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Benchmarking Methodology for SDN Controller Performance
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Abstract

This document defines methodologies for benchmarking control plane performance of SDN controllers. SDN controller is a core component in software-defined networking architecture that controls the network behavior. SDN controllers have been implemented with many varying designs in order to achieve their intended network functionality. Hence, the authors have taken the approach of considering an SDN controller as a black box, defining the methodology in a manner that is agnostic to protocols and network services supported by controllers. The intent of this document is to provide a method to measure the performance of all controller implementations.

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1. Introduction

This document provides generic methodologies for benchmarking SDN controller performance. An SDN controller may support many northbound and southbound protocols, implement a wide range of applications, and work solely, or as a group to achieve the desired functionality. This document considers an SDN controller as a black box, regardless of design and implementation. The tests defined in the document can be used to benchmark SDN controller for performance, scalability, reliability and security independent of northbound and southbound protocols. Terminology related to benchmarking SDN controllers is described in the companion terminology document [[I-D.sdn-controller-benchmark-term](#)]. These tests can be performed on an SDN controller running as a virtual machine (VM) instance or on a bare metal server. This document is intended for those who want to measure the SDN controller performance as well as compare various SDN controllers performance.

Conventions used in this document

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in [BCP 14](#) [[RFC2119](#)] [[RFC8174](#)] when, and only when, they appear in all capitals, as shown here.

2. Scope

This document defines methodology to measure the networking metrics of SDN controllers. For the purpose of this memo, the SDN controller is a function that manages and controls Network Devices. Any SDN controller without a control capability is out of scope for this memo. The tests defined in this document enable benchmarking of SDN Controllers in two ways; as a standalone controller and as a cluster of homogeneous controllers. These tests are recommended for execution in lab environments rather than in live network deployments. Performance benchmarking of a federation of controllers, set of SDN controllers managing different domains, is beyond the scope of this document.

3. Test Setup

The tests defined in this document enable measurement of an SDN controller's performance in standalone mode and cluster mode. This section defines common reference topologies that are later referred to in individual tests.

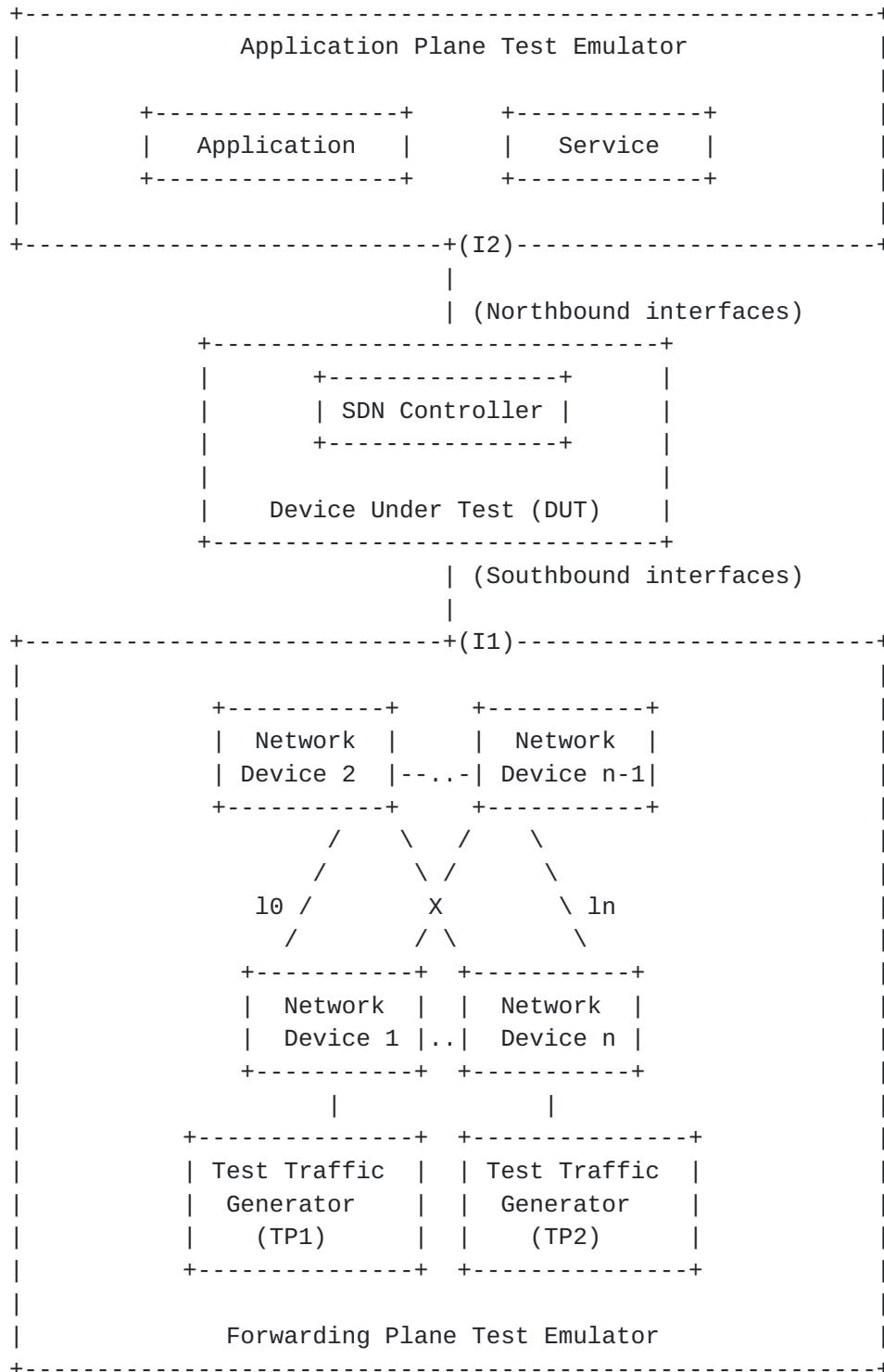
3.1. Test setup - Controller working in Standalone Mode

