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 [12]. 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 [32], OpenBox [20], CoMb [37], xOMB [18], Stratos [21], OpenNetVM [25, 40], ClickOS [29]. 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 [35, 38] and flow migration [22, 36, 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 [19]. 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 [10] maintain TCP connection-related states by parsing TCP SYN/ACK/FIN packets for each flow. Some load-balancers [11] 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 [38].

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 [8]; video-streaming [6] and file-downloading [7] 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 [22]; 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 [22][36]. 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.* [22] report that it needs to add 3.3K LOC for Bro [3] and 7.8K LOC for Squid caching proxy [15]. 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 [22], 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, 14, 31]. 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 [22, 38] 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. **Chuan:** idea of the following sentence has been covered by the paragraph above; instead you should describe how this per-flow management can enable better scalability and high speed packet processing 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 [31]. 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 [22]. The controller in *NFActor* is only used for controlling dynamic scaling and initiating flow migration and replication, **Chuan:** describe what the controller is used for, 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 [24]. **Chuan:** clarify why the controller is failure resilient. In addition, *NFActor* is implemented on top of the high speed packet I/O library, DPDK [9], 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 [16] **Chuan:** complete the url in the bib. **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 [17] 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 [25, 23, 29, 33], scaling and managing NFV systems [21, 32], flow migration among different NF instances [36, 27, 22], NF replication [35, 38], and traffic steering [34]. 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 [29] 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.

Chuan: cite as many as possible the systems you mentioned in the introduction in the following paragraph, E2 [32], OpenBox [20], CoMb [37], xOMB [18], Stratos [21], OpenNetVM [25, 40], ClickOS [29]; discuss more of the recent work [26] and [20]

A number of NFV systems [32, 20, 37, 18, 25, 40, 29, 39] have been proposed to manage NF service chains or graphs in an effective and high-performance way. Among these work, Flurries [39] 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 [32] and OpenBox [20] 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 [25, 29].

To achieve flow migration, existing work such as OpenNF [22] require direct modification of the core processing logic of NF software, which is tedious and difficult to achieve. In addition, existing NFV management [36] [22] systems **Chuan:** add citation 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 **Chuan:** clarify what process image this is referring to, NF process? and creating a replica for the created process image [38] [35]. The checkpointing method, such as the one used by [38], may require temporary pause of an NF process, leading to flow packet losses **Chuan:** this claim does not appear to be rigorous: does all checking-pointing require pausing a process? double check and revise. *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. **Chuan:** briefly describe how *NFActor*can achieve this, enabling transparent replication of NFs and service chains. Existing work [38] 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. **Chuan:** explain why these tools are not ideal.

2.2 Actor

The actor programming model has been used for constructing massive, distributed systems [1, 14, 31, 30]. 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 **Chuan:** not intuitive why an actor's state can be status of peer actors; change to another example), 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. **Chuan:** explain how the actor model 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. **Chuan:** not clear what it implies by 'running in a dedicated process' - clarify what benefits it brings. The actors usually run on a powerful runtime system [5, 14, 4], which is a uniform platform to schedule actors to execute **Chuan:** explain what runtime means here, 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. **Chuan:** clarify what 'network transparency' means here. **Chuan:** discuss more how the actor model provides a natural and unified way for migrating/replicating actors. 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 [14], Erlang [5], Orleans [13] 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 [14]. 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 **Chuan:** describe what performance metrics you are referring to, 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 [29]. This inspires us to create a customized actor framework for *NFActor* with significantly improved performance.

Chuan: move the following discussion to the runtime section **Lightweight Execution Context.** There has been a recent study on constructing lightweight execution context [28] in the kernel. In this work, the authors construct a lightweight execution context is contructed by creating multiple memory mapping tables in the same process. Switching among different memory tables can be viewed as switching among different lightweight execution contexts. NFActor provides a similar execution context, not for kernel processes, but for network functions. Each actor inside *NFActor*provides a lightweight execution context for processing a packet along a service chain. Being a lightweight context, the actors do not introduce too much overhead as we can see from the experiment results. On the other hand, packet processing is fully monitored by the execution context, thereby providing a transparent way for migrating and replicating flow states.

