Network Monitoring for SDN Virtual Networks

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***Abstract*—This paper proposes V-Sight, a network monitoring framework for software-defined networking (SDN)-based virtual networks. Network virtualization with SDN (SDN-NV) makes it possible to realize programmable virtual networks; so, the technology can give many benefits to cloud services for tenants. However, to the best of our knowledge, network monitoring, although it is a vital prerequisite for managing and optimizing virtual networks, has not been investigated in the context of SDN-NV. Thus, virtual networks suffer from non-isolated statistics between virtual networks, high monitoring delays, and excessive control channel consumption for gathering statistics, which critically hinders the benefits of SDN-NV. To solve these problems, V-Sight presents three key mechanisms: 1) statistics virtualization for isolated statistics, 2) transmission disaggregation for reduced transmission delay, and 3) pCollector aggregation for efficient control channel consumption. V-Sight is implemented on top of OpenVirteX, and the evaluation results demonstrate that V-Sight successfully reduces monitoring delay and control channel consumption up to 454 times.**

***Index Terms*—Network monitoring, network virtualization, Software-defined networking**

I. Introduction

Network virtualization (NV) based on software-defined networking allows network operators to compose and manage virtual networks (VN) in their preferences. Network hypervisor (NH) [1]–[3] is an enabling technology that supports VN abstractions such as virtual switches, links, ports [1], and addresses [3]. NH sits between switches and VN controllers. With NH, VN users can create their own VN topology and control it using their VN controllers (e.g., POX [4], ONOS [5], OpenDayLight [6]).

Until now, NHs have evolved to be more scalable [7]–[9] and flexible [10]. However, to the best of our knowledge, none of the NHs provides network traffic monitoring, which is a vital prerequisite for network management. Thus, network traffic monitoring in SDN-NV causes three main issues: 1) inaccurate statistics, 2) high monitoring delay, and 3) excessive control channel traffic consumption. First, because VN controllers attempt to optimize and manage their VNs based on statistics, it is essential to have accurate statistics. However, in SDN-NV, the statistics collected in physical network are the aggregate of multiple VNs running on the network, and yet there is no mechanism to retrieve the statistics and isolate them for each VN.

Second, SDN-NV architecture inevitably increases the delay (so-called transmission delay) between the statistics request from the controller and the reply from switches. When the statistics request message arrives from the controller to the NH, the NH must send the corresponding network statistics request messages to the physical network (switches) and wait to receive the results. Therefore, the transmission delay increases. As an example, if a VN controller sends a request for "all flow entries of a virtual switch," the transmission delay can be very high since the statistics of individual flow entries are collected sequentially before being sent back to the VN controller. Our experiment shows that the transmission delay increases up to 333 times when compared to non-virtualized SDN (§II-C2). The increased delay means that the collected statistics can be out-of-date.

Third, the NH excessively consumes control channel traffic compared with non-virtualized SDN. In our experiment, control channel consumption increases up to three times (§II-C3) when the VN controller asks for the statistics of all the flow entries per switch. This high consumption is because the NH has to send multiple messages to switches in order to respond to a request from the controller. Since such messages go through the control channel, the control channel consumption increases, and other traffic gets affected [11]. For instance, our experiment finds that flow rule installation time increases 4.3 times due to the control channel consumption for retrieving the statistics.

To sum up, the problems caused by the lack of network monitoring preclude network optimization and essential network controls. To solve these problems, we design V-Sight, a comprehensive network monitoring framework for SDN-NV. V-Sight provides three mechanisms: 1) statistics virtualization to isolate statistics per VN, 2) transmission disaggregation to reduce the transmission delay, and 3) pCollector aggregation to reduce the control channel consumption.

Statistics virtualization calculates virtual network statistics (vStatistics) per VN from physical network statistics (pStatistics) (§III-B). Transmission disaggregation (§III-C) uses caching of the frequently used pStatistics. The caching is done with pCollector that retrieves the pStatistics routinely and stores the data in NH, which removes the delays for pStatistics transmission. We design pCollector aggregation (§III-D) to reduce the control channel consumption of pCollector. Rather than collecting pStatistics from individual pCollectors, pCollector aggregation attempts to merge pCollectors so that multiple pStatistics are retrieved with a single request message, which reduces the number of messages and thus control channel consumption.

This is an accepted version. Final article—DOI: 10.1109/INFOCOM41043.2020.9155260

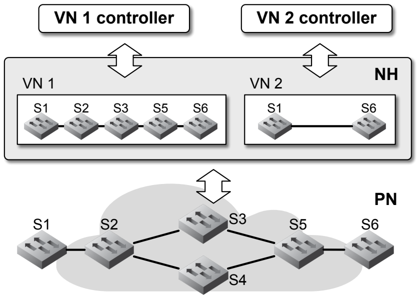


Fig. 1: SDN-based network virtualization.

V-Sight accomplishes the following contributions:

- We address the problems of network monitoring for SDN-NV: statistics isolation, improved monitoring delay, and enhanced control channel consumption for NHs.
- We design and develop V-Sight, the first network monitoring framework that leads to accurate statistics and low-overhead monitoring for virtualized SDN.
- We implement V-Sight in an open-source network hypervisor, OpenVirteX (OVX), and evaluate the framework rigorously.

The remainder of this paper is organized as follows. §II describes the background, motivation, and particular problems of network monitoring in SDN-NV. The fundamental concepts and the complete design of V-Sight are given in §III, and §IV presents the evaluation results. §V elaborates on the related work. Finally, §VI concludes this paper.

II. Background and Motivation

Here, we explain the background of this study: SDN-NV and network monitoring. Then, we identify issues for network monitoring on SDN-NV.

A. SDN-based Network Virtualization

SDN-NV is composed of three layers, as shown in Fig. 1: the VN controllers, NH, and physical network (PN). A VN controller can create its VN topology with VN resources, such as virtual switches, links, and ports. This is done when the VN controller sends a request to the NH. When the NH receives the request, it substantiates the VN resources with the mappings to the PN switches or ports. For instance, a virtual switch operates based on the mapping of one physical switch, or a set of physical switches and links. The virtual port (vp) for each virtual switch is also mapped to the physical port (pp). In addition, a virtual link can be created by connecting two vps.