Figure 1

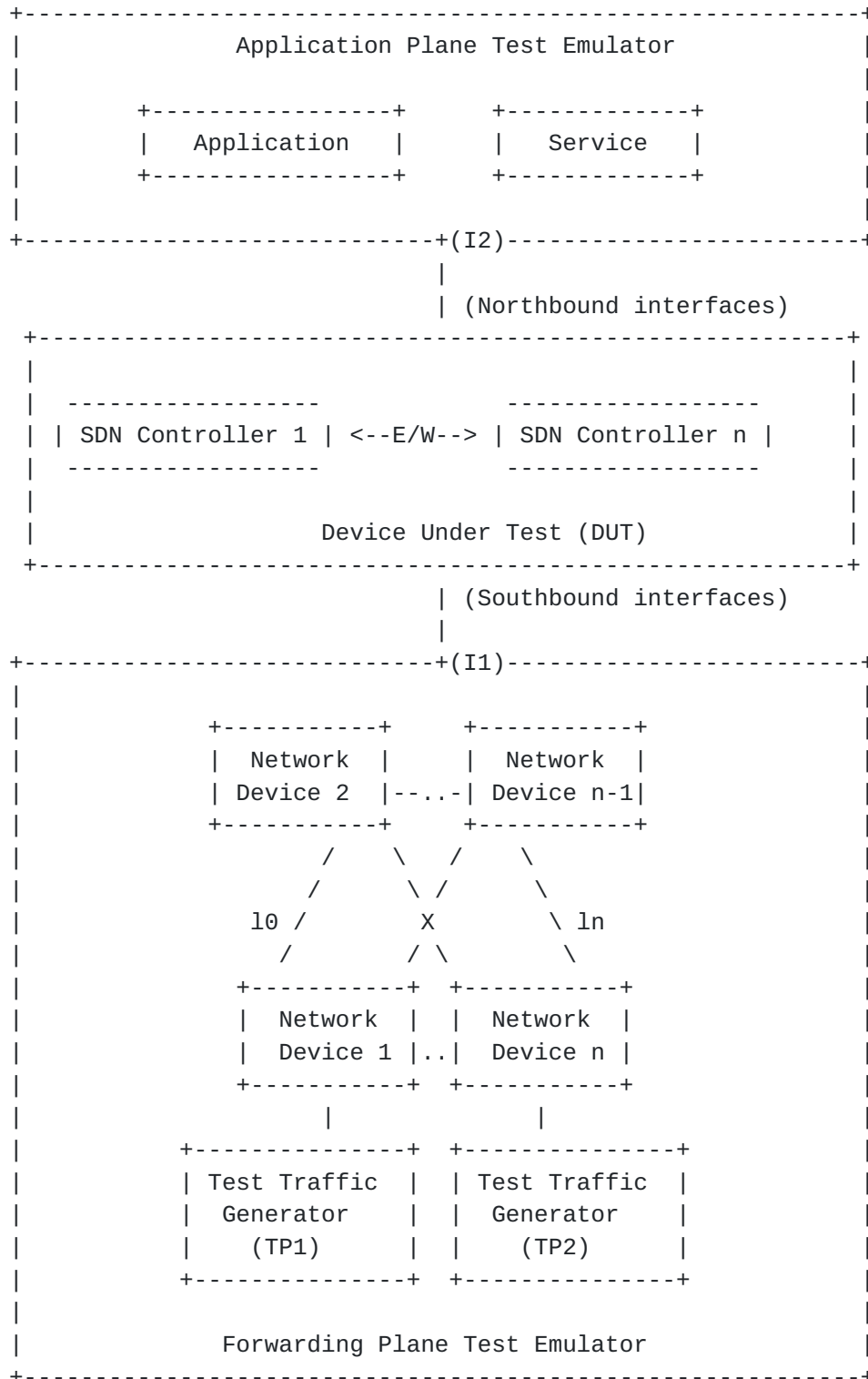
3.2. Test setup - Controller working in Cluster Mode

Figure 2

4. Test Considerations

4.1. Network Topology

The test cases SHOULD use Leaf-Spine topology with at least 2 Network Devices in the topology for benchmarking. The test traffic generators TP1 and TP2 SHOULD be connected to the leaf Network Device 1 and the leaf Network Device n. To achieve a complete performance characterization of the SDN controller, it is recommended that the controller be benchmarked for many network topologies and a varying number of Network Devices. Further, care should be taken to make sure that a loop prevention mechanism is enabled either in the SDN controller, or in the network when the topology contains redundant network paths.

