OFRewind: Enabling Record and Replay Troubleshooting for Networks

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Abstract

Debugging operational networks can be a daunting task, due to their size, distributed state, and the presence of *black box* components such as commercial routers and switches, which are poorly instrumentable and only coarsely configurable. The debugging tool set available to administrators is limited, and provides only aggregated statistics (SNMP), sampled data (NetFlow/sFlow), or local measurements on single hosts (tcpdump). In this paper, we leverage *split forwarding architectures* such as OpenFlow to add *record and replay debugging* capabilities to networks – a powerful, yet currently lacking approach. We present the design of **OFRewind**, which enables *scalable*, *multi-granularity*, *temporally consistent recording* and *coordinated replay* in a network, with fine-grained, dynamic, centrally orchestrated control over both record and replay. Thus, **OFRewind** helps operators to reproduce software errors, identify data-path limitations, or locate configuration errors.

1 Introduction

Life as a network operator can be hard. In spite of many efforts to the contrary, problem localization and troubleshooting in operational networks still remain largely unsolved problems today. Consider the following anecdotal evidence:

Towards the end of October 2009, the administrators of the Stanford production OpenFlow network began observing strange CPU usage patterns in their switches. The CPU utilization oscillated between 25% and 100% roughly every 30 minutes and led to prolonged flow setup times, which where unacceptable for many users. The network operators began debugging the problem using standard tools and data sets, including SNMP statistics, however the cause for the oscillation of the switch CPU remained inexplicable. Even an analysis of the entire control channel data could not shed light on the cause of the problem, as no observed parameter (number of: packets in, packets out, flow modifications, flow expirations, statistics requests, and statistics replies) seemed to correlate with the CPU utilization. This left the network operator puzzled regarding the cause of the problem.

This anecdote (further discussion in Section 4.2) hints at some of the challenges encountered when debugging problems in networks. Networks typically contain *black box* devices, e.g., commercial routers, switches, and middleboxes, that can be only coarsely configured and instrumented, via command-line or simple protocols such as SNMP. Often, the behavior of black box components in the network cannot be understood by analytical means alone – controlled replay and experimentation is needed.

Furthermore, network operators remain stuck with a fairly simplistic arsenal of tools. Many operators record statistics via NetFlow or sFlow [33]. These tools are valuable for observing general traffic trends, but often too coarse to pinpoint the origin problems. Collecting full packet traces, e.g., by tcpdump or specialized hardware, is often unscalable due to high volume data plane traffic. Even when there is a packet trace available, it typically only contains the traffic of a single VLAN or switch port. It is thus difficult to infer temporal or causal relationships between messages exchanged between multiple ports or devices.

Previous attempts have not significantly improved the situation. Tracing frameworks such as XTrace [35] and Netreplay [11] enhance debugging capabilities by pervasively instrumenting the entire network ecosystem, but face serious deployment hurdles due to the scale of changes involved. There are powerful tools available in the context of distributed applications that enable fully deterministic recording and replay, oriented toward end hosts [16, 24]. However, overhead for the fully-deterministic recording of a large network with high data rates can be prohibitive and the instrumentation of 'black' middleboxes and closed source software often remains out of reach.

In this paper, we present a new approach to enable practical network recording and replay, based upon an emerging class of network architectures called *split forwarding architectures*, such as OpenFlow [28], Tesseract [41], and Forces [2]. These architectures *split* control plane decision-making off from data plane forwarding. In doing so, they enable custom programmability and centralization of the control plane, while allowing for commodity high-throughput, high-fanout data plane forwarding elements.

We discuss, in Section 2, the design of **OFRewind**, a tool that takes advantage of these properties to significantly improve the state-of-the-art for recording and replaying network domains. **OFRewind** enables *scalable*, *temporally consistent*, *centrally controlled* network recording and *coordinated* replay of traffic in an OpenFlow controller domain. It takes advantage of the flexibility afforded by the programmable control plane, to dynamically *select* data plane traffic for recording. This improves data-path component scalability and enables *always-on* recording of critical, low-volume traffic, e.g., routing control messages. Indeed, a recent study has shown that the control plane traffic accounts for less than 1% of the data volume, but $95 - 99\%$ of the observed bugs [10]. Data plane traffic can be *load-balanced* across multiple *data plane recorders*. This enables recording even in environments with high data rates. Finally, thanks to the centralized perspective of the controller, **OFRewind** can record a *temporally consistent* trace of the controller domain. This facilitates investigation of the temporal and causal interdependencies of the messages exchanged between the devices in the controller domain.

During replay, **OFRewind** enables the operator to select which parts of the traces are to be replayed and how they should be mapped to the replay environment. By partitioning (or *bisecting*) the trace and automatically repeating the experiment, our tool helps to narrow down and isolate the problem causing component or traffic. A concrete implementation of the tool based on OpenFlow is presented in Section 3 and is released as free and open source software [4].

Our work is primarily motivated by operational issues in the OpenFlow-enabled production network at Stanford University. Accordingly, we discuss several case studies where our system has proven useful, including: switch CPU inflation, broadcast storms, anomalous forwarding, NOX packet parsing errors, and other invalid controller actions (Section 4). We in addition present a case study in which **OFRewind** successfully pinpoints faulty behavior in the Quagga RIP software routing daemon. This indicates that **OFRewind** is not limited to locating OpenFlow-specific bugs alone, but can also be used to reproduce other network anomalies.

Our evaluation (Section 5) shows *(a)* that the tool scales at least as well as current OpenFlow hardware implementations, *(b)* that recording does not impose an undue performance penalty on the throughput achieved, and *(c)* that the messaging overhead for synchronization in our production network is limited to 1.13% of all data plane traffic.

While using our tool, we have made and incorporated the following key observations:

(1) A full recording of all events in an entire production network is infeasible, due to the data volumes involved and their asynchronous nature. However, one usually needs not record all information to be able to reproduce or pinpoint a failure. It suffices to focus on *relevant subparts*, e.g., control messages or packet headers. By selectively recording critical traffic subsets, we can afford to turn *recording on by default* and thus reproduce many unforeseen problems *post facto*.

(2) Partial recordings, while missing some data necessary for fully deterministic replay, can be used to reproduce symptomatic network behavior, useful for gaining insights in many debugging situations. With careful initialization, the behavior of many network devices turns out to be *deterministic with respect to the network input*.

(3) By replaying *subsets of traffic* at a *controlled pace*, we can, in many cases, rapidly repeat experiments with different settings (parameters/code hooks) while still reproducing the error. We can, for instance, *bisect* the traffic and thus localize the sequence of messages leading to an error.

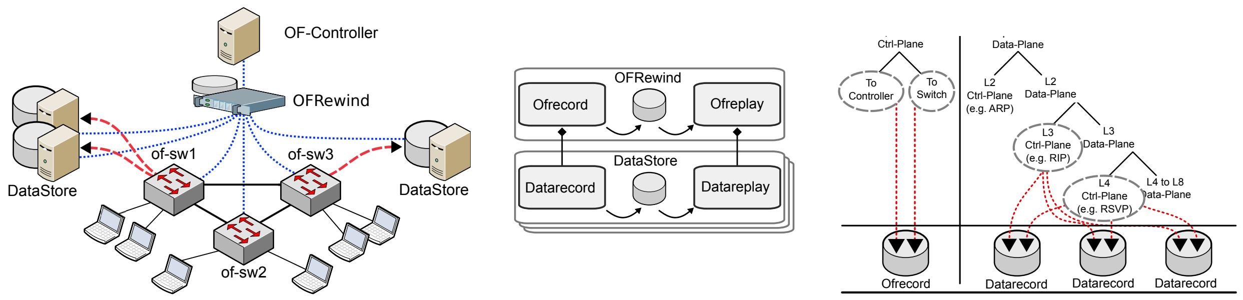
In summary, **OFRewind** is, to the best of our knowledge, the first tool which leverages the properties of split architecture forwarding to enable practical and economically feasible recording and replay debugging of network domains. It has proven useful in a variety of practical case studies, and our evaluation shows **OFRewind** does not significantly affect the scalability of OpenFlow controller domains and does not introduce undue overhead.