Once the VN topology is created, the VN controller[1] runs to manage the created virtual resources. The VN controller connects with the virtual switches through south-bound interfaces (e.g., OpenFlow) and implements flow entries that match packets so that it processes (e.g., forward) the matched packets. These operations are done by control messages from the VN controller, and the control messages go through the control channel.

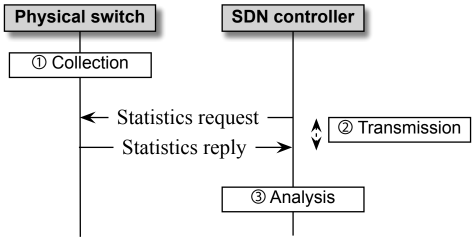


Fig. 2: Three steps of network monitoring in SDN.

VN resources and flow entries are mapped to the corresponding resources in the PN. This means that the PN resources can be mapped to either one or more of the VN resources. Thus, the flow entries from multiple VN controllers can be mapped to the smaller number of physical flow entries [7], [8]. Throughout this paper, we use the term V to represent a virtualization function and V' to represent a de-virtualization function that gets the mapped resources to the physical resource, or vice versa. For example, when a physical flow entry (pf) is given, $V(pf)$ gives the virtual flow entries (vfs) mapped to the pf. Also, given a virtual switch S, $V(S)$ generates the list of physical switches and links mapped to S.

B. Network Monitoring in SDN

Network monitoring in SDN goes through three steps as Fig. 2 [12]: ① collection, ② transmission, and ③ analysis. The statistics are recorded at the switches, which measure the processed amount of packets per flow entry or port (① collection). Then, an SDN controller gathers the statistics from a switch (② transmission). With the collected information, the SDN controller analyses, manages, and optimizes the networks (③ analysis).

For example, ONOS [5] collects the statistics of flow entries and ports at 5 s intervals. Also, ONOS checks the consistency of the implemented flow entries, which needs to collect a large number of flow entry statistics. Therefore, it is well-known that such network monitoring causes enormous overheads to SDN controllers [13]. The overheads are considered as a critical problem for SDN controllers; therefore, many studies have tried to reduce the monitoring overheads. Typically, their solutions use a trade-off relationship between statistics accuracy and monitoring overhead, so they lower the accuracy in order to reduce the monitoring overhead. For example, transmission sampling [14]–[16], statistics hashing [17], and statistics prediction [18] compromise the accuracy by omitting the collection of some statistics values. Therefore, directly applying these solutions to SDN-NV makes the monitoring overhead worse. It is because multiple VNs increase the monitoring overhead which can easily void the validity of monitoring itself.

[1] Typically, SDN controllers (e.g., POX, ONOS, OpenDayLight) are used as VN controllers. So, throughout this paper, we use the term ‘SDN controller,’ and ‘VN controller’ interchangeably. For non-virtualized SDN context, we use the term ‘SDN controller,’ and ‘VN controller’ is used for SDN-NV.

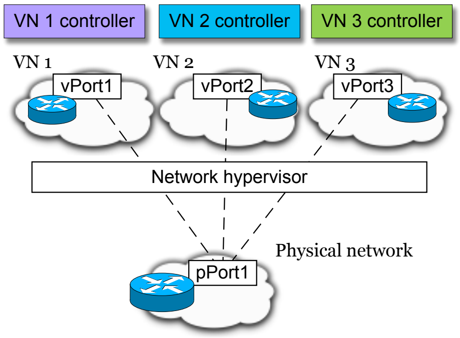


Fig. 3: Non-isolated statistics example.

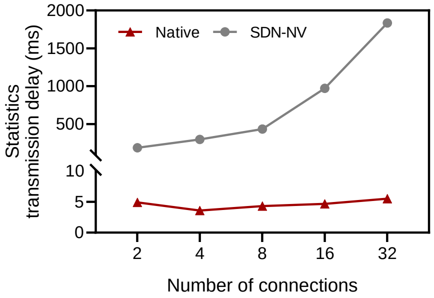


Fig. 4: Statistics transmission delay comparison (ms).

C. Issues of Network Monitoring for SDN-based Network Virtualization

Here, we discuss three issues caused by the lack of network monitoring in SDN-NV in detail, which motivates V-Sight.

1) Non-isolated statistics: In SDN-NV, the PN resources (e.g., switch and port) are shared between multiple VNs. So, the collected statistics from physical resources are not isolated between the VNs. Figure 3 shows an example of three VNs, each having one vp. In this scenario, all vps are mapped to the same pp (pPort1). Suppose that the VN1 controller retrieves the statistics of vPort1. As pPort1 does not know about the presence of multiple VNs, it does not separately collect the statistics per VN. Thus, the VN1 controller ends up with the aggregated statistics, not its own. Statistics are used for various network management operations of VN controllers, such as cost-based central routing, traffic engineering features, and quality-of-service. However, with the non-isolated statistics, VN controllers cannot fulfill their desired goals. Thus, V-Sight should isolate statistics in the sense that the statistics provided to each VN controller should only contain information regarding the VN, not the others.

2) High transmission delay: Network monitoring is performed repeatedly to track changing statistics. The reply to the statistics request should arrive as soon as possible because the transmission delay between the request and reply messages distances the value of the statistics from the request time.

We experiment to see how much the transmission delay increases in SDN-NV. Because existing NHs do not support network monitoring, we implement a simple monitoring function on OVX. The implementation receives the statistics requests from VN controllers and then gathers the corresponding statistics from PN based on the mappings between VNs and PN. The monitoring function replies to VN controllers after all pStatistics from the physical switches arrive. The experiment is conducted in a 4-ary fat-tree topology with 2, 4, 8, 16, and 32 TCP connections in a VN. The VN controller issues statistics requests at a 5 s interval for every switch in its network, asking for the statistics of all flow entries of each switch.