3. NFACTOR OVERVIEW

Figure 1 demonstrates the basic architecture of *NFActor*, consisting of a light-weight controller, input and output virtual switches and several runtime systems (re-

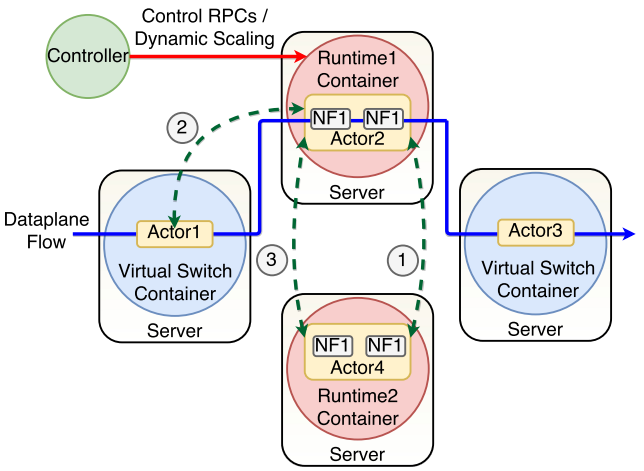


Figure 1: An overview of NFActor framework.

ferred to as *runtime* in short). Both runtime and virtual switch are uniform platforms to run actors, they are inter-connected through a L2 network and executed inside containers for quick rebooting in case of failure and elastic scaling in case of overload. Each runtime hosts a single NF service chain that is determined during runtime boot phase. In the runtime, each flow is served by a unique actor, which loads runtime's service chain upon creation and passes all the received packet through the service chain. The actor sends the packets to their final destination after the switch chain processing is finished. The virtual switch is a special runtime that serves as a load-balancer. Incoming dataplane flows are first sent to the input virtual switch, which dispatches them to all the runtimes in a load-balanced fashion. A controller does exists in *NFActor*, which is a relatively light-weighted one. Its tasks are to monitor the workload of each runtime, control dynamic scaling and participate in the initiation phase of flow migration and replication.

4. NF MODULE API

To facilitate transparent resilience, *NFActor*needs to ensure a clean separation between the NF processing logic and the flow states associated with each flow. To enforce this criteria, we build a set of easy to use APIs that can be used to create a broad range of NF modules for *NFActor*.

Table 1: The public API methods that must be implemented for each NF modules in NFActor framework.

API	Usage
nf.allocate_new_fs()	Allocate a new flow state for a new flow actor.
nf.deallocate_fs(fs)	Deallocate the flow state when the flow actor expires or quits.
nf.process_pkt(input_pkt, fs)	Process the input packet using the current flow state associated with the flow actor.
nf.get_migration_target(cluster_cfg, fs)	Query the NF using the current cluster configuration and the current flow state about where the flow actor should be migrated to. This method enables each actor to do active migration.

Table 1 summarizes these APIs, which are provided as four public methods for each NF module. The allocation and deallocation methods enforce each NF module to allocate a flow state that is stored by a flow actor, therefore transferring the primary access right of the flow state to the flow actor. When the flow actor receives a input packet message, it calls the packet processing method to process the input packet passing along the flow state, so that any changes to the flow state when calling the third method is immediately visible to the flow actor when the flow actor finishes processing an input packet.

When the flow actor processes messages during resilience operations, it always has direct access to the latest flow state, which could be transmitted without disturbing the normal of NF processing. Therefore, the combination of the three methods servers as the basis for the transparent resilience in *NFActor*. These three methods are simple to use and properly generalize the structure of NFs that processes flow packets based on per-flow state. Using these three methods, we are able to create several representing NFs as shown in **??**. **Cui:** give a clearer description on why the four APIs can facilitate transparent resilience and build a rich set of NFs.