2 OFRewind System Design

In this section, we discuss the expected operational environment of **OFRewind**, its design goals, and the components and their interaction. We then focus on the need to synchronize specific system components during operation.

2.1 Environment / Abstractions

We base our system design upon *split forwarding architectures*, for instance, OpenFlow [28], Tesseract [41], or Forces [2], in which *standardized data plane elements* (switches) perform fast and efficient packet forwarding, and the control plane is *programmable* via an external



(a) System components (b) Software modules (c) Traffic strata

Figure 1: Overview of **OFRewind**

controlling entity, known as the *controller*. Programmability is achieved through *forwarding rules* that *match* incoming traffic and associate them with *actions*. We call this layer of the network the *substrate*, and the higher-layer *superstrate* network running on top of it *guest*. We call the traffic exchanged between the switches and the controller the substrate *control plane*. The higher-layer control plane traffic running inside of the substrate *data plane* (e.g., IP routing messages) is called the guest *control plane*. The relationship between these layers and traffic strata is shown in Figure 1(c).

Even though not strictly mandated almost all split-architecture deployments group several switches to be centrally managed by one controller, creating a *controller domain*. We envision one instance of **OFRewind** to run in one such controller domain. Imagine, e.g., a campus building infrastructure with 5-10 switches, 200 hosts attached on Gigabit links, a few routers, and an uplink of 10GB/s.

2.2 Design Goals and Non-Goals

As previously stated, recording and replay functionalities are not usually available in networks. We aim to build a tool that leverages the flexibility afforded by split-architectures to realize such a system. We do not envision **OFRewind** to do automated *root-cause analysis*. We do intend it to help *localize* problem causes. Additionally, we do not envision it to *automatically tune recording* parameters. This is left to an informed administrator who knows what scenario is being debugged.

Recording goals: We want a *scalable* system that can be used in a realistic-sized controller domain. We want to be able to record critical traffic, e.g., routing messages, in an *always-on* fashion. What is monitored should be specified in *centralized configuration*, and we want to be able to attain a *temporally consistent* view of the recorded events in the controller domain.

Replay goals: We want to be able to replay traffic in a *coordinated* fashion across the controller domain. For replaying into a different environment or topology (e.g., in a lab environment) we want to *sub-select* traffic and potentially *map* traffic to other devices. We include *time dilation* to help investigate timer issues, create stress tests, and allow “fast forwarding” to skip over irrelevant portions of the traffic. *Bisection* of the traffic between replays can assist problem localization whereby the user repeatedly partitions and sub-selects traffic to be replayed based on user-defined criteria (e.g., by message types), performs a test run, then continues the bisection based on whether a problem was reproducible.

(Absence of) determinism guarantees: As opposed to host-oriented replay debugging systems which strive for determinism guarantees, **OFRewind** does not – and cannot – provide strict determinism guarantees, as *black boxes* do not lend themselves to the necessary instrumentation. Instead, we leverage the insight that network device behavior is *largely deterministic* on control plane events (messages, ordering, timing). In some cases, when devices deliberately behave non-deterministically, protocol specific approaches must be taken.

2.3 OFRewind System Components

As seen in Figure 1(a), the main component of our system, **OFRewind**, runs as a proxy on the substrate control channel, i.e., between the switches and the original controller. It can thus intercept and modify substrate control plane messages to control recording and replay. It delegates recording and replay of *guest* traffic to *DataStore* components that are locally attached at regular switch ports. The number of *DataStores* attached at each switch can be chosen freely, subject to the availability of ports.

Both components can be broken down further into two modules each, as depicted in Figure 1(b): They consist of a recording and a replay module with a shared local storage, labeled *Ofrecord* and *Ofreplay*, and *Datarecord* and *Datareplay* respectively.

Record: *Ofrecord* captures *substrate* control plane traffic directly. When *guest* network traffic recording is desired, *Ofrecord* translates control messages to instruct the relevant switches to selectively mirror *guest* traffic to the *Datarecord* modules. **OFRewind** supports dynamic selection of the *substrate* or *guest* network traffic to record. In addition, flow-based-sampling can be used to record only a fraction of the data plane flows.

Replay: *Ofreplay* re-injects the traces captured by *Ofrecord* into the network, and thus enables domain-wide *replay debugging*. It emulates a controller towards switches or a set of switches towards a controller, and directly replays *substrate* control plane traffic. *Guest* traffic is replayed by the *Datareplay* modules, which are orchestrated by *Ofreplay*.

2.4 *Ofrecord* Traffic Selection

While it is, in principle, possible to collect full data recordings for every packet in the network, this introduces a substantial overhead both in terms of storage as well as in terms of performance. *Ofrecord*, however, allows selective traffic recording to reduce the overhead.

Selection: Flows can be classified and selected for recording. We refer to traffic *selection* whenever we make a conscious decision on what subset of traffic to record. Possible categories include: *substrate* control traffic, *guest* network control traffic, or *guest* data traffic, possibly sub-selected by arbitrary match expressions. We illustrate an example selection from these categories in Figure 1(c).

Sampling: If selection is unable to reduce the traffic sufficiently, one may apply either packet or flow sampling on either type of traffic as a reduction strategy.

Cut-offs: Another data reduction approach is to record only the first X bytes of each packet or flow. This often suffices to capture the critical meta-data and has been used in the context of intrusion detection [26].

2.5 *Ofreplay* Operation Modes

To support testing of the different entities involved (switches, controller, end hosts) and to enable different playback scenarios, *Ofreplay* supports several different operation modes:

ctrl: In this operation mode, replay is directed towards the controller. *Ofreplay* plays the recorded substrate control messages from the local *storage*. This mode enables debugging of a controller application on a single developer host, without need for switches, end-hosts, or even a network. Recorded data plane traffic is not required.

switch: This operation mode replays the recorded *substrate* control messages toward the switches, reconstructing each switch's *flow table* in real time. No controller is needed, nor is *guest* traffic replayed.

datahdr: This mode uses packet headers captured by the *Datarecord* modules to re-generate the exact flows encountered at recording time, with dummy packet payloads. This enables full testing of the switch network, independent of any end hosts.

datafull: In this mode, data traffic recorded by the *DataStores* is replayed with complete payload, allowing for selective inclusion of end host traffic into the tests.

In addition to these operation modes, *Ofreplay* enables the user to further tweak the recorded traffic to match the replay scenario. Replayed messages can be *sub-selected* based on source or destination host, port, or message type. Further, message destinations can be *re-mapped* on a per-host or per-port basis. These two complementary features allow traffic to be re-targeted toward a particular host, or restricted such that only relevant messages are replayed. They enable *Ofreplay* to play recorded traffic either toward the original sources or to alternative devices, which may run a different firmware version, have a different hardware configuration, or even be of a different vendor. These features enable **OFRewind** to be used for *regression testing*. Alternately, it can be useful to map traffic of multiple devices to a single device, to perform stress tests.