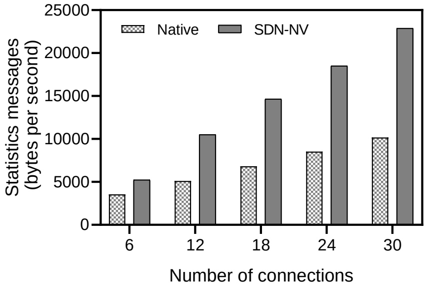


Fig. 5: Control channel consumption comparison (bytes per second).

As described in Fig. 4, non-virtualized SDN (Native) exhibits almost constant statistics transmission delay, at 4.6 ms on average, regardless of the number of network connections. In contrast, SDN-NV shows a delay of 187 ms to 1,836 ms, which is 38 to 333 times higher than that of Native. The reason for the increased delay is that, for a request for statistics for all flow entries in the switch, the implementation performs statistics transmission as many as the number of flow entries in the switch. After the statistics of each flow entry are collected, the VN controller receives the reply. As a result, the transmission delay in SDN-NV increases up to 1.84 s (Fig. 4).

3) Excessive control channel consumption: Statistics transmission is realized through the control channel. The control channel is also utilized by VN controllers for operations like switch connection handshaking, flow entry installation and modification, topology discovery process, and ARP processing. So, when the control channel consumption for statistics increases from 5.11 KB/s to 22 KB/s, we find that flow entry installation suffers four times higher delay (from 86 ms to 368 ms). Since operations like flow entry installation can affect the throughput of network connections, the consumption of the control channel for network monitoring should be reduced.

To be precise, we evaluate the control channel consumption for the network monitoring of SDN-NV. We set a linear topology with five switches and three VNs. Each VN has two hosts at the edge of the topology with 6, 12, 18, 24, and 30 network connections in PN. We conduct experiments with the same monitoring function on the NH and statistics requests as §II-C2. Figure 5 shows the control channel consumption for the flow statistics transmission. The results are 1.5 to 2.3 times higher than Native. In Native, most SDN controllers collect all pf statistics with a single request message for a switch. On the contrary, the NH collects the statistics for each pf one-by-one. If 30 pfs exist in a switch and only three pfs are used for the VN, collecting all pfs for three pfs is very inefficient.

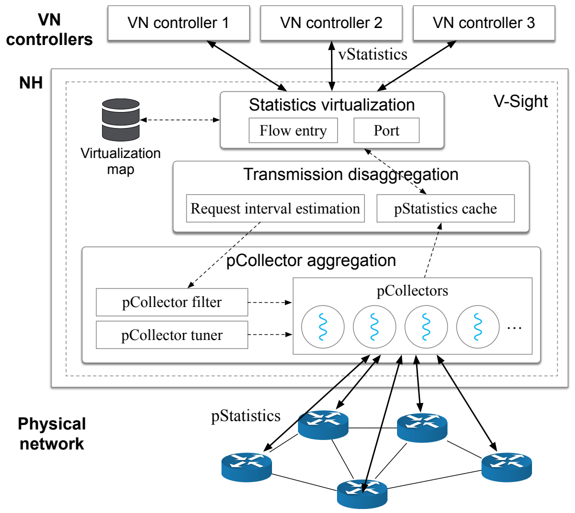


Fig. 6: V-Sight architecture.

III. V-Sight Design

In this section, we first introduce the overall architecture of V-Sight framework and its operations. We then present three mechanisms of V-Sight: 1) statistics virtualization for isolated statistics, 2) transmission disaggregation for improved transmission delay, and 3) pCollector aggregation for reduced control channel consumption.

A. V-Sight Framework Architecture

Figure 6 illustrates the architecture of V-Sight framework. The processing sequence of V-Sight is as follows. When a statistics request (e.g., vf or vp) from a VN controller is sent, statistics virtualization of V-Sight in Fig. 6 (§III-B) receives the message and calculates the requested vStatistics based on pStatistics. For calculation, V-Sight references virtualization map that maintains mappings between VN and PN resources.

The pStatistics needed for vStatistics calculation is obtained from pStatistics cache. Transmission disaggregation (§III-C) maintains the 'pStatistics cache,' and the cache is filled by pCollector. What transmission disaggregation does is to have a pCollector run before the vStatistics request. A key point of the transmission disaggregation is to prepare the pStatistics needed for the vStatistics requested with disaggregating the time the vStatistics comes in and the time the pStatistics are ready. In other words, transmission disaggregation allows the pStatistics in the pStatistics cache before the vStatistics request arrives. To achieve this, transmission disaggregation performs 'request interval estimation.'

pCollector aggregation (§III-D) consists of two tasks: 'pCollector filter' decides the execution period of each pCollector and checks whether pCollectors can be merged as one pCollector for a specific physical switch; 'pCollector tuner' decides the starting delay of a pCollector for improved accuracy.

B. Statistics Virtualization

Statistics virtualization aims to provide per-VN vStatistics from non-isolated pStatistics. We develop calculation algorithms for vfs (flow entry) and vps (port), which are the most fine-grained resources of network monitoring in SDN networks [19]. Other resources (e.g., flow table, switch, or entire network) could be derived from the per-VN statistics.

Algorithm 1: Per-tenant flow entry statistics.

```
Input: $vf$: virtual flow entry for which the VN
       controller requires statistics
Output: $S(vf)$: statistics of the $vf$
$pf = V'(vf)$
if $|V(pf)| == 1$ then
    $S(vf) = S(pf)$
else
    if $|V(pf)| > 1$ then
        $E_{pf}$ = Find edge $pf$ of $vf$
        $S(vf) = S(E_pf)$
Return $S(vf)$
```

1) Per-VN flow entry statistics: vf statistics contain the packet count, byte count, and duration of the installed entry. For statistics isolation, V-Sight checks the mapping between vf and pf from the virtualization map (Fig. 6). The mapping of vf is used in two ways. First, if pf is not shared with the other VNs ($|V(pf)| = 1$), the statistics of pf become the statistics of vf. Second, pf is shared between VNs ($|V(pf)| > 1$) [8], [11]. In this case, because the pf aggregates all the statistics of vfs mapped to the pf, V-Sight should not return the pf statistics directly to the VN controller. Instead, V-Sight isolates the pf statistics with the following observation: even though multiple vfs are mapped to one pf, the vfs for edge switches (first and last switches on the forwarding path) are installed individually per VN like the mapping case $|V(pf)| = 1$. It is because, in the edge switches, the packets are dealt with separately per VN to ensure isolation in NV [8], [20]. That is, pf in the edge is allocated per-VN so that the packets at the edge are delivered to the host (or virtual machine). Thus, V-Sight returns the pStatistics of the edge switch pf as the requested vStatistics. Algorithm 1 summarizes how to get the per-VN flow entry statistics.