Finally, the flow actor could use the fourth method to check where the NF would like the actor to migrate to, by passing the current cluster configuration and the current flow state. This enables the flow actor to actively migrate itself instead of waiting for migration initiation command sends from the controller **??**, and sparkles several useful applications (i.e. decreasing the output bandwidth during deduplication and ensuring reliable MPTCP subflow processing **??**) that none of existing NFV systems can achieve.

5. RUNTIME ARCHITECTURE

5.1 Runtime

Figure 2 demonstrates the internal architecture of a runtime. The runtime serves as a uniform program to run actors. *NFActor* runs each runtime inside a container for fast boot up and assigns each runtime with a global unique ID to ease management. The uniform runtime design increases the scalability of *NFActor*, as *NFActor*could be horizontally scaled up by adding more runtimes.

The runtime consists of a single worker thread for actor scheduling, and an RPC thread for receiving RPC requests sent from the controller. The single-worker-thread design guarantees a sequential actor execution

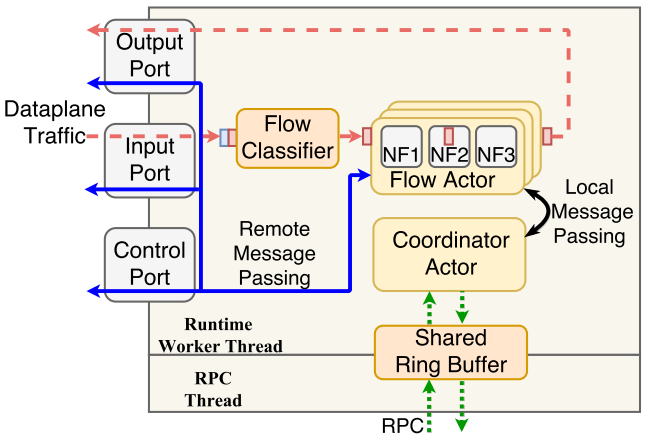


Figure 2: The internal architecture of a NFActor runtime system.

order, therefore completely eliminate the need to protect message passing by lock, resulting in a good performance achieved by *NFActor*. It is configured with three ports, from which it can send and receive packets. Input packets of the runtime are first sent to a flow classifier, which uses traditional flow-5-tuple (i.e. IP destination address, IP source address, transmission layer protocol, source port and destination port) as the key to classify flows. The flow classifier creates one flow actor for each new flow and forwards all the flow packets to that flow actor.

The runtime is configured with a specific service chain during the boot phase and initializes all the NF modules as specified in the service chain. When a flow actor is created, it loads these modules and uses the flow state allocation method in Table 1 to allocates all the flow states and passes input packet along the NF modules in sequence. Besides service chain processing, the flow actor also provides an execution context for distributed flow migration and replication.

There is a coordinator actor who is responsible for executing the RPC requests sent from the controller and coordinate flow actors during flow migration and replication. Flow actor and coordinator actor could directly exchanges local messages, or exchange remote messages through a reliable message passing module **??**.

5.2 Virtual Switch

The virtual switch is a special runtime without service chain, it automatically balances the input traffic among all the runtimes, increasing the scalability of the system. We refer to the flow actor created by the virtual switch as virtual switch actor throughout this paper.

The virtual switch actor selects one of the available runtimes as its destination runtime in a round-robin way when it is created. Round-robin algorithm is used because it imposes the smallest overhead. Whenever the virtual switch actor receives an input packet, it replaces the destination MAC address of the packet to destination runtime's input port MAC address, and modifies the source MAC address of the input packet to virtual switch's output port mac address. it then sends the packet out from the output port.

