is increased. Another important factor to notice is that the *NFActor* runtime does not scale linearly as the number of worker threads increases. The primary reason is that inside a *NFActor* runtime, there is only one packet polling thread. As the number of input packets increases, the packet polling thread will eventually become the bottleneck of the system. However, *NFActor* runtime scales almost linearly as the total number of *NFActor* runtimes increases in the cluster. When the number of runtimes is increased to 4 in the system, the maximum packet throughput is increased to 2.4M pps, which confirms to the line speed requirement of NFV system.

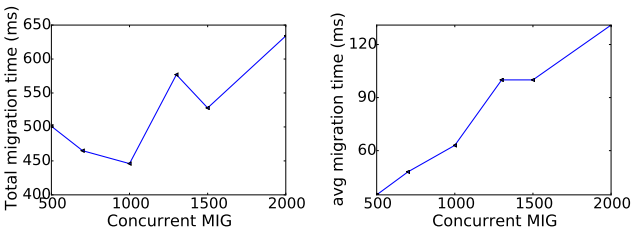
7.2 Flow Migration Performance

We present the evaluation result of flow migration in this section. In order to evaluate flow migration performance, we initialize the cluster with 2 runtimes running with 2 worker threads and then generate flows to one of the runtimes. Each flow is processed by the service chain consisting of all the 3 NF modules. We generate different number of flows, each flow has the same per-flow packet rate. In order to see how the evaluation performs under different per-flow packet rate, we also tune the per-flow packet rate with 10pps, 50pps and 100pps. When all the flows arrive on the migration source runtime. The migration source runtime starts migrating all the flows to the other runtime in the cluster. We calculate the total migration time and the average per-flow migration time. In order to control the workload during the migration, the runtime only allows 1000 concurrent migrations all the time. The result of this evaluation is shown in figure 7.

We can see that as the number of migrated flows increase, the migration completion time increases almost linearly. This is because the average flow migration time remains almost a constant value and the runtime controls the maximum number of concurrent migrations. Note that when the system is not overloaded at all (100 flows), the average flow migration completion time is as small as 636us.

When the per-flow packet rate is 100pps, the maximum number of flows that we use to evaluate the system is 6000. Continuing the evaluation with 8000 and 10000 flows just overloads the runtime as shown in figure 5a.

Since we control the number of concurrent migrations, we also want to see what happens if we change the number of concurrent migrations. We generate 6000



(a) The total time to migrate all the flows when changing the maximum concurrent migrations.

(b) The average flow migration time of a single flow when changing the maximum concurrent migrations.

Figure 7: The flow migration performance of *NFActor* when changing the maximum concurrent migrations.

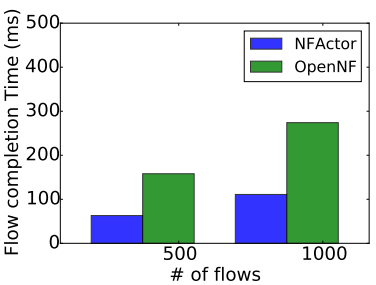
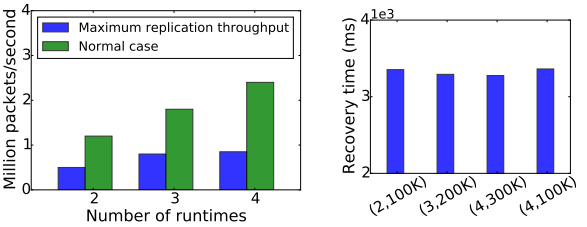


Figure 8: The flow migration performance of *NFActor*. Each flow in *NFActor* runtime goes through the service chain consisting of the 3 customzied NF modules. OpenNF controlls PRADS asset monitors.

flows, each with 50 pps per-flow packet rate, and change the the number of concurrent migrations. The result of this evaluation is shown in fig 7. As we can see from fig 7b, increasing the maximum concurrent migrations increase the average flow migration completion time. However, whether the total flow migration completion time increased depends on the total number of flows that wait to be migrated. From the result of fig 6b, the choice of 1000 concurrent migrations sits in the sweat spot and accelerates the overall migration process.