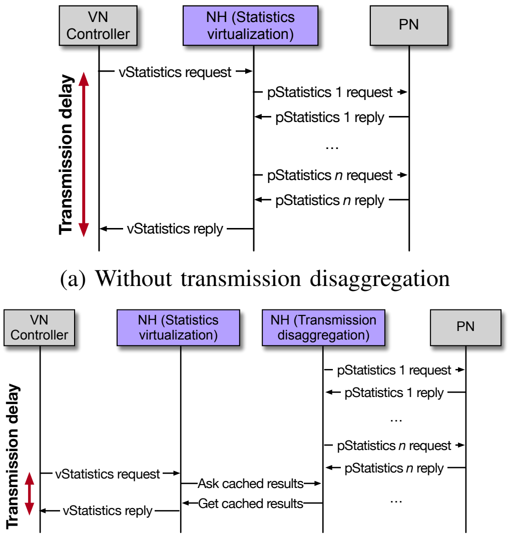
2) Per-VN port statistics: vp statistics include the amounts of received (RX) and transmitted (TX) packets. Similar to the flow entry, pp can be shared by one or more VNs. If only a single VN utilizes the physical port, the statistics of pp become vp statistics. On the other hand, if pp is mapped to multiple vps, it receives and transmits the traffic of multiple VNs. In this case, V-Sight uses vf statistics obtained in Alg. 1 since vfs process the packets going to and from the vp of a switch. For RX, V-Sight accumulates the vStatistics of vfs that have vp as its input port. To calculate the TX, V-Sight adds up the vStatistics of the vfs that send packets out to the vp. This calculation is summarized in Alg. 2.

C. Transmission Disaggregation

The transmission delay for vStatistics (Fig. 7a) is composed of the following parts: 1) vStatistics request and reply message transmission time (d_v) between the VN controller and NH,

Algorithm 2: Per-tenant port statistics.

```
Input: $vp$: virtual port for which the VN controller
         requires statistics
       $vs$: virtual switch to which the $vp$ belongs
       $vf$, $vf^{in}$, $vf^{out}$: virtual flow entry,
       input port of the $vf$, output port of the $vf$
Output: $S(vp)$: statistics of the $vp$
$pp = V'(vp)$
if $|V(pp)| == 1$ then
    $S(vp) = S(pp)$
else
    for $vf_i$ belongs to $vs$ do
        if $vf_i^{in} == vp$ then
            $S(vp).RX+ = S(vf_i)$;
        else if $vf_i^{out} == vp$ then
            $S(vp).TX+ = S(vf_i)$
Return $S(vp)$
```



(a) Without transmission disaggregation

(b) With transmission disaggregation

Fig. 7: Transmission delay comparison.

2) pStatistics request and reply message transmission time (d_p) between the NH and physical switches, which may occur multiple times depending on the vStatistics request, and 3) processing time in the NH for statistics calculation (d_{NH}). Then, if the number of pStatistics needed for vStatistics is n, the total transmission delay is formulated as $d_v + nd_p + d_{NH}$.

For comparison, the total transmission delay in non-virtualized SDN is d_c since single statistics transmission between PN and the SDN controller is enough to get statistics. d_v is equivalent to d_c because both are for transmitting messages through the control channel. So, the transmission delay of SDN-NV has the additional time of $nd_p + d_{NH}$. The time d_{NH} is to perform statistics virtualization (§III-B), and so the focus to reduce the transmission delay is on reducing nd_p, which is the time for pStatistics transmissions (Fig. 7b). To reduce nd_p, transmission disaggregation introduces the pStatistics cache and request interval estimation.

1) pStatistics cache: The pStatistics cache tracks the time when pStatistics is stored and whether pStatistics has already been used per VN. If the pStatistics cache contains pStatistics not used for the requesting VN before (hit), the pStatistics can be directly returned without retrieving pStatistics from any physical switches. On the other hand, if pStatistics does not exist in the pStatistics cache (miss) or they are out-of-date because they have been previously used for the requesting VN (old), the cache retrieves pStatistics from physical switches. Figure 7b shows how transmission disaggregation works.

When the number of pStatistics needed for vStatistics is n, and k of pStatistics are hit (meaning $n - k$ accesses to the pStatistics cache are miss or old), physical transmissions of $n - k$ times are conducted for vStatistics. Then, the entire transmission delay can be reduced to $(1 + n - k)d_p + d_{NH}$. Therefore, increasing the number k is important for improving the transmission delay.

2) Request interval estimation: The pStatistics cache is filled by pCollectors. pCollector exists per-pf which means that a pCollector executes to retrieve pStatistics of a pf of a physical switch. To be clear, we use the term 'interval' for the time between two consecutive requests from a VN controller for a pf, and 'period' for the time difference between two consecutive executions of a pCollector.

For each pCollector, the period of execution should be determined. If the period of the pCollector is much shorter than the request interval, the pCollector will end up executing multiple times before the hit, which wastes the CPU and control channel. Conversely, if the pCollector is executed less often than the vStatistics requests, the transmission delay cannot be reduced because the pStatistics are old. Therefore, determining the execution period is very important, and this is what request interval estimation does.