4.2. Test Traffic

Test traffic is used to notify the controller about the asynchronous arrival of new flows. The test cases SHOULD use frame sizes of 128, 512 and 1508 bytes for benchmarking. Tests using jumbo frames are optional.

4.3. Test Emulator Requirements

The Test Emulator SHOULD time stamp the transmitted and received control messages to/from the controller on the established network connections. The test cases use these values to compute the controller processing time.

4.4. Connection Setup

There may be controller implementations that support unencrypted and encrypted network connections with Network Devices. Further, the controller may have backward compatibility with Network Devices running older versions of southbound protocols. It may be useful to measure the controller performance with one or more applicable connection setup methods defined below. For cases with encrypted communications between the controller and the switch, key management and key exchange MUST take place before any performance or benchmark measurements.

1. Unencrypted connection with Network Devices, running same protocol version.
2. Unencrypted connection with Network Devices, running different protocol versions.

Example:

- a. Controller running current protocol version and switch running older protocol version
 - b. Controller running older protocol version and switch running current protocol version
3. Encrypted connection with Network Devices, running same protocol version
4. Encrypted connection with Network Devices, running different protocol versions.

Example:

- a. Controller running current protocol version and switch running older protocol version
 - b. Controller running older protocol version and switch running current protocol version

4.5. Measurement Point Specification and Recommendation

The measurement accuracy depends on several factors including the point of observation where the indications are captured. For example, the notification can be observed at the controller or test emulator. The test operator **SHOULD** make the observations/measurements at the interfaces of test emulator unless it is explicitly mentioned otherwise in the individual test. In any case, the locations of measurement points **MUST** be reported.

4.6. Connectivity Recommendation

The SDN controller in the test setup **SHOULD** be connected directly with the forwarding and the management plane test emulators to avoid any delays or failure introduced by the intermediate devices during benchmarking tests. When the controller is implemented as a virtual machine, details of the physical and logical connectivity **MUST** be reported.

4.7. Test Repeatability

To increase the confidence in measured result, it is recommended that each test **RECOMMENDED** be repeated a minimum of 10 times.

4.8. Test Reporting

Each test has a reporting format that contains some global and identical reporting components, and some individual components that are specific to individual tests. The following test configuration parameters and controller settings parameters **MUST** be reflected in the test report.

Test Configuration Parameters:

1. Controller name and version
2. Northbound protocols and versions
3. Southbound protocols and versions
4. Controller redundancy mode (Standalone or Cluster Mode)
5. Connection setup (Unencrypted or Encrypted)
6. Network Device Type (Physical or Virtual or Emulated)
7. Number of Nodes
8. Number of Links
9. Dataplane Test Traffic Type
10. Controller System Configuration (e.g., Physical or Virtual Machine, CPU, Memory, Caches, Operating System, Interface Speed, Storage)
11. Reference Test Setup (e.g., [Section 3.1](#) etc.,)

Controller Settings Parameters:

1. Topology re-discovery timeout
2. Controller redundancy mode (e.g., active-standby etc.,)
3. Controller state persistence enabled/disabled

To ensure the repeatability of test, the following capabilities of test emulator SHOULD be reported

1. Maximum number of Network Devices that the forwarding plane emulates
2. Control message processing time (e.g., Topology Discovery Messages)

One way to determine the above two values are to simulate the required control sessions and messages from the control plane.

[5. Benchmarking Tests](#)

[5.1. Performance](#)

[5.1.1. Network Topology Discovery Time](#)

Objective:

The time taken by controller(s) to determine the complete network topology, defined as the interval starting with the first discovery message from the controller(s) at its Southbound interface, ending with all features of the static topology determined.

Reference Test Setup:

The test SHOULD use one of the test setups described in [section 3.1](#) or [section 3.2](#) of this document.

Prerequisite:

1. The controller MUST support network discovery.
2. Tester should be able to retrieve the discovered topology information either through the controller's management interface, or northbound interface to determine if the discovery was successful and complete.
3. Ensure that the controller's topology re-discovery timeout has been set to the maximum value to avoid initiation of re-discovery process in the middle of the test.

Procedure:

1. Ensure that the controller is operational, its network applications, northbound and southbound interfaces are up and running.
2. Establish the network connections between controller and Network Devices.
3. Record the time for the first discovery message (T_{m1}) received from the controller at forwarding plane test emulator interface $I1$.
4. Query the controller every t seconds (RECOMMENDED value for t is 3) to obtain the discovered network topology information through the northbound interface or the management interface and compare it with the deployed network topology information.
5. Stop the trial when the discovered topology information matches the deployed network topology, or when the discovered topology information return the same details for 3 consecutive queries.
6. Record the time last discovery message (T_{mn}) sent to controller from the forwarding plane test emulator interface ($I1$) when the trial completed successfully. (e.g., the topology matches).