Finally, we compare the flow migration performance of *NFActor* against OpenNF [24]. We generate the same number of flows to both *NFActor* runtimes and NFs controlled by OpenNF and calculate the total time to migrate these flows. The evaluation result is shown in figure 8. Under both settings, the migration completion time of *NFActor* is more than 50% faster than OpenNF. This performance gain primarily comes from the simplified migration protocol design with the help of actor framework. In *NFActor*, a flow migration process only involves transmitting 3 request-responses. Under light workload, the flow migration can complete within several hundreds of microseconds. Under high workload, *NFActor* runtime system controls the maximum number of concurrent migrations to control the migration workload, which may increase the migration performance as



(a) The packet throughput of a *NFActor* cluster when replication is enabled. The throughput is compared against the throughput when replication is disabled.

(b) The recovery time of a failed runtime under different settings. The tuple on the x axis represents the number of the runtime used in the evaluation and the total input packet rate.

Figure 9: The flow migration performance of *NFActor*

indicated in figure 7a. All of these factors contribute to the improved flow migration performance of *NFActor* framework.

7.3 Replication Performance

In this section, we present the flow state replication evaluation result. In our evaluation, the actor creates a flow snapshot for every 10 flow packets that it has processed. Then it sends the flow state snapshot to the replica storage. In this evaluation, we first generate flows to the *NFActor* cluster to test the maximum throughput of a *NFActor* cluster when enabling replication. Then we calculate the recovery time of failed *NFActor* runtime. The recovery time is the from time that the controller detects a *NFActor* runtime failure, to the time that the recovered *NFActor* finishes replaying all of its replicas and responds to the controller to rejoin the cluster. Through out this evaluation, the runtime uses the service chain consisting of the 3 NF modules to process the flow. The result of the evaluation is shown in figure 9.

In figure 9a, we can see that there is an obvious overhead to enable replication on *NFActor* runtimes. The overall throughput when replication is enabled drops around 60%. This is due to the large amount of replication messages that are exchanged during the replication process. Internally, the replication messages are sent over Linux kernel networking stack, which involves data copy and context switching, thus increasing the performance overhead of using replication. However, the overall throughput when replication is enabled could scale to 850K pps when 4 runtimes are used, which is enough to use in some restricted settings.

Finally, figure 9b shows the recovery time of *NFActor* runtime when replication is enabled. We found that the recovery time remains a consistent value of 3.3s, no matter how many runtimes are used or how large the input traffic is. The reason of this consistent recovery time is that the *NFActor* runtime maintains one replica

on every other *NFActor* runtimes in the cluster. During recovery, several recovery threads are launched to fetch only one replica from another runtime. Then each recovery thread independently recovers actors by replaying its own replica. In this way, the recovery process is fully distributed and scales well as the number of replica increases. Note is that the average time it takes for a recovered runtime to fetch all the replicas and recover all of its actors is only 1.2s. So actually around 2.1s is spent in container creation and connection establishment.

8. DISCUSSION

Even though *NFActor*provides transparent resilience for stateful NFs, *NFActor*focuses on handling per-flow state. Currently, *NFActor*could not correctly handle shared states, *i.e.*, the states shared by a bunch of flows. Even though the NF API in *NFActor*achieves a clean separation between per-flow state and NF processing logic, it can not correctly separate shared state. Therefore, migrating and replicating flows that share states with other flows may cause un-predicted errors in *NFActor*. A potential solution to this limitation is to enforce the programmer to write a handler that explicitly deals with the inconsistency during resilience operation. We leave this to our future work.

Another limitation of *NFActor*is that *NFActor*may incorrectly handle flows with packet encapsulation. *NFActor*uses the flow-5-tuple to differentiate flows. However, different flows may share the same flow-5-tuple if their flow packets are encapsulated. This is a common for flows that are sent over the same VxLAN tunnel. In that case, those flows are handled by the same flow actor, resulting in incorrect flow processing. If *NFActor*knows what kind of encapsulation the input packet uses, *NFActor*could add a decapsulation function in the virtual switch to correctly extract different flows. This is also left in our future work.