Request interval estimation calculates the mean (μ) and variance (σ) per pf that characterize the VN controller's request intervals. For pf_i, the request of VN j is denoted as $pf_{i,j}$ and its distribution is $(\mu_{i,j}, \sigma_{i,j})$. The pStatistics cache contains pf identifier (pf_i) and VN identifier (j). The kth interval for $pf_{i,j}$ is denoted as $pf_{i,j}^k$.

Figure 8 shows the flowchart of the entire request interval estimation. This process is executed every time the pf identifier (pf_i) and the VN identifier (j) is received. This process is executed whenever the pf identifier (pf_i) and the VN identifier (j) is received as per each vStatistics request. First, request interval estimation records the interval between consecutive requests (① in Fig. 8). Once enough intervals are accumulated (②), request interval estimation calculates $(\mu_{i,j}, \sigma_{i,j})$ (③). The number of intervals used for the calculation is denoted as 'interval window $(w)^2$.' When the $(w + 1)$th request comes, the distribution of $pf_{i,j}$ $(\mu_{i,j}, \sigma_{i,j})$ is calculated based on the $pf_{i,j}^1$ to $pf_{i,j}^w$. Then, among the distributions of multiple VNs, V-Sight chooses the interval distribution that has the

[2] Due to the space limit of this paper, we do not include the experiments for changing the w value. However, for the default monitoring operation of ONOS, 30 is enough to obtain a stable and reliable interval distribution.

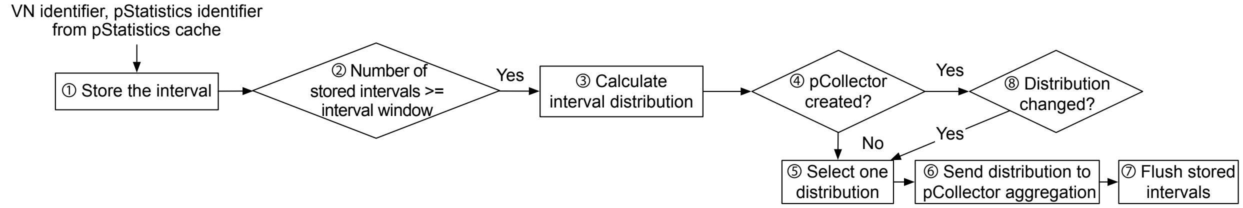

VN identifier, pStatistics identifier
from pStatistics cache
① Store the interval
② Number of stored intervals >= interval window
Yes
③ Calculate interval distribution
④ pCollector created?
Yes
⑧ Distribution changed?
Yes
No
⑤ Select one distribution
⑥ Send distribution to pCollector aggregation
⑦ Flush stored intervals

Fig. 8: Flowchart of request interval estimation.

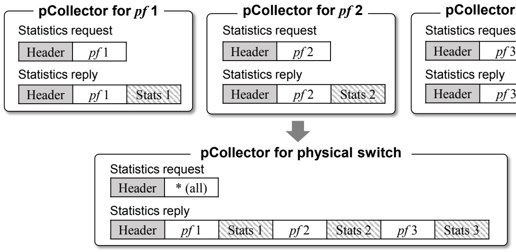


Fig. 9: Control channel consumption for two kinds of pCollectors.

minimum μ value (⑤). In other words, (μ_i, σ_i) = $(\mu_{i,l}, \sigma_{i,l})$ where $l = \arg\min_j \mu_{i,j}$. The requests that have higher μ than the selected pf_i will hit because the pCollector for pf_i based on (μ_i, σ_i) stores the statistics of pf_i for those requests in a timely way. The selected distribution is passed to pCollector aggregation (⑥, §III-D) as a triple (pf_i, μ_i, σ_i). Note that a pCollector is created after the w number of intervals are accumulated. Before the interval window, pStatistics cache generates 'miss' for the required pStatistics of pf_i which makes V-Sight collect pStatistics from the physical network for each request.

Obviously, the request interval of each VN controller can change. The request estimation interval flushes the w number of the past intervals ($pf^1_{i,j}$ to $pf^w_{i,j}$) after sending a new interval distribution (⑦), and accumulates the intervals from 1 to w again. So for the w number of recorded intervals (②), $(\mu_{i,j}, \sigma_{i,j})$ is updated (③). If the pCollector for pf_i is already created (④), request interval estimation checks how much the newly updated $\mu_{i,j}$ is changed from the previous value (⑧). If the changed amount is large (say, 25%), this function selects a new distribution for pf_i (⑤) and delivers a new triple (pf_i, μ_i, σ_i) to pCollector aggregation (⑥).

D. pCollector Aggregation

The objective of pCollector aggregation is to execute and merge pCollectors. Given a triple (pf_i, μ_i, σ_i) from transmission disaggregation, a pCollector for pf_i is created. The pCollector periodically retrieves the pf_i statistics from a switch. However, if the number of pCollectors increases, the pCollectors can consume too much of the control channel (as discussed in §II-C3).

There are two types of pCollectors as Fig. 9. At the top of Fig. 9, three pCollectors retrieves statistics from their own pf. The bottom shows one pCollector that collects multiple statistics at once. For the former, the request message should contain the match fields and actions of pf. In contrast, for the latter, the request message contains "all" as its request. Obviously, the latter pCollector consumes less control channel than the former.