Measurement:

Topology Discovery Time $Tr1 = T_{mn} - T_{m1}$.

$$\text{Average Topology Discovery Time (TDm)} = \frac{Tr1 + Tr2 + Tr3 \dots Trn}{\text{Total Trials}}$$

$$\text{Topology Discovery Time Variance (TDv)} = \frac{\text{SUM}[\text{SQUAREOF}(Tri - \text{TDm})]}{\text{Total Trials} - 1}$$

Reporting Format:

The Topology Discovery Time results MUST be reported in the format of a table, with a row for each successful iteration. The last row of the table indicates the Topology Discovery Time variance and the previous row indicates the average Topology Discovery Time.

If this test is repeated with varying number of nodes over the same topology, the results SHOULD be reported in the form of a graph. The X coordinate SHOULD be the Number of nodes (N), the Y coordinate SHOULD be the average Topology Discovery Time.

5.1.2. Asynchronous Message Processing Time**Objective:**

The time taken by controller(s) to process an asynchronous message, defined as the interval starting with an asynchronous message from a network device after the discovery of all the devices by the controller(s), ending with a response message from the controller(s) at its Southbound interface.

Reference Test Setup:

This test SHOULD use one of the test setup described in [section 3.1](#) or [section 3.2](#) of this document.

Prerequisite:

1. The controller MUST have successfully completed the network topology discovery for the connected Network Devices.

Procedure:

1. Generate asynchronous messages from every connected Network Device, to the SDN controller, one at a time in series from the forwarding plane test emulator for the trial duration.
2. Record every request transmit time (T1) and the corresponding response received time (R1) at the forwarding plane test emulator interface (I1) for every successful message exchange.

Measurement:

$$\text{Asynchronous Message Processing Time } Tr1 = \frac{\text{SUM}\{R_i\} - \text{SUM}\{T_i\}}{Nrx}$$

Where N_{rx} is the total number of successful messages exchanged

$$\text{Average Asynchronous Message Processing Time} = \frac{Tr_1 + Tr_2 + Tr_3 \dots Tr_n}{\text{Total Trials}}$$

Asynchronous Message Processing Time Variance (TAMv) =

$$\frac{\text{SUM}[\text{SQUAREOF}(Tr_i - \text{TAMm})]}{\text{Total Trials} - 1}$$

Where TAMm is the Average Asynchronous Message Processing Time.

Reporting Format:

The Asynchronous Message Processing Time results MUST be reported in the format of a table with a row for each iteration. The last row of the table indicates the Asynchronous Message Processing Time variance and the previous row indicates the average Asynchronous Message Processing Time.

The report SHOULD capture the following information in addition to the configuration parameters captured in [section 4.8](#).

- Successful messages exchanged (N_{rx})
- Percentage of unsuccessful messages exchanged, computed using the formula $(1 - N_{rx}/N_{tx}) * 100$, Where N_{tx} is the total number of messages transmitted to the controller.

If this test is repeated with varying number of nodes with same topology, the results SHOULD be reported in the form of a graph. The X coordinate SHOULD be the Number of nodes (N), the Y coordinate SHOULD be the average Asynchronous Message Processing Time.

5.1.3. Asynchronous Message Processing Rate

Objective:

Measure the number of responses to asynchronous messages (such as new flow arrival notification message, link down, etc.) for which

the controller(s) performed processing and replied with a valid and productive (non-trivial) response message

This test will measure two benchmarks on Asynchronous Message Processing Rate using a single procedure. The two benchmarks are (see section 2.3.1.3 of [[I-D.sdn-controller-benchmark-term](#)]):

1. Loss-free Asynchronous Message Processing Rate
2. Maximum Asynchronous Message Processing Rate

Here two benchmarks are determined through a series of trials where the number of messages are sent to the controller(s), and the responses from the controller(s) are counted over the trial duration. The message response rate and the message loss ratio are calculated for each trial.

Reference Test Setup:

The test SHOULD use one of the test setups described in [section 3.1](#) or [section 3.2](#) of this document.

Prerequisite:

1. The controller(s) MUST have successfully completed the network topology discovery for the connected Network Devices.
2. Choose and record the Trial Duration (T_d), the sending rate step-size (STEP), the tolerance on equality for two consecutive trials (P%), and the maximum possible message sending rate (N_{tx1}/T_d).

Procedure:

1. Generate asynchronous messages continuously at the maximum possible rate on the established connections from all the emulated/simulated Network Devices for the given trial Duration (T_d).
2. Record the total number of responses received from the controller (N_{rx1}) as well as the number of messages sent (N_{tx1}) to the controller within the trial duration (T_d).
3. Calculate the Asynchronous Message Processing Rate ($Tr1$) and the Message Loss Ratio ($Lr1$). Ensure that the controller(s) have returned to normal operation.
4. Repeat the trial by reducing the asynchronous message sending rate used in last trial by the STEP size.
5. Continue repeating the trials and reducing the sending rate until both the maximum value of N_{rxn} (number of responses received from

the controller) and the N_{rxn} corresponding to zero loss ratio have been found.

6. The trials corresponding to the benchmark levels MUST be repeated using the same asynchronous message rates until the responses received from the controller are equal ($\pm P\%$) for two consecutive trials.
7. Record the number of responses received from the controller (N_{rxn}) as well as the number of messages sent (N_{txn}) to the controller in the last trial.