The *pace* of the replay is also adjustable within *Ofreplay*, enabling investigation of pace-dependent performance problems. Adjusting replay can also be used to "fast-forward" over portions of a trace, e.g., memory leaks in a switch, which typically develop over long time periods may be reproduced in an expedited manner.

2.6 Event Ordering and Synchronization

For some debugging scenarios, it is necessary to preserve the exact message order or mapping between *guest* and *substrate* flow data to be able to reproduce the problem. In concrete terms, the guest (data) traffic should not be replayed until the substrate (control) traffic (containing the corresponding substrate actions) has been replayed. Otherwise, *guest* messages might be incorrectly forwarded or simply dropped by the switch, as the necessary flow table state would be invalid or missing.

We do not assume tightly synchronized clocks or low latency communication channels between our **OFRewind** and the *DataStores* components. Accordingly, we cannot assume that synchronization between recorded *substrate* and *guest* flow traces, or order between flows recorded by different *DataStores* is guaranteed per se. Our design does rely on the following assumptions: (1) The *substrate* control plane channel is reliable and order-preserving. (2) The *control channel* between **OFRewind** and each individual *DataStore* is reliable and order-preserving, and has a reasonable mean latency l_c (e.g., 5 ms in a LAN setup.) (3) The *data plane* channel from **OFRewind** to the *DataStores* via the switch is not necessarily fully, but sufficiently reliable (e.g., 99.9% of messages arrive). It is not required to be order-preserving in general, but there should be some means of explicitly guaranteeing order between two messages. We define the data plane channel mean latency as l_d.

Record: Based on these assumptions, we define a logical clock C [25] on *Ofrecord*, incremented for each *substrate* control message as they arrive at *Ofrecord*. *Ofrecord* logs the value of C with each *substrate* control message. It also broadcasts the value of C to the *DataStores* in two kinds of synchronization markers: *time binning markers* and *flow creation markers*.

Time binning markers are sent out at regular time intervals i_t, e.g., every 100ms. They group flows into bins and thus constrain the search space for matching flows during replay and help reconstruct traffic characteristics within flows. Note that they do not impose a strict order on the flows within a time bin.

Flow creation markers are optionally sent out whenever a new flow is created. Based on the previous assumptions, they induce a total ordering on all flows whose creation markers have been successfully recorded. However, their usage limits the scalability of the system, as they must be recorded by all *DataStores*.

Replay: For synchronization during replay, *Ofreplay* assumes the role of a synchronization master, reading the value of C logged with the *substrate* messages. When a *DataStore* hits a synchronization marker while replaying, it synchronizes with *Ofreplay* before continuing. This assures that in the presence of *time binning markers*, the replay stays loosely synchronized between the markers (within an interval $I = i_t + l_d + l_c$). In the presence of *flow creation markers*, it guarantees that the order between the marked flows will be preserved.

2.7 Typical Operation

We envision that users of **OFRewind** run *Ofrecord* in an always-on fashion, always recording selected *substrate* control plane traffic (e.g., OpenFlow messages) onto a ring storage. If necessary, selected *guest* traffic can also be continuously recorded on *Datarecord*. To preserve space, low-rate control plane traffic, e.g., routing announcements, may be selected, sampling may be used, and/or the ring storage may be shrunk. When the operator (or an automated analytics tool) detects an anomaly, a replay is launched onto a separate set of hardware, or onto the production network during off-peak times. Recording settings are adapted as necessary until the anomaly can be reproduced during replay.

During replay, one typically uses some kind of debugging by elimination, either by performing binary search along the time axis or by eliminating one kind of message at a time. Hereby, it is important to choose orthogonal subsets of messages for effective problem localization.

3 Implementation

In this section, we describe the implementation of **OFRewind** based on OpenFlow, selected for currently being the most widely used *split forwarding architecture*. OpenFlow is currently in rapid adoption by testbeds [20], university campuses [1], and commercial vendors [3].

OpenFlow realizes *split forwarding architecture* as an open protocol between packet-forwarding hardware and a commodity PC (the *controller*). The protocol allows the *controller* to exercise flexible and dynamic control over the forwarding behavior of OpenFlow enabled Ethernet switches at a per-flow level. The definition of a flow can be tailored to the specific application case—OpenFlow supports an 11-tuple of packet header parts, against which incoming packets can be matched, and flows classified. These range from Layer 1 (switch ports), to Layer 2 and 3 (MAC and IP addresses), to Layer 4 (TCP and UDP ports). The set of matching rules, and the actions associated with and performed on each match are held in the switch and known as the *flow table*.

We next discuss the implementation of **OFRewind**, the synchronization among the components and discuss the benefits, limitations, and best-practices of using OpenFlow to implement our system. The implementation, which is an OpenFlow controller in itself, and based on the source code of FlowVisor [36] is available under a free and open source license at [4].

3.1 Software Modules

To capture both the *substrate* control traffic and *guest* network traffic we use a hybrid strategy for implementing **OFRewind**. Reconsider the example shown in Figure 1(a) from an OpenFlow perspective. We deploy a proxy server in the OpenFlow protocol path (labeled **OFRewind**) and attach local *DataStore* nodes to the switches. The **OFRewind** node runs the *Ofrecord* and *Ofreplay* modules, and the *DataStore* nodes run *Datarecord* and *Datareplay*, respectively. We now discuss the implementation of the four software components *Ofrecord*, *Datarecord*, *Ofreplay* and *Datareplay*.

***Ofrecord*:** *Ofrecord* intercepts all messages passing between the switches and controller and applies the selection rules. It then stores the selected OpenFlow control (*substrate*) messages to locally attached data storage. Optionally, the entire flow table of the switch can be dumped on record startup. If recording of the *guest* network control and/or data traffic is performed, *Ofrecord* transforms the `FLOW-MOD` and `PACKET-OUT` commands sent from the controller to the switch to *duplicate* the packets of selected flows to a *DataStore* attached to a switch along flow path. Multiple *DataStores* can be attached to each switch, .e.g., for load-balancing. The order of flows on the different *DataStores* in the system is retained with the help of synchronization markers. Any match rule supported by OpenFlow can be used for packet selection. Additionally, flow-based-sampling can be used to only record a fraction of the flows.

***Datarecord*:** The *Datarecord* components located on the *DataStores* record the selected guest traffic, as well as synchronization and control metadata. They are spawned and controlled by *Ofrecord*. Their implementation is based on `tcpdump`, modified to be controlled by *Ofrecord* via a TCP socket connection. Data reduction strategies that cannot be implemented with OpenFlow rules (e.g., packet sampling, cut-offs) are executed by *Datarecord* before writing the data to disk.

***Ofreplay*:** *Ofreplay* re-injects OpenFlow control plane messages as recorded by *Ofrecord* into the network and orchestrates the guest traffic replay by the *Datareplay* components on the *DataStores*. It supports replay towards the *controller* and *switches*, and different levels of data plane involvement (*switch*, *datahdr*, *datafull*, see Section 2.5.) Optionally, a flow table dump created by *Ofrecord* can be installed into the switches prior to replay. It supports traffic *sub-selection* and *mapping* towards different hardware and *time dilation*.

***Datareplay*:** The *Datareplay* components are responsible for re-injecting guest traffic into the network. They interact with and are controlled by *Ofreplay* for timing and synchronization. The implementation is based on `tcpreplay`. Depending on the record and replay mode, they reconstruct or synthesize missing data before replay, e.g., dummy packet payloads, when only packet headers have been recorded.

3.2 Synchronization

As we do not assume precise time synchronization between *Ofrecord* and the *DataStores*, the implementation uses *time binning markers* and *flow creation markers*, as discussed in Section 2.6. These are packets with unique ids flooded to all *DataStores* and logged by *Ofrecord*. The ordering of these markers relative to the recorded traffic is ensured by OpenFlow `BARRIER` messages[1]. We now discuss by example how the markers are used.