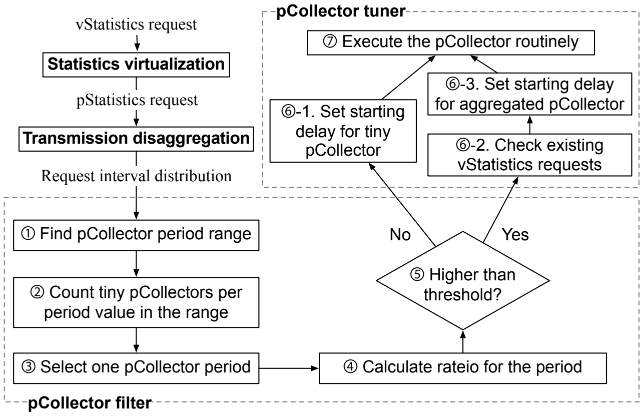
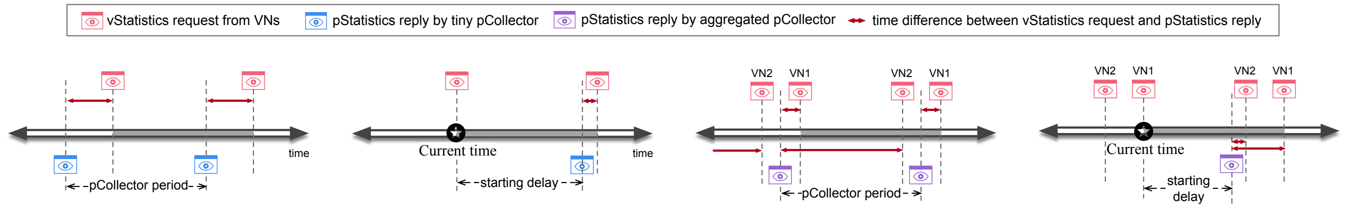

vStatistics request
Statistics virtualization
pStatistics request
Transmission disaggregation
Request interval distribution
pCollector tuner
⑦ Execute the pCollector routinely
⑥-3. Set starting delay for aggregated pCollector
⑥-1. Set starting delay for tiny pCollector
⑥-2. Check existing vStatistics requests
No
Yes
① Find pCollector period range
② Count tiny pCollectors per period value in the range
⑤ Higher than threshold?
③ Select one pCollector period
④ Calculate rateio for the period
pCollector filter

Fig. 10: Flowchart of pCollector aggregation. This routine is executed according to statistics virtualization and transmission disaggregation.

We call the pCollector for a single pf (former) as 'tiny pCollector' and the other pCollector as 'aggregated pCollector.' An aggregated pCollector is created when many tiny pCollectors follow a similar period for pfs in a switch. pCollector aggregation is done by two tasks: 1) pCollector filter to determine the execution period of tiny and aggregated pCollectors and 2) pCollector tuner for improving the accuracy of vStatistics using pCollector's results. Figure 10 explains the operation of the two tasks to be discussed in the following subsections.

1) pCollector filter: From (pf_i, μ_i, σ_i), pCollector filter decides a period of the pCollector for pf_i. For the tiny pCollector, it is simple. However, for the aggregated pCollector, even if VN controllers issue statistics requests with a similar interval, each μ_i of pf_i can be slightly different (e.g., 4.7 s, 4.9 s, and 5.1 s) since the distribution is estimated based on w samples. So, it is challenging to decide the period of aggregated pCollector.

To solve this problem, pCollector filter starts with tiny pCollectors to have a similar period. From the cumulative probability distribution function derived by μ_i and σ_i, pCollector filter finds a period range that satisfies a certain hit rate, such as 90% to 95% (① in Fig. 10). The requests that have longer intervals than the pCollector's period will hit, so this task can stochastically derive the period range using μ_i and


vStatistics request from VNs
pStatistics reply by tiny pCollector
pStatistics reply by aggregated pCollector
time difference between vStatistics request and pStatistics reply
time
pCollector period
Current time
time
starting delay
VN2
VN1
VN2
VN1
pCollector period
VN2
VN1
VN2
VN1
Current time
starting delay

(a) Low vStatistics accuracy (tiny pCollector).

(b) Enhanced vStatistics accuracy with starting delay for tiny pCollectors.

(c) Low vStatistics accuracy (aggregated pCollector).

(d) Enhanced vStatistics accuracy with starting delay for aggregated pCollectors.

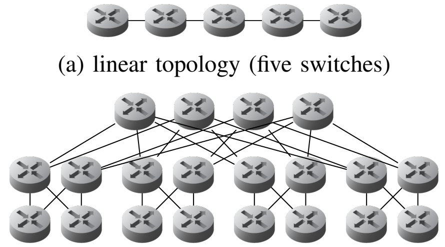
Fig. 11: Starting delay for tiny and aggregated pCollectors.

σ_i. Then, for every possible period value within the range, pCollector filter counts the number of tiny pCollectors that have the period for the value (②), and the period value with the largest number of tiny pCollectors is selected (③). Once a period is selected, pCollector filter calculates the ratio of the number of tiny pCollectors that follow a similar period to the number of existing pfs in the switch (④). If the ratio is low, an aggregated pCollector consumes more control traffic than the tiny pCollectors. So, only when the ratio is high, for instance, 70%[3], (⑤), pCollector tuner merges existing tiny pCollectors into an aggregated pCollector.

2) pCollector tuner: The role of pCollector tuner is to give additional delay to the first execution of each pCollector in order to improve the accuracy of vStatistics. In Fig. 11a, a time difference exists between the time the vStatistics requests arrive and the time pStatistics are gathered through pCollector. This time difference depends on the time when the pCollector first runs. If the pCollector is executed slightly before the vStatistics request, the time difference will become small as in Fig. 11b, which means that the cached pStatistics are up-to-date. As the time difference becomes bigger, it hurts the accuracy of vStatistics. Therefore, V-Sight introduces 'starting delay' to add the delay to the first execution of the pCollectors.

For tiny pCollectors, the starting delay should be set in order to execute the tiny pCollector right before the vStatistics requests (coming after interval window). Also, the starting delay should not be too large to avoid the pCollector to be executed after the vStatistics request as Fig. 11a. Empirically, we set the starting delay at 95% of the pCollector period (⑥-1 in Fig. 10).

On the other hand, for aggregated pCollectors, the way of setting the starting delay for tiny pCollectors rather leads to poor accuracy. It is because the multiple requests that are handled by an aggregated pCollector exist at different times in terms of the pCollector period. Figure 11c illustrates an example with two vStatistics requests from different VNs (VN2 followed by VN1). If the starting delay is set to 95% of the aggregated pCollector, the execution time of the aggregated pCollector can be after VN2 and before VN1. As Fig. 11c shows, VN2 suffers a long delay because the aggregated pCollector executes right after VN2's request.



(a) linear topology (five switches)

(b) fat-tree topology (4-ary)

Fig. 12: Experiment topologies.