Measurement:

$$\text{Asynchronous Message Processing Rate } Trn = \frac{N_{rxn}}{T_d}$$

Maximum Asynchronous Message Processing Rate = $\text{MAX}(Trn)$ for all n

$$\text{Asynchronous Message Loss Ratio } Lrn = 1 - \frac{N_{rxn}}{N_{txn}}$$

Loss-free Asynchronous Message Processing Rate = $\text{MAX}(Trn)$ given $Lrn=0$

Reporting Format:

The Asynchronous Message Processing Rate results MUST be reported in the format of a table with a row for each trial.

The table should report the following information in addition to the configuration parameters captured in [section 4.8](#), with columns:

- Offered rate (N_{txn}/T_d)
- Asynchronous Message Processing Rate (Trn)
- Loss Ratio (Lr)
- Benchmark at this iteration (blank for none, Maximum, Loss-Free)

The results MAY be presented in the form of a graph. The X axis SHOULD be the Offered rate, and dual Y axes would represent Asynchronous Message Processing Rate and Loss Ratio, respectively.

If this test is repeated with varying number of nodes over same topology, the results SHOULD be reported in the form of a graph. The

X axis SHOULD be the Number of nodes (N), the Y axis SHOULD be the Asynchronous Message Processing Rate. Both the Maximum and the Loss-Free Rates should be plotted for each N.

5.1.4. Reactive Path Provisioning Time

Objective:

The time taken by the controller to setup a path reactively between source and destination node, defined as the interval starting with the first flow provisioning request message received by the controller(s) at its Southbound interface, ending with the last flow provisioning response message sent from the controller(s) at its Southbound interface.

Reference Test Setup:

The test SHOULD use one of the test setups described in [section 3.1](#) or [section 3.2](#) of this document. The number of Network Devices in the path is a parameter of the test that may be varied from 2 to maximum discovery size in repetitions of this test.

Prerequisite:

1. The controller MUST contain the network topology information for the deployed network topology.
2. The controller should have the knowledge about the location of destination endpoint for which the path has to be provisioned. This can be achieved through dynamic learning or static provisioning.
3. Ensure that the default action for 'flow miss' in Network Device is configured to 'send to controller'.
4. Ensure that each Network Device in a path requires the controller to make the forwarding decision while paving the entire path.

Procedure:

1. Send a single traffic stream from the test traffic generator TP1 to test traffic generator TP2.
2. Record the time of the first flow provisioning request message sent to the controller (Tsf1) from the Network Device at the forwarding plane test emulator interface (I1).
3. Wait for the arrival of first traffic frame at the Traffic Endpoint TP2 or the expiry of trial duration (Td).
4. Record the time of the last flow provisioning response message received from the controller (Tdf1) to the Network Device at the forwarding plane test emulator interface (I1).

Measurement:

Reactive Path Provisioning Time $Tr1 = Tdf1 - Tsf1$.

$$\text{Average Reactive Path Provisioning Time} = \frac{Tr1 + Tr2 + Tr3 \dots Trn}{\text{Total Trials}}$$

$$\text{Reactive Path Provisioning Time Variance (TRPv)} = \frac{\text{SUM}[\text{SQUAREOF}(Tri - TRPm)]}{\text{Total Trials} - 1}$$

Where TRPm is the Average Reactive Path Provisioning Time.

Reporting Format:

The Reactive Path Provisioning Time results MUST be reported in the format of a table with a row for each iteration. The last row of the table indicates the Reactive Path Provisioning Time variance and the previous row indicates the Average Reactive Path Provisioning Time.

The report should capture the following information in addition to the configuration parameters captured in [section 4.8](#).

- Number of Network Devices in the path

[5.1.5](#). Proactive Path Provisioning Time**Objective:**

The time taken by the controller to setup a path proactively between source and destination node, defined as the interval starting with the first proactive flow provisioned in the controller(s) at its Northbound interface, ending with the last flow provisioning response message sent from the controller(s) at its Southbound interface.

Reference Test Setup:

The test SHOULD use one of the test setups described in [section 3.1](#) or [section 3.2](#) of this document.

Prerequisite:

1. The controller MUST contain the network topology information for the deployed network topology.
2. The controller should have the knowledge about the location of destination endpoint for which the path has to be provisioned. This can be achieved through dynamic learning or static provisioning.
3. Ensure that the default action for flow miss in Network Device is 'drop'.

Procedure:

1. Send a single traffic stream from test traffic generator TP1 to TP2.
2. Install the flow entries to reach from test traffic generator TP1 to the test traffic generator TP2 through controller's northbound or management interface.
3. Wait for the arrival of first traffic frame at the test traffic generator TP2 or the expiry of trial duration (Td).
4. Record the time when the proactive flow is provisioned in the Controller (Tsf1) at the management plane test emulator interface I2.
5. Record the time of the last flow provisioning message received from the controller (Tdf1) at the forwarding plane test emulator interface I1.

Measurement:

Proactive Flow Provisioning Time $Tr1 = Tdf1 - Tsf1$.

$$\text{Average Proactive Path Provisioning Time} = \frac{Tr1 + Tr2 + Tr3 \dots Trn}{\text{Total Trials}}$$

$$\text{Proactive Path Provisioning Time Variance (TPPv)} = \frac{\text{SUM}[\text{SQUAREOF}(Tri - \text{TPPm})]}{\text{Total Trials} - 1}$$

Where TPPm is the Average Proactive Path Provisioning Time.