The architectural consistency of virtual switch and runtime also facilitates flow migration and replication. The flow actor on the destination runtime could analyze the source MAC address of the packet and determine which virtual switch this packet comes from. This enables the flow actor to contact the virtual switch actor during flow migration and replication to change the destination runtime selected by the virtual switch actor **??**.

5.3 Controller and Control RPCs

The *NFActor*'s controller is responsible for monitoring the workload of each runtime and executing dynamic scaling. Due to the use of light-weight and distributed flow actors, the controller only needs to participate in the initiation phase of flow migration and replication. This feature differentiates *NFActor*'s controller with the controllers in OpenNF [22] and Split/Merge [36], which need to fully coordinate the entire flow migration process. This simplifies the design of the controller and improve the failure resilience, as the controller does not need to maintain complicated states associated with flow migration.

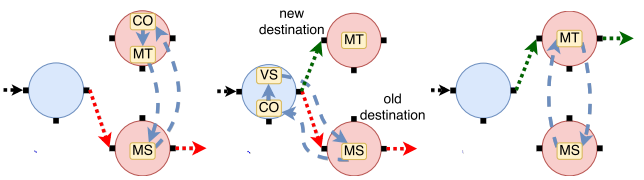
The controller manages *NFActor* using a series of control RPCs exposed by each runtime, which are summarized in Table 2. The controller uses PollWorkload RPC to acquire the current workload on a runtime and generates dynamic scaling decision. The controller maintains the configuration of the cluster, which include the mac address of input/output/control port and the ID of all the runtime and virtual switches. The controller notifies the cluster configuration to a runtime using NotifyClusterCfg RPC. 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 with the controller.

Table 2: Control RPCs exposed from each runtime.

Control RPC	Functionality
PollWorkload()	Poll the workload information from the runtime.
NotifyClusterCfg(cfg)	Notify a runtime the current cluster configuration.
SetMigrationTarget(runtime_id, migration_number)	Initiate flow migration. It tells the runtime to migrate migration_num flows to 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.

5.4 Resilience

5.4.1 *Distributed Flow Migration*



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

Figure 3: 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**: Coordinator actor. **VS**: Virtual switch actor. **Dotted line**: Dataplane flow packets. **Dashed line**: Actor messages.)

Figure 3 shows workflow of *NFActor*'s flow migration, which involves passing three request-response. 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 [22]) and (ii) the same **order-preserving** property as in OpenNF [22]. There has been a long understanding that providing good properties for flow migration would compromise the performance of flow migration [22]. *NFActor* breaks this misunderstanding using the novel distributed flow migration.

The details of the three request-responses are summarized below.

- **1st req-rep:** The migration source actor sends its flow-5-tuple to the coordinator actor on the migration target runtime. The coordinator actor creates a migration target actor using the flow-5-tuple contained in the request, which returns a response back to the migration source actor. During the execution of the first request-response, migration source actor continues to process packet.

- **2nd req-rep:** The current flow actor sends its flow-5-tuple and the ID of the migration target runtime to the coordinator actor on the virtual switch. The coordinator actor uses the flow-5-tuple to find out the virtual switch actor and notifies it to change the destination runtime to migration target runtime. After changing the destination runtime, the virtual switch actor sends a response back to the migration source actor. The migration target actor starts to receive packets after the destination runtime of the virtual switch actor is changed and buffer all the received packets until it receives the third request. In the meantime, the migration source actor keeps processing the input packets until it receives the second response.

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

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.

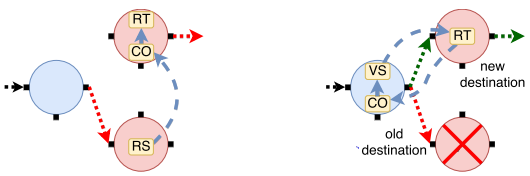
Because the second response are sent after the destination runtime of the virtual switch actor is changed

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.