Record synchronization: Figure 2(a) illustrates the use of *flow creation markers* during recording. Consider a simple *Ofrecord* setup with two hosts *c1* and *s1* connected to switch *sw*. The switch is controlled by an instance of *Ofrecord*, which in turn acts as a client to the network controller *ctrl*. *Ofrecord* records to the local storage *of-store*, and controls an instance of *Datarecord* running on a *DataStore*. Assume that a new TCP connection is initiated at *c1* toward *s1*, generating a *tcp syn* packet (Step 1). As no matching flow table entry exists, *sw* sends *msg1*, an OpenFlow `PACKET-IN` to *Ofrecord* (Step 2), which in turn relays it to *ctrl* (step 3). *Ctrl* may respond with *msg2*, a `FLOW-MOD` message (step 4). To enable synchronized replay and reassembly of the control and data records, *Ofrecord* now creates a flow creation marker (*sync*), containing a unique id, the current time, and the matching rule of *msg1* and *msg2*. Both *msg1* and *msg2* are then annotated with the id of *sync* and saved to *of-store* (step 5). *Ofrecord* then sends out 3 messages to *sw1*: first, a `PACKET-OUT` message containing the *flow creation marker* sent to *all DataStores* in step 6. This prompts the switch to send out *sync* to all its attached *DataStores* (step 7). The second message sent from *Ofrecord* is a `BARRIER` message (step 8), which ensures that the message from step 7 is handled before any subsequent messages. In step 9, *Ofrecord* sends a modified `FLOW-MOD` message directing the flow to both the original receiver, as well as *one DataStore* attached to the switch. This prompts the switch to output the flow both to *s1* (step 10a) and *DataStore* (step 10b).

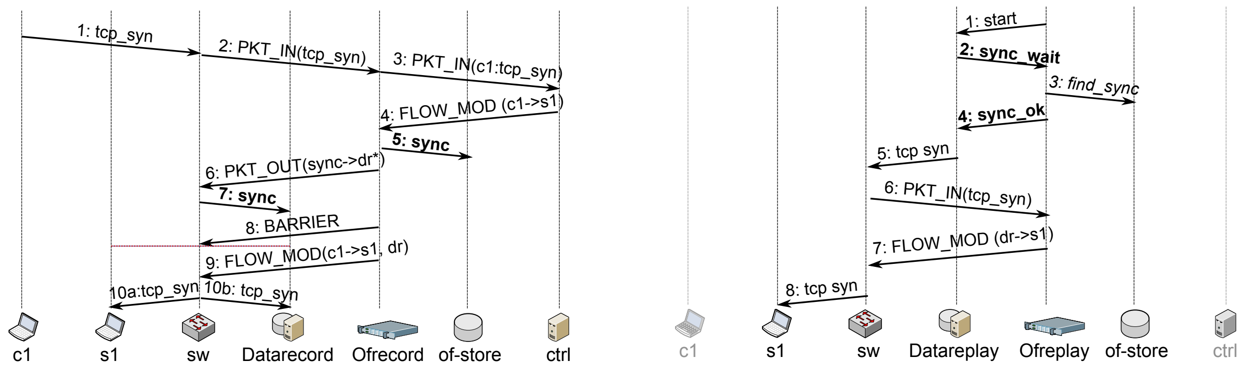
Replay synchronization: For synchronizing replay, *Ofreplay* matches data plane events to control plane events with the help of the flow creation markers recorded by *Ofrecord*. Consider the example in Figure 2(b). Based on the previous example, we replay the recording in *data plane mode* towards the switch *sw* and host *s1*. To begin, *Ofreplay* starts *Datareplay* playback on the *DataStore* in step 1. *Datareplay* hits the flow creation marker *sync*, then sends a `sync_wait` message to the controller, and goes to sleep (step 2). *Ofrecord* continues replay operation, until it hits the corresponding flow creation marker *sync* on the *of-store* (step 3). Then, it signals *Datareplay* to continue with a `sync_ok` message (step 4). *Datareplay* outputs the packet to the switch (step 5), generating a `PACKET-IN` event (step 6). *Ofreplay* responds with the matching `FLOW-MOD` event from the OpenFlow log (step 7). This installs a matching flow rule in the switch and causes the flow to be forwarded as recorded (step 8).

3.3 Discussion

We now discuss the limitations imposed by OpenFlow on our implementation, and best practices for avoiding replay inaccuracies.

OpenFlow limitations: While OpenFlow provides a useful basis for implementing **OFRewind**, it does not support all the features required to realize all operation modes. OpenFlow does not currently support **sampling** of either flows or packets. Thus, *flow sampling* is performed by *Ofrecord*, and packet sampling is performed by *Datarecord*. This imposes additional load on the channel between the switches and the *DataStores*

[1]A BARRIER message ensures that all prior OpenFlow messages are processed before subsequent messages are handled. In its absence, messages may be reordered.



(a) *Ofrecord* (b) *Ofreplay*

Figure 2: *DataStore* synchronization mechanism in **OFRewind**

for data that is not subsequently recorded. Similarly, the OpenFlow data plane does not support forwarding of **partial packets**[2]. Consequently, full packets are forwarded to the *DataStore* and only their headers may be recorded. OpenFlow also does not support automatic **flow cut-offs** after a specified amount of *traffic*[3]. The cut-off can be performed in the *DataStore*. Further optimizations are possible, e.g., regularly removing flows that have surpassed the threshold.

Avoiding replay inaccuracies: To reliably reproduce failures during replay in a controlled environment, one must ensure that the environment is properly initialized. We suggest therefore, to use the flow table dump feature and, preferably, reset (whenever possible) the switches and controller state before starting the replay operation. This reduces any unforeseen interference from previously installed bad state.

When bisecting during replay, one must consider the interdependencies among message types. `FLOW-MOD` messages are for example, responsible for creating the flow table entries and their arbitrary bisection may lead to incomplete or nonsense forwarding state on the switch.

Generally speaking, replay inaccuracies can occur when: (a) the chain of causally correlated messages is recorded incompletely, (b) synchronization between causally correlated messages is insufficient, (c) timers influence system behavior, and (d) network communication is partially non-deterministic. For (a) and (b), it is necessary to adapt the recording settings to include more or better-synchronized data. For (c) a possible approach is to *reduce* the traffic being replayed via subselection to reduce stress on the devices and increase accuracy. We have not witnessed this problem in our practical case studies. Case (d) requires the replayed traffic to be modified. If the non-determinism stems from the transport layer (e.g., TCP random initial sequence numbers), a custom transport-layer handler in *Datareplay* can shift sequence numbers accordingly for replay. For application non-determinism (e.g., cryptographic nonces), application-specific handlers must be used.

[2]It *does* support a cut-off for packets forwarded to the *controller*.

[3]Expiration after a specified amount of *time* is supported.

When the failure observed in the production network does not appear during replay, we call this a **false negative** problem. When the precautions outlined above have been taken, a repeated *false negative* indicates that the failure is likely not triggered by network traffic, but other events. In a **false positive** case, a failure is observed during replay which does not stem from the same root cause. Such inaccuracies can often be avoided by careful comparison of the symptoms and automated repetition of the replay.

4 Case Studies

In this section, we demonstrate the use of **OFRewind** for localizing problems in *black box network devices*, *controllers*, and *other software components*, as summarized in Table 1. These case studies also demonstrate the benefits of *bisecting* the control plane traffic (4.2), of *mapping* replays onto different pieces of hardware (4.3), from a production network onto a developer machine (4.5), and the benefit of a *temporally consistent* recording of multiple switches (4.6).