Reporting Format:

The Proactive Path Provisioning Time results MUST be reported in the format of a table with a row for each iteration. The last row of the table indicates the Proactive Path Provisioning Time variance and

the previous row indicates the Average Proactive Path Provisioning Time.

The report should capture the following information in addition to the configuration parameters captured in [section 4.8](#).

- Number of Network Devices in the path

[5.1.6](#). Reactive Path Provisioning Rate

Objective:

The maximum number of independent paths a controller can concurrently establish per second between source and destination nodes reactively, defined as the number of paths provisioned per second by the controller(s) at its Southbound interface for the flow provisioning requests received for path provisioning at its Southbound interface between the start of the test and the expiry of given trial duration.

Reference Test Setup:

The test SHOULD use one of the test setups described in [section 3.1](#) or [section 3.2](#) of this document.

Prerequisite:

1. The controller MUST contain the network topology information for the deployed network topology.
2. The controller should have the knowledge about the location of destination addresses for which the paths have to be provisioned. This can be achieved through dynamic learning or static provisioning.
3. Ensure that the default action for 'flow miss' in Network Device is configured to 'send to controller'.
4. Ensure that each Network Device in a path requires the controller to make the forwarding decision while provisioning the entire path.

Procedure:

1. Send traffic with unique source and destination addresses from test traffic generator TP1.
2. Record total number of unique traffic frames (Ndf) received at the test traffic generator TP2 within the trial duration (Td).

Measurement:

$$\text{Reactive Path Provisioning Rate Tr1} = \frac{Ndf}{Td}$$

$$\text{Average Reactive Path Provisioning Rate} = \frac{Tr1 + Tr2 + Tr3 \dots Trn}{\text{Total Trials}}$$

$$\text{Reactive Path Provisioning Rate Variance(RPPv)} = \frac{\text{SUM}[\text{SQUAREOF}(\text{Tri-RPPm})]}{\text{Total Trials} - 1}$$

Where RPPm is the Average Reactive Path Provisioning Rate.

Reporting Format:

The Reactive Path Provisioning Rate results MUST be reported in the format of a table with a row for each iteration. The last row of the table indicates the Reactive Path Provisioning Rate variance and the previous row indicates the Average Reactive Path Provisioning Rate.

The report should capture the following information in addition to the configuration parameters captured in [section 4.8](#).

- Number of Network Devices in the path
- Offered rate

[5.1.7](#). Proactive Path Provisioning Rate

Objective:

Measure the maximum number of independent paths a controller can concurrently establish per second between source and destination nodes proactively, defined as the number of paths provisioned per second by the controller(s) at its Southbound interface for the paths requested in its Northbound interface between the start of the test and the expiry of given trial duration. The measurement is based on dataplane observations of successful path activation

Reference Test Setup:

The test SHOULD use one of the test setups described in [section 3.1](#) or [section 3.2](#) of this document.

Prerequisite:

1. The controller MUST contain the network topology information for the deployed network topology.
2. The controller should have the knowledge about the location of destination addresses for which the paths have to be provisioned. This can be achieved through dynamic learning or static provisioning.
3. Ensure that the default action for flow miss in Network Device is 'drop'.

Procedure:

1. Send traffic continuously with unique source and destination addresses from test traffic generator TP1.
2. Install corresponding flow entries to reach from simulated sources at the test traffic generator TP1 to the simulated destinations at test traffic generator TP2 through controller's northbound or management interface.
3. Record total number of unique traffic frames received Ndf) at the test traffic generator TP2 within the trial duration (Td).

Measurement:

$$\text{Proactive Path Provisioning Rate Tr1} = \frac{\text{Ndf}}{\text{Td}}$$

$$\text{Average Proactive Path Provisioning Rate} = \frac{\text{Tr1} + \text{Tr2} + \text{Tr3} \dots \text{Trn}}{\text{Total Trials}}$$

$$\text{Proactive Path Provisioning Rate Variance(PPV)} = \frac{\text{SUM}[\text{SQUAREOF}(\text{Tri}-\text{PPM})]}{\text{Total Trials} - 1}$$

Where PPM is the Average Proactive Path Provisioning Rate.

Reporting Format:

The Proactive Path Provisioning Rate results MUST be reported in the format of a table with a row for each iteration. The last row of the table indicates the Proactive Path Provisioning Rate variance and the previous row indicates the Average Proactive Path Provisioning Rate.

The report should capture the following information in addition to the configuration parameters captured in [section 4.8](#).

- Number of Network Devices in the path
- Offered rate

[5.1.8](#). Network Topology Change Detection Time**Objective:**

The amount of time required for the controller to detect any changes in the network topology, defined as the interval starting with the notification message received by the controller(s) at its Southbound interface, ending with the first topology rediscovery messages sent from the controller(s) at its Southbound interface.

Reference Test Setup:

The test SHOULD use one of the test setups described in [section 3.1](#) or [section 3.2](#) of this document.

Prerequisite:

1. The controller MUST have successfully discovered the network topology information for the deployed network topology.
2. The periodic network discovery operation should be configured to twice the Trial duration (Td) value.