Therefore, pCollector tuner sets the starting delay for the aggregated pCollector as follows. First, pCollector tuner checks request interval estimation (§III-C2) which stores the vStatistics request times for each VN (⑥-2 in Fig. 10). Then, the starting delay is set to be right before the first vStatistics request among the VN requests that the aggregated pCollector merged, which is the VN2's request in Fig. 11d (⑥-3). In this way, the sum of time differences from the time the aggregated pCollector executes to the time each vStatistics request arrives is minimized. Finally, pCollector tuner executes the pCollector periodically with the starting delay (⑦).

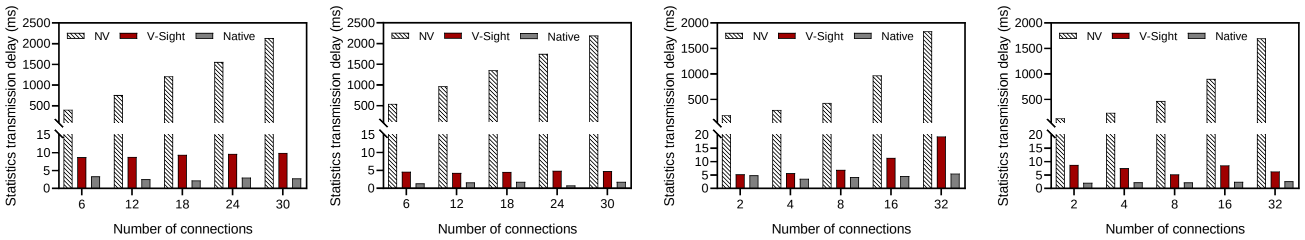
IV. Evaluation

In this section, we show the evaluation results of V-Sight. V-Sight is implemented on OVX v0.1 as independent modules (1.8K LoCs). We measure transmission delay, control channel consumption, and accuracy overheads that are explained in details below. Each experiment is repeated to gain more than 40 measured results.

A. Test Setup

We use three physical servers with Intel Xeon E5-2600 and 64G memory. Each server runs Mininet [21], OVX with V-Sight implementation, and ONOS as VN controllers, respectively. Mininet emulates PN based on Open vSwitch, and we emulate two kinds of topologies (Fig. 12): 1) linear topology consisting of five switches and 2) 4-ary fat-tree topology to evaluate the effects for datacenters. We create three and one VNs for fat-tree and linear topologies, respectively. Each VN is managed by an ONOS controller. ONOS monitors all the flow entries and ports of each switch at 5 s interval (default settings). We generate TCP connections through the iperf3 [22], and stress V-Sight by varying the number of TCP

[3] In our evaluation, we run many different ratio values and find that the improvement comes from 70%.



(a) linear (flow entry).

(b) linear (port).

(c) fat-tree (flow entry).

(d) fat-tree (port).

Fig. 13: Average statistics transmission delay (ms).

connections in PN (e.g., 6 to 30 for linear and 2 to 32 for fat-tree topologies).

We evaluate V-Sight performance for the following metrics.

- **Transmission delay**: Average interval between vStatistics request and reply messages from/to VN controllers.
- **Control channel consumption**: Average bytes per second of control channel traffic to get pf statistics between the NH and the physical switches.
- **Accuracy overheads**: Time difference between vStatistics request time and pStatistics collection time of pCollectors – Average value with 95% confidence interval.

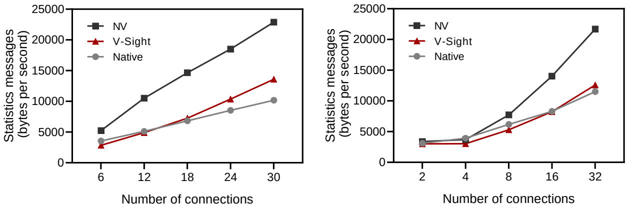
The above metrics are measured in the following cases:

- **NV**: the basis of experiments with OVX similar to the implementation in §II-C2.
- **V-Sight**: OVX with the full implementation of V-Sight.
- **Native**: Non-virtualized SDN in which physical switches are directly connected to ONOS without NH.

B. Transmission Delay

1) V-Sight improvement: Figure 13 shows that, in NV, transmission delay increases significantly in proportion to the number of TCP connections (even over 2 s). However, V-Sight disaggregates pStatistics transmission routines from vStatistics virtualization, thereby reducing this delay. In linear topology, V-Sight consumes 9.35 ms and 4.68 ms, on average, for flow entry and port statistics transmission, respectively (Fig. 13a and Fig. 13b). The delays in V-Sight improve 46 times (flow entry statistics, six connections) to 454 times (port statistics, 30 connections) compared to those in NV. For fat-tree topology, V-Sight takes 9.75 ms and 7.29 ms of transmission delay for flow entry and port, respectively (Fig. 13c and Fig 13d). V-Sight's delay improves 14 times (port statistics, two connections) to 269 times (port statistics, 32 connections).

In detail, the transmission delay in NV increases in proportion to the number of TCP connections, since the number of pStatistics needed for vStatistics increases as the connection numbers increases. Then, vStatistics are returned to the VN controller only after the corresponding pStatistics are collected. In contrast, V-Sight disaggregates pStatistics transmission routines from vStatistics virtualization, thereby reducing this delay.



(a) linear.

(b) fat-tree.

Fig. 14: Control channel traffic usage (bytes/second).