To achieve transparent resilience, *NFActor* requires NF to be rewritten a new set of API to achieve clean separation between flow state and NF core logic, making legacy NFs difficult to run on *NFActor*. However, with the development of NFV system, there is a practical need for people to create new NFs. NFs that process flows based on flow state could achieve transparent resilient if they are implemented using *NFActor*.

9. CONCLUSION

In this work, we present a new framework for building resilient NFV system, called NFActor framework. Unlike existing NFV system, where NF instances run as a program inside a virtual machine or a container, NFActor framework provides a set of API to implement NF modules which executes on the runtime system of NFActor framework. Inside the NFActor framework, packet processing of a flow is dedicated to an actor. The actor provides an execution context for processing packets along the service chain, reacting to flow migration and replication messages. NF modules written using the API provided by NFActor framework achieves flow migration and state replication functionalities in a transparent fashion. The implementer of the NF module therefore only needs to concentrate on designing the core logic. Evaluation result shows that even though the NFActor framework incurs some overhead when processing packets, the scalability of NFActor runtime is good enough to support line-speed requirement. NFActor framework outperforms existing works by more than 50% in flow migration completion time. Finally, the flow state replication of NFActor is scalable and achieves consistent recovery time.

10. REFERENCES

[1] Actor Modle. `https://en.wikipedia.org/wiki/Actor_model`.

[2] BESS: Berkeley Extensible Software Switch. `https://github.com/NetSys/bess`.

[3] Bro. `https://www.bro.org/`.

[4] C++ Actor Framework. `http://actor-framework.org/`.

[5] CRIU. `https://criu.org/Main_Page`.

[6] Erlang. `https://www.erlang.org/`.

[7] FFMPEG. `https://ffmpeg.org/`.

[8] FTP. `https://en.wikipedia.org/wiki/File_Transfer_Protocol`.

[9] HTTP Keep Alive. `https://en.wikipedia.org/wiki/HTTP_persistent_connection`.

[10] Intel Data Plane Development Kit. `http://dpdk.org/`.

[11] iptables. `https://en.wikipedia.org/wiki/Iptables`.

[12] Linux Virtual Server. `www.linuxvirtualserver.org/`.

[13] NFV White Paper. `https://portal.etsi.org/nfv/nfv_white_paper.pdf`.

[14] Orleans. `research.microsoft.com/en-us/projects/orleans/`.

[15] Scala Akka. `akka.io/`.

[16] Squid Caching Proxy. `www.squid-cache.org/`.

[17] The NFActor Project. `http://` 2017.

[18] Network Functions Virtualization - White Paper. https://portal.etsi.org/NFV/NFV_White_Paper2.pdf.

[19] J. W. Anderson, R. Braud, R. Kapoor, G. Porter, and A. Vahdat. xOMB: Extensible Open Middleboxes with Commodity Servers. In *Proc. of the eighth ACM/IEEE symposium on Architectures for networking and communications systems (ANCS'12)*, 2012.

[20] H. Ballani, P. Costa, C. Gkantsidis, M. P. Grosvenor, T. Karagiannis, L. Koromilas, and

G. O'Shea. Enabling End-host Network Functions. In *Proc. of ACM SIGCOMM*, 2015.

[21] A. Bremler-Barr, Y. Harchol, and D. Hay. OpenBox: Enabling Innovation in Middlebox Applications. In *Proc of the 2015 ACM SIGCOMM Workshop on Hot Topics in Middleboxes and Network Function Virtualization (HotMiddlebox'15)*, 2015.

[22] A. Bremler-Barr, Y. Harchol, and D. Hay. OpenBox: A Software-Defined Framework for Developing, Deploying, and Managing Network Functions. In *Proc. of ACM SIGCOMM*, 2016.

[23] A. Gember, R. Grandl, A. Anand, T. Benson, and A. Akella. Stratos: Virtual Middleboxes as First-class Entities. Technical report, UW-Madison 2012.

[24] A. Gember-Jacobson, R. Viswanathan, C. Prakash, R. Grandl, J. Khalid, S. Das, and A. Akella. OpenNF: Enabling Innovation in Network Function Control. In *Proc. of ACM SIGCOMM*, 2014.