Procedure:

1. Trigger a topology change event by bringing down an active Network Device in the topology.

2. Record the time when the first topology change notification is sent to the controller (Tcn) at the forwarding plane test emulator interface (I1).
3. Stop the trial when the controller sends the first topology re-discovery message to the Network Device or the expiry of trial duration (Td).
4. Record the time when the first topology re-discovery message is received from the controller (Tcd) at the forwarding plane test emulator interface (I1)

Measurement:

Network Topology Change Detection Time $Tr1 = Tcd - Tcn$.

$$\text{Average Network Topology Change Detection Time} = \frac{Tr1 + Tr2 + Tr3 \dots Trn}{\text{Total Trials}}$$

Network Topology Change Detection Time Variance(NTDv) =

$$\frac{\text{SUM}[\text{SQUAREOF}(Tri - \text{NTDm})]}{\text{Total Trials} - 1}$$

Where NTDm is the Average Network Topology Change Detection Time.

Reporting Format:

The Network Topology Change Detection Time results MUST be reported in the format of a table with a row for each iteration. The last row of the table indicates the Network Topology Change Detection Time variance and the previous row indicates the average Network Topology Change Time.

5.2. Scalability

5.2.1. Control Session Capacity

Objective:

Measure the maximum number of control sessions the controller can maintain, defined as the number of sessions that the controller can accept from network devices, starting with the first control

session, ending with the last control session that the controller(s) accepts at its Southbound interface.

Reference Test Setup:

The test SHOULD use one of the test setups described in [section 3.1](#) or [section 3.2](#) of this document.

Procedure:

1. Establish control connection with controller from every Network Device emulated in the forwarding plane test emulator.
2. Stop the trial when the controller starts dropping the control connections.
3. Record the number of successful connections established with the controller (CCn) at the forwarding plane test emulator.

Measurement:

Control Sessions Capacity = CCn.

Reporting Format:

The Control Session Capacity results MUST be reported in addition to the configuration parameters captured in [section 4.8](#).

[5.2.2. Network Discovery Size](#)

Objective:

Measure the network size (number of nodes, links and hosts) that a controller can discover, defined as the size of a network that the controller(s) can discover, starting from a network topology given by the user for discovery, ending with the topology that the controller(s) could successfully discover.

Reference Test Setup:

The test SHOULD use one of the test setups described in [section 3.1](#) or [section 3.2](#) of this document.

Prerequisite:

1. The controller MUST support automatic network discovery.

2. Tester should be able to retrieve the discovered topology information either through controller's management interface or northbound interface.

Procedure:

1. Establish the network connections between controller and network nodes.
2. Query the controller every t seconds (RECOMMENDED value for t is 30) to obtain the discovered network topology information through the northbound interface or the management interface.
3. Stop the trial when the discovered network topology information remains the same as that of last two query responses.
4. Compare the obtained network topology information with the deployed network topology information.
5. If the comparison is successful, increase the number of nodes by 1 and repeat the trial.
If the comparison is unsuccessful, decrease the number of nodes by 1 and repeat the trial.
6. Continue the trial until the comparison of step 5 is successful.
7. Record the number of nodes for the last trial run (N_s) where the topology comparison was successful.

Measurement:

Network Discovery Size = N_s .

Reporting Format:

The Network Discovery Size results MUST be reported in addition to the configuration parameters captured in [section 4.8](#).

[5.2.3](#). Forwarding Table Capacity

Objective:

Measure the maximum number of flow entries a controller can manage in its Forwarding table.

Reference Test Setup:

The test SHOULD use one of the test setups described in [section 3.1](#) or [section 3.2](#) of this document.

Prerequisite:

1. The controller Forwarding table should be empty.
2. Flow Idle time MUST be set to higher or infinite value.
3. The controller MUST have successfully completed network topology discovery.
4. Tester should be able to retrieve the forwarding table information either through controller's management interface or northbound interface.

Procedure:**Reactive Flow Provisioning Mode:**

1. Send bi-directional traffic continuously with unique source and destination addresses from test traffic generators TP1 and TP2 at the asynchronous message processing rate of controller.
2. Query the controller at a regular interval (e.g., 5 seconds) for the number of learned flow entries from its northbound interface.
3. Stop the trial when the retrieved value is constant for three consecutive iterations and record the value received from the last query (Nrp).

Proactive Flow Provisioning Mode:

1. Install unique flows continuously through controller's northbound or management interface until a failure response is received from the controller.
2. Record the total number of successful responses (Nrp).

Note:

Some controller designs for proactive flow provisioning mode may require the switch to send flow setup requests in order to generate flow setup responses. In such cases, it is recommended to generate bi-directional traffic for the provisioned flows.

Measurement:**Proactive Flow Provisioning Mode:**

Max Flow Entries = Total number of flows provisioned (Nrp)

Reactive Flow Provisioning Mode:

Max Flow Entries = Total number of learned flow entries (Nrp)

Forwarding Table Capacity = Max Flow Entries.

Reporting Format:

The Forwarding Table Capacity results MUST be tabulated with the following information in addition to the configuration parameters captured in [section 4.8](#).