5.4.2 *Lightweight Flow Replication*



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

Figure 4: Flow replication that replicates the original actor running on the original runtime to replica runtime. (**RT**: Replication target actor. **RS**: Replication source actor. **CO**: Coordinator actor. **VS**: Virtual switch actor. **Dotted line**: Dataplane flow packets. **Dashed line**: Actor messages.)

The biggest difference of the *NFActor*'s replication method and existing works such as [38] is that NFActor framework replicates individual flow, not NF. This replication strategy is transparent to the NF modules and improves the scalability and resource utilization rate of *NFActor*. as flows could be directly replicated on another runtime, without the need for a dedicated backup server. In the mean time, this fine grained replication strategy provides a the same output-commit property as indicated in [38] with a desirable replication throughput and fast recovery time.

The detailed flow replication process is shown in figure 4. When a flow actor is created, it acquires its replica runtime by querying a round-robin list. If the flow actor has a valid replica runtime, whenever it finishes processing the packet, it sends a remote message, containing the current flow state and the packet, to the coordinator actor on the replication target runtime. The coordinator actor on the replication target runtime creates a replica flow actor using the same flow-5-tuple as the original flow actor to handle all the replication messages. The replica flow actor saves the flow state and sends the packet out from the output port of the replica runtime. Similar with [38], the receiver on the side of the output port of the replica runtime can only observe an output packet when the flow state has been replicated.

When a runtime fails, the controller sends recovery RPC requests **??** to all the replica runtime of the failed runtime. This RPC enables replica flow actor to send a request to the virtual switch actor, asking it to change the destination runtime to the replica runtime. When the response is received by the replica flow actor, the original flow is successfully restored on the replica runtime.

5.5 Design Discussion

A runtime in NFActor framework is configured with a single service chain. Each flow is handled by a unique actor, which carries out all the processing on the configured service chain. Alternative design options do exist, however, they may not fully achieve our design goal to achieve low overhead and high scalability.

There are two alternatives to the one-flow-one-actor design. First of all, using a single flow actor to process multiple flows compromise the efficiency of flow migration protocol, especially when multiple flows come from different virtual switch actors. Under this situation, the flow actor must synchronize the responses sent from different virtual switch actors, therefore decreasing the performance of migration. Secondly, chaining several flow actors together to process the same flow imposes unnecessary overhead for flow processing. Therefore, the one-flow-one-actor design achieves a sweet point in minimizing the actor processing overhead and improving the efficiency of flow migration protocol design.

The alternative design to one-runtime-one-service-chain is to dynamically configure multiple service chains on a single runtime. Then due to the one-flow-one-actor design, we need to do an additional service chain selection, based on some pre-defined rules. This adds additional overhead to the flow actor processing and increases the complexity when managing the NFActor cluster, because the controller must populates the service chain rule dynamically to each runtime. With the one-runtime-on-service-chain design, if another service chain is needed, the system administrator could launch a new NFActor cluster and configure a different service chain to use.

6. 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.