4.1 Experimental Setup

For our case studies we use a network with switches from three vendors: **Vendor A**, **Vendor B**, **Vendor C**. Each switch has two PCs connected to it. Figure 3 illustrates the connectivity. All switches in the network have a control-channel to *Ofrecord*. *DataStores* running *Datarecord* and *Datareplay* are attached to the switches as necessary. We use NOX [31], unless specified otherwise, as the high level controller performing the actual routing decisions. It includes the *routing* module, which

Case study	Class	OF-specific
Switch CPU Inflation	black box (switch)	no
Anomalous Forwarding	black box (switch)	yes
Invalid Port Translation	OF controller	yes
NOX Parsing Error	OF controller	yes
Faulty Route Advertisements	software router	no

Table 1: Overview of the case studies

Counts	Match
duration=181s	in_port=8
n_packets=0	dl_type=arp
n_bytes=3968	dl_src=00:15:17:d1:fa:92
idle_timeout=60	dl_dst=ff:ff:ff:ff:ff:ff
hard_timeout=0	actions=`FLOOD`

Table 2: **Vendor C** switch flow table entry, during replay.

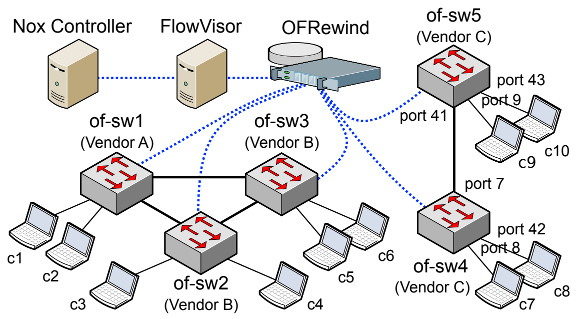


Figure 3: Lab environment for case studies

performs shortest path routing by learning the destination MAC address, and the $spanning - tree$ module, which prevents broadcast storms in the network by using Link Layer Discovery Protocol (LLDP) to identify if there is a loop in the network. All OpenFlow applications, viz. NOX, FlowVisor, *Ofreplay*, and *Ofrecord*, are run on the same server.

4.2 Switch CPU Inflation

Figure 4 shows our attempt at reproducing the CPU oscillation we reported in Section 1. As stated earlier, there is no apparent correlation between the ingress traffic and the CPU utilization. We record all control traffic in the production network, as well as the traffic entering/exiting the switch, while the CPU oscillation is happening. Figure 4(a) shows the original switch performance during recording. We, then, iteratively replay the corresponding control traffic over a similar switch in our isolated experimental setup. We replay the recorded data traffic to 1 port of the switch and connect hosts that send `ICMP` datagrams to the other ports. In each iteration, we have *Ofreplay bisect* the trace by OpenFlow message type, and check whether the symptom persists. When replaying the port and table statistic requests, we observe the behavior as shown in Figure 4(b). Since the data traffic is synthetically generated, the amplitude of the CPU oscillation and the flow setup time variation is different from that in the original system. Still, the sawtooth pattern is clearly visible. This successful reproduction of the symptom helps us identify the issue to be related to port and table statistics requests. Note that these messages have been causing the anomaly, even though their arrival rate (24 messages per minute) is not in any way temporally correlated with the perceived symptoms (30-minute CPU sawtooth pattern). We reported this issue to the vendor, since at this point we have no more visibility into the switch software implementation.

OFRewind thus, has proved useful in localizing the cause for the anomalous behavior of a black box component that would otherwise have been difficult to debug. Even though the bug in this case is related to a prototype OpenFlow device, the scenario as such (misbehaving black box component) and approach (debugging by replay and bisection of control-channel traffic) are arguably applicable to non-OpenFlow cases as well.

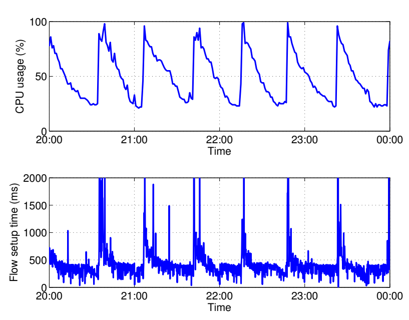
4.3 Anomalous Forwarding

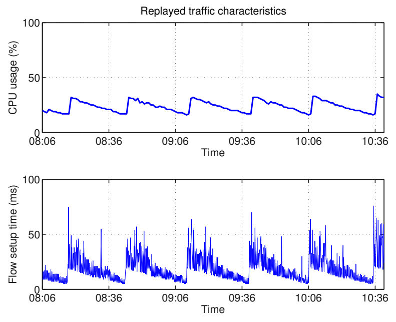
To investigate the performance of devices from a new vendor, **Vendor C**, we record the substrate and guest traffic for a set of flows, sending 10 second delayed `ping` between a pair of hosts attached to the switch from **Vendor B** (`of-sw3` in Figure 3). We then use the device/port mapping feature of *Ofreplay* to play back traffic from $c7$ to $c8$ over port 8 and port 42 belonging to the switch from **Vendor C**, in Figure 3.

Upon replay, we observe an interesting limitation of the switch from **Vendor C**. The `ping` flow stalls at the ARP resolution phase. The ARP packets transmitted from host $c7$ are received by host $c10$, but not by $c8$ nor $c9$. The flow table entry created in `of-sw4` during replay, is shown in Table 2, similar to that created during the original run. We conclude that the `FLOOD` action is not being properly applied by the switch from **Vendor C**.

Careful observation reveals that traffic received on a "low port" (one of the first 24 ports) to be flooded to any "high ports" (last 24 ports) and vice-versa is not flooded correctly. Effectively, the flood is restricted within a 24 port group within the switch (lower or higher). This fact has been affirmed by the vendor, confirming the successful debugging.

We additionally perform the replay after adding static ARP entries to the host $c7$. In this case, we observe that flow setup time for the subsequent unicast `ping` traffic on **Vendor C** is consistently higher than that observed for **Vendor B** and **Vendor A** switches. This indicates that **OFRewind** has further potential in profiling switches and controllers.


(a) Switch performance with original traffic


(b) Switch performance with replayed traffic

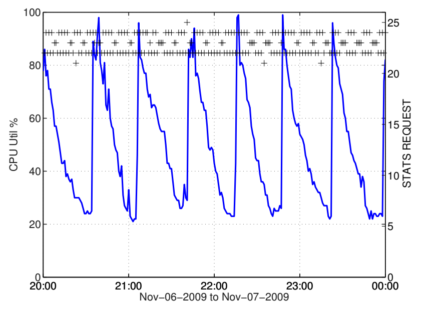

(c) `STATS-REQUEST` vs. CPU

Figure 4: Sawtooth CPU pattern reproduced during replay of port and table `STATS-REQUEST` messages. Figure (c) shows no observable temporal correlation to message arrivals.

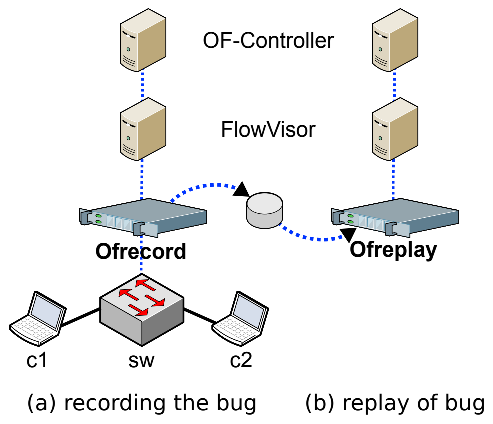


Figure 5: Debugging of FlowVisor bug #68

4.4 Invalid Port Translation

In this case study, we operate *Ofreplay* in the *ctrl* mode in order to debug a controller issue. The controller we focus on is the publicly available FlowVisor [36].