[25] S. Han, K. Jang, A. Panda, S. Palkar, D. Han, and S. Ratnasamy. SoftNIC: A Software NIC to Augment Hardware. Technical report, EECS Department, University of California, Berkeley, 2015.

[26] J. Hwang, K. Ramakrishnan, and T. Wood. NetVM: High Performance and Flexible Networking Using Virtualization on Commodity Platforms. *IEEE Transactions on Network and Service Management*, 12(1):34–47, 2015.

[27] J. Khalid, A. Gember-Jacobson, R. Michael, A. Abhashkumar, and A. Akella. Paving the Way for NFV: Simplifying Middlebox Modifications Using StateAlyzr. In *Proc. of the 13th USENIX Symposium on Networked Systems Design and Implementation (NSDI'16)*, 2016.

[28] J. Martins, M. Ahmed, C. Raiciu, V. Olteanu, M. Honda, R. Bifulco, and F. Huici. ClickOS and the Art of Network Function Virtualization. In *Proc. of the 11th USENIX Conference on Networked Systems Design and Implementation (NSDI'14)*, 2014.

[29] S. Mohindra, D. Hook, A. Prout, A.-H. Sanh, A. Tran, and C. Yee. Big Data Analysis using Distributed Actors Framework. In *Proc. of the 2013 IEEE High Performance Extreme Computing Conference (HPEC)*, 2013.

[30] A. Newell, G. Kliot, I. Menache, A. Gopalan, S. Akiyama, and M. Silberstein. Optimizing Distributed Actor Systems for Dynamic Interactive Services. In *Proc. of the Eleventh European Conference on Computer Systems (EuroSys'16)*, 2016.

[31] S. Palkar, C. Lan, S. Han, K. Jang, A. Panda, S. Ratnasamy, L. Rizzo, and S. Shenker. E2: a Framework for NFV Applications. In *Proc. of the 25th Symposium on Operating Systems Principles (SOSP'15)*, 2015.

[32] A. Panda, S. Han, K. Jang, M. Walls, S. Ratnasamy, and S. Shenker. NetBricks: Taking the V out of NFV. In *Proc. of the 12th USENIX Symposium on Operating Systems Design and Implementation (OSDI'16)*, 2016.

[33] Z. A. Qazi, C.-C. Tu, L. Chiang, R. Miao, V. Sekar, and M. Yu. SIMPLE-fying Middlebox Policy Enforcement Using SDN. In *Proc. of ACM SIGCOMM*, 2013.

[34] S. Rajagopalan, D. Williams, and H. Jamjoom. Pico Replication: A High Availability Framework for Middleboxes. In *Proc. of the 4th Annual Symposium on Cloud Computing (SOCC'13)*, 2013.

[35] S. Rajagopalan, D. Williams, H. Jamjoom, and A. Warfield. Split/Merge: System Support for Elastic Execution in Virtual Middleboxes. In *Proc. of the 10th USENIX Symposium on Networked Systems Design and Implementation (NSDI'13)*, 2013.

[36] V. Sekar, N. Egi, S. Ratnasamy, M. K. Reiter, and G. Shi. Design and Implementation of a Consolidated Middlebox Architecture. In *Proc. of the 9th USENIX Symposium on Networked Systems Design and Implementation (NSDI'12)*, 2012.

[37] J. Sherry, P. X. Gao, S. Basu, A. Panda, A. Krishnamurthy, C. Maciocco, M. Manesh, J. Martins, S. Ratnasamy, L. Rizzo, et al. Rollback-Recovery for Middleboxes. In *Proc. of SIGCOMM*, 2015.

[38] W. Zhang, G. Liu, W. Zhang, N. Shah, P. Lopreiato, G. Todeschi, K. Ramakrishnan, and T. Wood. OpenNetVM: A Platform for High Performance Network Service Chains. In *Proc. of the 2016 ACM SIGCOMM Workshop on Hot Topics in Middleboxes and Network Function Virtualization (HotMiddlebox'16)*, 2016.