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;
```

7. 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 running on different servers together.

7.1 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 coordinate these tasks, 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.

7.2 Customized Actor Library

To minimize the overhead of actor programming, we implement our own actor library. Due to the single-worker-thread design, when actor transmits local messages, there is no need to use a mailbox [4] [14] protected by synchronization primitives to receive the message. The local message transmission are directly implemented as a function call, therefore eliminate the overhead of enqueuing and dequeuing the message from the 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 is able to access the high-speed hash maps for storing flow-key to actor mapping and actor-id to actor mapping in the flow classifier **??**. The flow actor scheduler directly indexes the hash map using the key contained in the incoming actor messages and redirect the message to the actor. The coordinator actor is scheduled by the fourth pipeline. The coordinator actor also has accesses to the hash maps in the flow classifier, therefore it is able to forward messages to other flow actors in the runtime.

This simple actor programming could not achieve perfect message matching and complete separation of the internal actor state, as other mature actor frameworks do [14] [4]. However, due to its simple architecture, it only imposes a small overhead when doing actor processing, therefore it is able to satisfy the high-speed packet processing requirement of modern NFV system.

7.3 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 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 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).

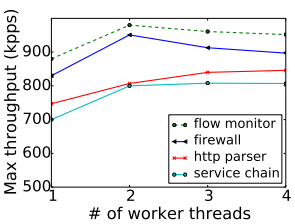
We do not use user-level TCP [**?**] to implement the reliable message passing module. Because compared with our simple goal of reliably transmitting remote actor messages over an inter-connected L2 network, using a user-level TCP imposes too much overhead for reconstructing byte stream into messages. 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 lossless 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.

8. EVALUATION

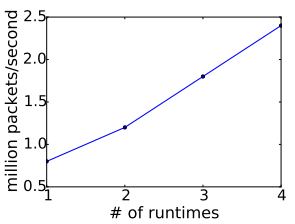
We evaluate *NFActor*framework using a Dell R430 Linux server, containing 20 logical cores, 48GB memory and 2 Intel X710 10Gb NIC. In our evaluation, we run the controller process, helper deamon process, virtual switch container and runtime containers on the same server.

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 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 capac-

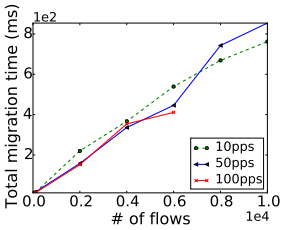


(a) Packet processing capacity of a single *NFActor* runtime system running with different number of worker threads.

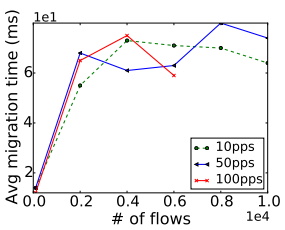


(b) Aggregate packet processing capacity of several *NFActor* runtimes.

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*

ity of *NFActor* framework? (Sec. 8.1) *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. 8.1) *Third,* how good is the flow migration performance of *NFActor* framework when compared with existing works like OpenNF? (Sec. 8.2) *Fourth,* what is the performance overhead of flow state replication and does the replication scale well? (Sec. 8.3)

8.1 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.

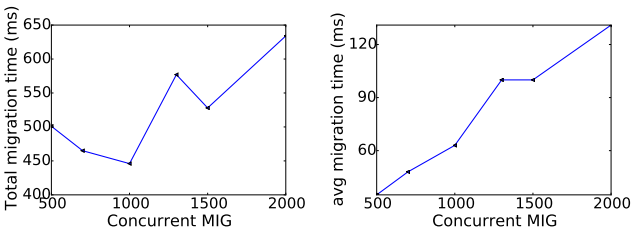
8.2 Flow Migration Performance

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 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



(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.

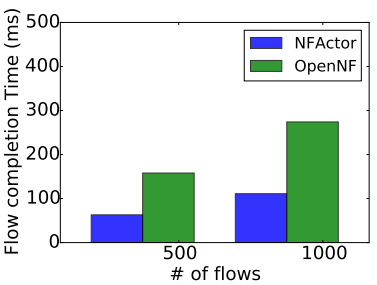
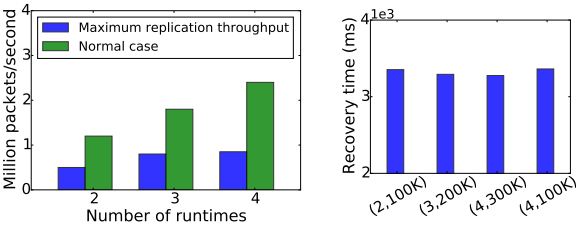


Figure 8: The flow migration performance of *NFActor*. Each flow in *NFActor* runtime goes through the service chain consisting of the 3 customzied NF modules. OpenNF controlls PRADS asset monitors.

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

8.3 Replication Performance



(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*

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.

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.

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