FlowVisor (FV) is a special purpose OpenFlow controller that acts as a proxy between multiple OpenFlow switches and controllers (*guests*), and thus assumes the role of a hypervisor for the OpenFlow control plane (see Figure 3). To this end, the overall flow space is partitioned by FV into distinct classes, e.g., based on IP addresses and ports, and each guest is given control of a subset. Messages between switches and controllers are then filtered and translated accordingly.

We investigate an issue in where the switch from **Vendor C** works fine with the NOX controller, but not through the FV. We record the OpenFlow control plane traffic from the switch to FV in our production setup, as seen on the left side of Figure 5. We then replay the trace on a developer system, running *Ofreplay*, FV and the upstream controller on a single host for debugging. *Ofreplay* thus assumes the role of the switch.

Through repeated automated replay of the trace on the development host, we track down the source of the problem: It is triggered by a switch announcing a non-contiguous range of port numbers (e.g., 1, 3, 5). When FV translates a `FLOOD` action sent from the upstream controller to such a switch, it incorrectly expands the port range to a contiguous range, including ports that are not announced by the switch (e.g., 1, **2**, 3, **4**, 5). The switch then drops the invalid action.

Here, **OFRewind** proves useful in localizing the root cause for the failure. Replaying the problem in the development environment enables much faster turnaround times, and thus reduces debugging time. Moreover, it can be used to verify the software patch that fixes the defect.

4.5 NOX `PACKET-IN` Parsing Error

We now investigate a problem, reported on the NOX [31] development mailing list, where the NOX controller consistently drops the ARP reply packet from a specific host. The controller is running the `pyswitch` module.

The bug reporter provides a `tcpdump` of the traffic between their switch and the controller. We verify the existence of the bug by replaying the control traffic to our instance of the NOX. We then gradually increase the debug output from NOX as we play back the recorded OpenFlow messages to NOX.

Repeating this processes reveals the root cause of the problem: NOX deems the destination MAC address `00:26:55:da:3a:40` to be invalid. This is because the MAC address contains the byte `0x3a`, which happens to be the binary equivalent of the character ':' in ASCII. This "fake" ASCII character causes the MAC address parser to interpret the MAC address as ASCII, leading to a parsing error and the dropped packet. Here, *Ofreplay* provides the necessary debugging context to faithfully reproduce a bug encountered in a different deployment, and leads us to the erroneous line of code.

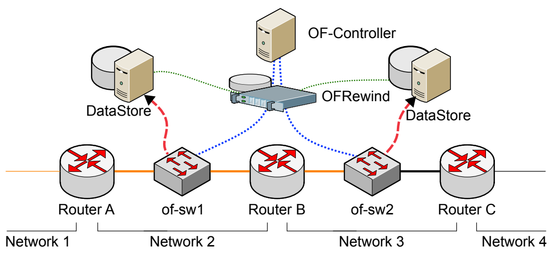


Figure 6: Quagga RIPv1 bug #235

4.6 Faulty Routing Advertisements

In a departure from OpenFlow network troubleshooting, we examine how **OFRewind** can be used to troubleshoot more general, event-driven network problems. We consider the common problem of a network suffering from a mis-configured or faulty router. In this case, we demonstrate how **OFRewind** can be advantageously used to identify the faulty component.

We apply **OFRewind** to troubleshoot a documented bug (Quagga Bugzilla #235) detected in a version of the RIPv1 implementation of the *Quagga* [34] software routing daemon. In the network topology given by Figure 6, a network operator notices that shortly after upgrading *Quagga* on software router B, router C subsequently loses connectivity to Network 1. As routing control plane messages are a good example of low-volume guest control plane traffic, they can be recorded by *Ofrecord* always-on or, alternatively, as a precautionary measure during upgrades. Enabling *flow creation sync markers* for the low-volume routing control plane messages ensures the global ordering is preserved.

The observation that router C loses its route to Network 1 while router B maintains its route, keys the operator to record traffic arriving at and departing from B. An analysis of the *Ofrecord* flow summaries reveals that although RIPv1 advertisements arrive at B from A, no advertisements leave B toward C. Host-based debugging of the RIPd process can then be used on router B in conjunction with *Ofreplay* to replay the trigger sequence and inspect the RIPd execution state. This reveals the root cause of the bug – routes toward Network 1 are not announced by router B due to this (0.99.9) version's handling of classful vs. CIDR IP network advertisements – an issue inherent to RIPv1 on classless networks.

4.7 Discussion

Without making any claims regarding the representativeness of the workload or switch behavior, in this limited space, we highlight in these case studies, the principle power and flexibility of **OFRewind**. We observe that **OFRewind** is capable of replaying subpopulations of control or data traffic, over a select network topology (switches and ports) or to select controllers, in a sandbox or production environment.

We further note that **OFRewind** has potential in switch (or controller) benchmarking. By creating a sandbox for experimentation that can be exported to a standard replay format, a network operator can concretely specify the desired behavior to switch (or controller) design engineers. The sandbox can then be run within the premises of the switch (or controller software) vendor on a completely new set of devices and ports. On receiving the device (or software), the network operator can conduct further benchmarking to compare performance of different solutions in a fair manner.

Comparison with traditional recording Based on the case presented in the last section, we compare the effort of recording and instrumenting the network with and without **OFRewind**. Note that while the specific traffic responsible for the failure is small (RIP control plane messages), the total traffic volume on the involved links may be substantial. To attain a synchronized recording of this setup without **OFRewind**, and in the absence of host-based instrumentation, one has to (1) deploy monitoring servers that can handle the *entire* traffic on each link of interest, e.g., [29], and redeploy as link interests change. Then, one must either (2a) reconfigure both switches to enable span ports (often limited to 2 on mid-range hardware) or (2b) introduce a tap into the physical wiring of the networks. Manually changing switch configurations runs a risk of operator error and introducing a tap induces downtime and is considered even riskier. (3) Additionally, the monitoring nodes may have to be synced to microsecond level to keep the flows globally ordered, requiring dedicated, expensive hardware. With **OFRewind**, one requires only a few commodity PCs acting as *DataStores*, and a single, central configuration change to record a *consistent* traffic trace.

of-simple	reference controller emulating a learning switch
nox-pyswitch	NOX controller running Python `pyswitch` module
nox-switch	NOX controller running C-language `switch` module
flowvisor	Flowvisor controller, running a simple allow-all policy for a single guest controller
ofrecord	*Ofrecord* with substrate mode recording
ofrecord-data	*Ofrecord* with guest mode recording, with one data port and sync beacons and barriers enabled

Table 3: Notation of controllers used in evaluation

5 Evaluation

When deploying **OFRewind** in a live production environment, we need to pay attention to its scalability, overhead and load on the switches. This section quantifies the general impact of deploying *Ofrecord* in a production network, and analyzes the replay accuracy of *Ofreplay* at higher flow rates.