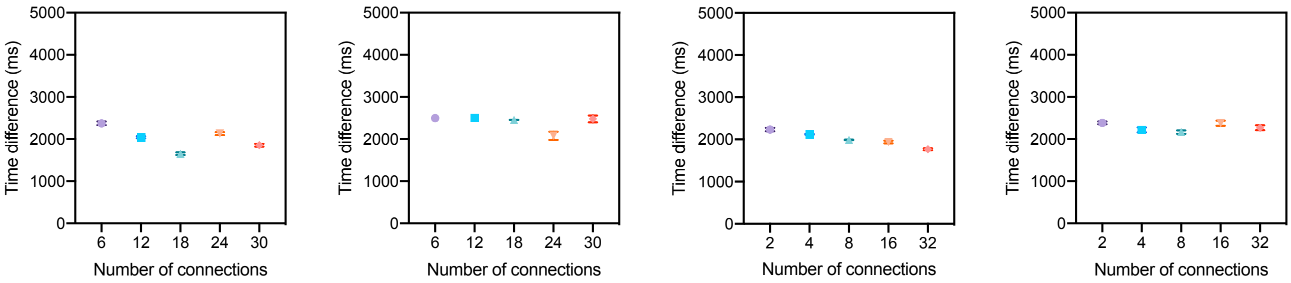
2) Virtualization overheads: We compare the transmission delay between V-Sight and Native to see the virtualization overheads. In linear topology, Native takes 2.8 ms and 1.5 ms for flow entry and port statistics transmission delay, respectively (Fig. 13a and Fig. 13b). The delays in V-Sight are 3.4 times higher, on average, than those of Native. Also, for the fat-tree topology, Native shows 4.6 ms and 2.37 ms delays for flow entry and port statistics transmission (Fig. 13c and Fig 13d), respectively. The results of V-Sight are 1.09 times (flow statistics, two connections) to 6.69 times (port statistics, two connections) higher than Native.

Although the delays of V-Sight are higher than those of Native, note that all the values are lower than 20 ms. The default monitoring intervals of ONOS, Floodlight, and OpenDayLight are 5 s, 10 s, and 15 s, respectively, so we believe that the transmission delay of V-Sight, which is 19.36 ms at maximum, is acceptable.

C. Control Channel Consumption

1) V-Sight improvement: Figure 14 shows control channel consumption for both topologies. The consumption increases in proportion to the number of connections because the monitoring of pfs increases with the number of connections. In linear topology (Fig. 14a), V-Sight improves the control channel consumption about 1.9 times, on average. In fat-tree topology (Fig. 14b), the average consumption of V-Sight is 1.44 times less than NV. This improvement is due to the benefit of aggregated pCollector that merges the multiple packet headers (§III-D).

2) Virtualization overheads: Comparing V-Sight with Native, V-Sight consumes 107% and 93% of control channel traffic in linear and fat-tree topologies, respectively, which means that the consumption of V-Sight is quite comparable



(a) linear (flow entry).

(b) linear (port).

(c) fat-tree (flow entry).

(d) fat-tree (port).

Fig. 15: Time difference between the vStatistics and pStatistics (ms).

to that of Native. Furthermore, in fat-tree topology with few network connections, V-Sight is even better than Native. The reason is that V-Sight only monitors switches that have the pStatistics needed for vStatistics. Fat-tree topology has 20 switches (Fig. 12b), and multiple paths between every host pair are available. In this topology, when the number of connections is small, not all switches are used for packet forwarding and so not for vStatistics.

In Native, however, the VN controller monitors all the switches in PN. So, request and reply messages are generated for all switches regularly. In V-Sight, transmission disaggregation controls the creation of pCollectors toward pfs required. Thus, pCollectors are created only for the required pfs and, thus, statistics request/reply messages are not created for switches not used.

D. Accuracy Overheads

V-Sight successfully improves transmission delay and control channel consumption. The improvements come with the accuracy overhead inevitably because disaggregated transmission and pCollector aggregation incur time difference between when vStatistics requests come and when pStatistics become available by pCollectors. Figure 15 shows the time differences for the number of network connections in linear and fat-tree topologies, plotted with average and 95% confidence interval. The results indicate that the average time differences in all cases of network connections are equal to or less than 2,500 ms in both topologies.

This means that V-Sight replies to the VN controller within 2.5 s which is the half of the request interval of VN controllers. So, the VN controller, at least, does not receive statistics from the previous statistics request, and therefore the accuracy overhead does not jeopardize the accuracy of vStatistics itself.

V. Related Work

A. Monitoring in non-virtualized SDN

Various studies for reducing monitoring overheads in SDN have been proposed. We mention the notable ones due to space limitation. FlowSense and PayLess [23], [24] introduced a technique for reducing the number of statistics transmissions using the control for flow removal of OpenFlow. MicroTE [25] implemented monitoring and traffic engineering functions on a separate machine from SDN controllers, so the bottleneck is removed from the controller itself. OpenSketch [17] introduced a hash-based switch measurement architecture to reduce the number of monitoring trials with a multistage hash-based switch measurement architecture. Zhang [26] introduced a prediction-based technique that balances the monitoring aggregation and accuracy.

The summarized studies all investigated non-virtualized SDN. Also, the ways of reducing overheads and retaining statistics accuracy are not quite suitable with SDN-NV.

B. Monitoring in SDN-NV

FlowVisor [1] introduced the first idea of NV in SDN, and FlowN [2] provided more scalable NH structure based on containers. OVX [3] defined the address virtualization schemes, and CoVisor [27] designed a policy composition framework for a network to be managed by heterogeneous SDN controllers. OnVisor [9] developed OVX functionalities on ONOS, enabling the deployment of NH into a physically distributed architecture.

Although monitoring is a well-investigated topic in SDN, to the best of our knowledge, there has not been any monitoring paper for SDN-NV. Without monitoring, operation and optimization for VN management are severely hampered.

VI. Conclusion

We present V-Sight, the first comprehensive network monitoring framework in SDN-NV. V-Sight makes it possible to isolate statistics between VNs, reduce statistics transmission delays, and scale the control channel consumption. To this end, V-Sight introduces statistics virtualization, transmission disaggregation, and pCollector aggregation. We fully implement V-Sight and evaluate its key performance characteristics in terms of transmission delay and control channel consumption. Furthermore, we evaluate the accuracy overhead to validate that V-Sight does not compromise the accuracy of network monitoring. The results show that V-Sight attains a level comparable to network monitoring in non-virtualized SDN.

As future research, we plan to extend V-Sight to cover P4's in-band telemetry. Also, based on the isolated and timely statistics from V-Sight, we will research the reliability and performance of traffic engineering.

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