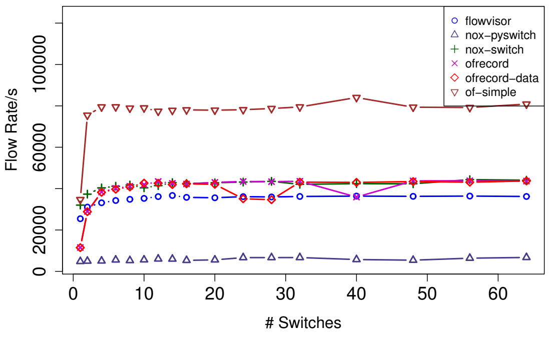


Figure 7: # Switches vs. median flow rate throughputs for different controllers using cbench.

5.1 *Ofrecord* Controller Performance

A key requirement for practical deployment of *Ofrecord* in a production environment is recording performance. It must record fast enough to prevent a performance bottleneck in the controller chain.

Using `cbench` [14], we compare the controller performance exhibited by several well known controllers, listed in Table 3. *Of-simple* and NOX are stand-alone controllers, while *flowvisor* and *ofrecord* act as a proxy to other controllers. *Ofrecord* is run twice: in substrate mode (*ofrecord*), recording the OpenFlow substrate traffic, and in guest mode (*ofrecord-data*), additionally performing OpenFlow message translations and outputting sync marker messages. Note that no actual guest traffic is involved in this experiment.

The experiment is performed on a single commodity server (Intel Xeon L5420, 2.5 GHz, 8 cores, 16 GB RAM, 4xSeagate SAS HDDs in a RAID 0 setup). We simulate, using `Cbench`, 1-64 switches connecting to the controller under test, and send back-to-back `PACKET-IN` messages to measure the maximum flow rate the controller can handle. `Cbench` reports the current flow rate once per second. We let each experiment run for 50 seconds, and remove the first and last 4 results for warmup and cool-down.

Figure 7 presents the results. We first compare the flow rates of the stand-alone controllers. *Nox-pyswitch* exhibits a median flow rate of *5,629* flows/s over all switches, *nox-switch* reports *42,233* flows/s, and *of-simple 78,908* flows/s. Consequently, we choose *of-simple* as the client controller for the proxy controllers. We next compare *flowvisor* and *ofrecord*. *Flowvisor* exhibits a median flow throughput of *35,595* flows/s. *Ofrecord* reports *42,380* flows/s, and *ofrecord-data* reports *41,743*. There is a slight variation in the performance of *ofrecord*, introduced by the I/O overhead. The minimum observed flow rates are *28,737* and *22,248*. We note that all controllers exhibit worse maximum throughput when only connected to a single switch, but show similar performance for $2 - 64$ switches.

We conclude that *Ofrecord*, while outperformed by *of-simple* in control plane performance, is unlikely to create a bottleneck in a typical OpenFlow network, which often includes a FlowVisor instance and guest domain controllers running more complex policies on top of NOX. Note that all controllers except *nox-pyswitch* perform an order of magnitude better than the maximum flow rates supported by current prototype OpenFlow hardware implementations (max. *1,000* flows/s).

5.2 Switch Performance During Record

When *Ofrecord* runs in *guest mode*, switches must handle an increase in OpenFlow control plane messages due to the sync markers. Additionally, `FLOW-MOD` and `PACKET-OUT` messages contain additional actions for mirroring data to the *DataStores*. This may influence the *flow arrival rate* that can be handled by a switch.

To investigate the impact of *Ofrecord* deployment on switch behavior, we use a test setup with two 8-core servers with 8 interfaces each, wired to two prototype OpenFlow hardware switches from **Vendor A** and **Vendor B**. We measure the supported flow arrival rates by generating minimum sized UDP packets with increasing destination port numbers in regular time intervals. Each packet thus creates a new flow entry. We record and count the packets at the sending and the receiving interfaces. Each run lasts for 60 seconds, then the UDP packet generation rate is increased.

Figure 8 presents the flow rates supported by the switches when controlled by *ofrecord*, *ofrecord-data*, and *of-simple*. We observe that all combinations of controllers and switches handle flow arrival rates of at least 200 flows/s. For higher flow rates, the **Vendor B** switch is CPU limited and the additional messages created by *Ofrecord* result in reduced flow rates (*ofrecord*: 247 flows/s, *ofrecord-data*: 187) when compared to *of-simple* (393 flows/s). **Vendor A** switch does not drop flows up to an ingress rate of 400 flows/s. However, it peaks at 872 flows/s for *ofrecord-data*, 972 flows/s for *ofrecord* and 996 flows/s for *of-simple*. This indicates that introducing *Ofrecord* imposes an acceptable performance penalty on the switches.

5.3 DataStore Scalability

Next we analyze the scalability of the *DataStores*. Note that *Ofrecord* is not limited to using a single *DataStore*. Indeed, the aggregate data plane traffic (T_s bytes in c_F flows) can be distributed onto as many *DataStores* as necessary, subject to the number of available switch ports. We denote the number of *DataStores* with n and enumerate each *DataStore* D_i subject to $0 \leq i < n$. The traffic volume assigned to each *DataStore* is T_i, such that $T_s = \sum T_i$. The flow count on each *DataStore* is c_i.

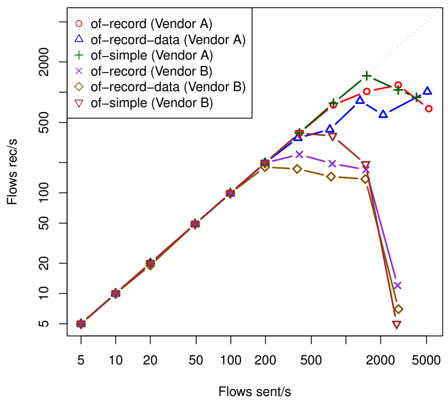


Figure 8: Mean rate of flows sent vs. successfully received with controllers *ofrecord*, *ofrecord-data*, and *of-simple* and switches from **Vendor A** and **B**.

The main overhead when using *Ofrecord* is caused by the *sync markers* that are flooded to *all DataStores* at the same time. Thus, their number limits the scalability of the system. *Flow-sync markers* are minimum-sized Ethernet frames that add constant overhead ($\theta = 64B$) per new flow. Accordingly, the absolute overhead for each *DataStore* is: $\Theta_i = \theta \cdot c_i$. The absolute overhead for the entire system is $\Theta = \sum \Theta_i = \theta \cdot c_F$, the relative overhead is: $\Theta_{rel} = \frac{\Theta}{T_s}$.

In the Stanford production network, of four switches with one *DataStore* each, a 9 hour day period on a workday in July 2010 generated $c_F = 3,891,899$ OpenFlow messages that required synchronization. During that period, we observed 87.977 GB of data plane traffic. Thus, the overall relative overhead is $\Theta_{rel} = 1.13\%$, small enough to not impact the capacity, and allow scaling up the deployment to a larger number of *DataStores*.

5.4 End-to-End Reliability And Timing

We now investigate the end-to-end reliability and timing precision of **OFRewind** by combining *Ofrecord* and *Ofreplay*. We use minimum size flows consisting of single UDP packets sent out at a uniform rate to obtain a worst-case bound. We vary the flow rate to investigate scalability. For each run, we first record the traffic with *Ofrecord* in guest mode with flow sync markers enabled. Then, we play back the trace and analyze the end-to-end drop rate and timing accuracy. We use a two-server setup connected by a single switch of **Vendor B**. Table 4 summarizes the results. Flow rates up to 200 Flows/s are handled without drops. Due to the flow sync markers, no packet reorderings occur and all flows are replayed in the correct order. The exact inter-flow timings vary though, upwards from 50 Flows/s.

To investigate the timing accuracy further, we analyze the relative deviation from the expected inter-flow delay.

Rate (Flows/s)	Drop %	sd(timing, in ms)
5	0 %	4.5
10	0 %	15.6
20	0 %	21.1
50	0 %	23.4
100	0 %	10.9
200	0 %	13.9
400	19%	15.8
800	41 %	21.5

Table 4: **OFRewind**—end-to-end measurements with uniformly spaced flows consisting of 1 UDP packet

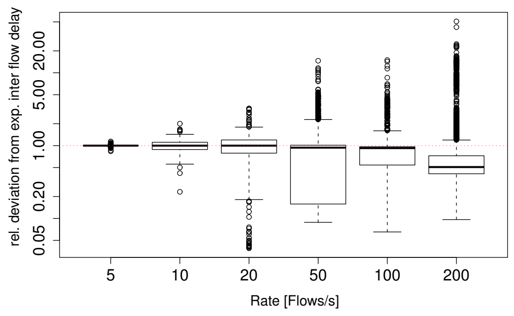


Figure 9: End-to-end flow time accuracy as a boxplot of the relative deviation from expected inter-flow delay.

Figure 9 presents the deviations experienced by the flows during the different phases of the experiment. Note that while there are certainly outliers for which the timing is far off, the *median* inter-flow delay remains close to the optimum for up to 100 Flows/s. Higher rates show room for improvement.

5.5 Scaling Further

We now discuss from a theoretical standpoint the limits of scalability intrinsic to the design of **OFRewind** when scaling beyond currently available production networks or testbeds. As with other OpenFlow-based systems, the performance of **OFRewind** is limited by the switch flow table size and the switch performance when updating and querying the flow table. We observe these to be the most common performance bottlenecks in OpenFlow setups today. Controller domain scalability is limited by the capacity of the link that carries the OpenFlow control channel, and the network and CPU performance of the controller. Specific to **OFRewind**, the control plane components require sufficient I/O performance to record the selected OpenFlow messages – not a problem in typical developments. When recording data plane network traffic, *DataStore* network and storage I/O capacity must be sufficient to handle the aggregate throughput of the selected flows. As load-balancing is performed over *DataStores* at flow granularity, **OFRewind** cannot fully record individual flows that surpass the network or storage I/O capacity of a single *DataStore*. When *flow creation markers* are used for synchronization, the overhead grows linearly with the number of *DataStores* and the number of flows. Thus, when the average flow size in a network is small, and synchronization is required, this may limit the scalability of a controller domain. For scaling further, **OFRewind** may in the future be extended to a *distributed controller domain*. While a quantitative evaluation is left for future study, we note that the lock-step approach taken to coordinate the replay of multiple instances of *Datarecord* and *Datareplay* (see Section 2.6) can be extended to synchronize multiple instances of **OFRewind** running as proxies to instances of a distributed controller. The same trade-offs between accuracy and performance apply here as well.

6 Related Work

Our work builds on a wealth of related work in the areas of recording and summarizing network traffic, replay debugging based on networks and on host primitives, automated problem diagnosis, pervasive tracing, and testing large-scale systems.

Recording/summarizing network traffic: Apart from the classical tool *tcpdump*[5], different approaches have been suggested in the literature to record high-volume network traffic, by performance optimization [12, 18], by recording abstractions of the network traffic [19, 27, 15], or omitting parts of the traffic [21, 26]. Our selection strategies borrow many of their ideas, more can be incorporated for improved performance. Note that these systems do not target network replay, and that all integrated control and data plane monitoring systems face scalability challenges when monitoring high-throughput links as the monitor has to consider all data plane traffic, even if only a subset is to be recorded. Similar to our approach of recording in a split-architecture environment, *OpenSafe* [13] leverages OpenFlow for flexible network monitoring but does not target replay or provide temporal consistency among multiple monitors. Complementary to our work, *OpenTM* [39] uses OpenFlow statistics to estimate the traffic matrix in a controller domain. *MeasuRouting* [37] enables flexible and optimized placement of traffic monitors with the help of OpenFlow, and could facilitate non-local *DataStores* in **OFRewind**.

Network replay debugging: *Tcpdump* and *tcpreplay* [6] are the closest siblings to our work that target network replay debugging. In fact, **OFRewind** uses these tools internally for data plane recording and replay, but significantly adds to their scope, scalability, and coherence: It records from a controller domain instead of a single network interface, can *select* traffic on the control plane and *load-balance* multiple *DataStores* for scalability, and can record a *temporally consistent* trace of the controller domain.

Replay debugging based on host primitives: Complementary to our network based replay, there exists a wealth of approaches that enable replay debugging for distributed systems on end-hosts [8, 17, 30]. DCR [9], a recent approach, emphasizes the importance of the control plane for debugging. These provide fully deterministic replay capabilities important for debugging complex end-host systems. They typically cannot be used for *black box* network components.

Automated problem diagnosis: A deployment of **OFRewind** can be complemented by a system that focuses on automated problem diagnosis. Sherlock diagnoses network problems based on passive monitoring [32], and other systems infer causality based on collected message traces [7, 38]. They target the debugging and profiling of individual applications while our purpose is to support debugging of networks.

Pervasive tracing: Some proposals integrate improved in-band diagnosis and tracing support directly into the Internet, e.g., by pervasively adding a trace ID to correlated requests [35] or by marking and remembering recently seen packets throughout the Internet [11]. We focus on the more controllable environment of a single administrative domain, providing replay support directly in the substrate, with no changes required to the network.

Testing large-scale networks: Many approaches experience scalability issues when dealing with large networks. The authors of [22] suggest to scale down large networks and map them to smaller virtualized testbeds, combining *time dilation* [23] and disk I/O simulation to enable accurate behavior. This idea may aid scaling replay testbeds for **OFRewind**.

7 Summary

This paper addresses an important void in debugging operational networks – scalable, economically feasible recording and replay capabilities. We present the design, implementation, and usage of **OFRewind**, a system capable of recording and replaying network events, motivated by our experiences troubleshooting network device and control plane anomalies. **OFRewind** provides control over the topology (choice of devices and their ports), timeline, and selection of traffic to be collected and then replayed in a particular debugging run. Using simple case studies, we highlight the potential of **OFRewind** for not only reproducing operational problems encountered in a production deployment but also localizing the network events that trigger the error. According to our evaluation, the framework is lightweight enough to be enabled per default in production networks.

Some challenges associated with network replay are still under investigation, including *improved timing accuracy*, *multi-instance synchronization*, and *online replay*. **OFRewind** can preserve flow order, and its timing is accurate enough for many use cases. However, further improvements would widen its applicability. Furthermore, synchronization among multiple *Ofrecord* and *Ofreplay* instances is desirable, but nontrivial, and might require hardware support for accurate time-stamping [29].

In a possible extension of this work, *Ofrecord* and *Ofreplay* are combined to form an *online replay* mode. Recorded messages are directly replayed upon arrival, e.g., to a different set of hardware or to a different *substrate* slice. This allows for online investigation and troubleshooting of failures in the sense of a *Mirror VNet* [40].

Our next steps involve gaining further experience with more complex use cases. We plan to collect and maintain a standard set of traces that serve as input for automated regression tests, as well as benchmarks, for testing new network components. Thus, we expect **OFRewind** to play a major role in helping ongoing OpenFlow deployment projects[4] resolve production problems.

8 Acknowledgements

We wish to extend gratitude toward our shepherd, George Candea, for his guidance and help in shaping our final paper version, as well as to our anonymous reviewers for their remarkably detailed and insightful feedback, and to Deutsche Telekom Laboratories and the GLAB project for funding our work.

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[4]There are ongoing production deployments of OpenFlow-enabled networks in Asia, Europe, as well as the US.