- Provisioning Type (Proactive/Reactive)

[5.3](#). Security

[5.3.1](#). Exception Handling

Objective:

Determine the effect of handling error packets and notifications on performance tests. The impact MUST be measured for the following performance tests

- a. Path Provisioning Rate
- b. Path Provisioning Time
- c. Network Topology Change Detection Time

Reference Test Setup:

The test SHOULD use one of the test setups described in [section 3.1](#) or [section 3.2](#) of this document.

Prerequisite:

1. This test MUST be performed after obtaining the baseline measurement results for the above performance tests.
2. Ensure that the invalid messages are not dropped by the intermediate devices connecting the controller and Network Devices.

Procedure:

1. Perform the above listed performance tests and send 1% of messages from the Asynchronous Message Processing Rate as invalid messages from the connected Network Devices emulated at the forwarding plane test emulator.
2. Perform the above listed performance tests and send 2% of messages from the Asynchronous Message Processing Rate as invalid messages from the connected Network Devices emulated at the forwarding plane test emulator.

Note:

Invalid messages can be frames with incorrect protocol fields or any form of failure notifications sent towards controller.

Measurement:

Measurement MUST be done as per the equation defined in the corresponding performance test measurement section.

Reporting Format:

The Exception Handling results MUST be reported in the format of table with a column for each of the below parameters and row for each of the listed performance tests.

- Without Exceptions
- With 1% Exceptions
- With 2% Exceptions

5.3.2. Denial of Service Handling**Objective:**

Determine the effect of handling DoS attacks on performance and scalability tests the impact MUST be measured for the following tests:

- a. Path Provisioning Rate
- b. Path Provisioning Time

c. Network Topology Change Detection Time

d. Network Discovery Size

Reference Test Setup:

The test SHOULD use one of the test setups described in [section 3.1](#) or [section 3.2](#) of this document.

Prerequisite:

This test MUST be performed after obtaining the baseline measurement results for the above tests.

Procedure:

1. Perform the listed tests and launch a DoS attack towards controller while the trial is running.

Note:

DoS attacks can be launched on one of the following interfaces.

- a. Northbound (e.g., Query for flow entries continuously on northbound interface)
- b. Management (e.g., Ping requests to controller's management interface)
- c. Southbound (e.g., TCP SYN messages on southbound interface)

Measurement:

Measurement MUST be done as per the equation defined in the corresponding test's measurement section.

Reporting Format:

The DoS Attacks Handling results MUST be reported in the format of table with a column for each of the below parameters and row for each of the listed tests.

- Without any attacks
- With attacks

The report should also specify the nature of attack and the interface.

5.4. Reliability

5.4.1. Controller Failover Time

Objective:

The time taken to switch from an active controller to the backup controller, when the controllers work in redundancy mode and the active controller fails, defined as the interval starting with the active controller bringing down, ending with the first re-discovery message received from the new controller at its Southbound interface.

Reference Test Setup:

The test SHOULD use the test setup described in [section 3.2](#) of this document.

Prerequisite:

1. Master controller election MUST be completed.
2. Nodes are connected to the controller cluster as per the Redundancy Mode (RM).
3. The controller cluster should have successfully completed the network topology discovery.
4. The Network Device MUST send all new flows to the controller when it receives from the test traffic generator.
5. Controller should have learned the location of destination (D1) at TP2.

Procedure:

1. Send uni-directional traffic continuously with incremental sequence number and source addresses from test traffic generator TP1 at the rate that the controller processes without any drops.
2. Ensure that there are no packet drops observed at TP2.
3. Bring down the active controller.
4. Stop the trial when a first frame received on TP2 after failover operation.
5. Record the time at which the last valid frame received (T1) at test traffic generator TP2 before sequence error and the first valid frame received (T2) after the sequence error at TP2

Measurement:

Controller Failover Time = (T2 - T1)

Packet Loss = Number of missing packet sequences.

Reporting Format:

The Controller Failover Time results MUST be tabulated with the following information.

- Number of cluster nodes
- Redundancy mode
- Controller Failover Time
- Packet Loss
- Cluster keep-alive interval

5.4.2. Network Re-Provisioning Time**Objective:**

The time taken to re-route the traffic by the Controller, when there is a failure in existing traffic paths, defined as the interval starting from the first failure notification message received by the controller, ending with the last flow re-provisioning message sent by the controller at its Southbound interface.

Reference Test Setup:

This test SHOULD use one of the test setup described in [section 3.1](#) or [section 3.2](#) of this document.

Prerequisite:

1. Network with the given number of nodes and redundant paths MUST be deployed.
2. Ensure that the controller MUST have knowledge about the location of test traffic generators TP1 and TP2.

3. Ensure that the controller does not pre-provision the alternate path in the emulated Network Devices at the forwarding plane test emulator.

Procedure:

1. Send bi-directional traffic continuously with unique sequence number from TP1 and TP2.
2. Bring down a link or switch in the traffic path.
3. Stop the trial after receiving first frame after network re-convergence.
4. Record the time of last received frame prior to the frame loss at TP2 (TP2-Tlfr) and the time of first frame received after the frame loss at TP2 (TP2-Tffr). There must be a gap in sequence numbers of these frames
5. Record the time of last received frame prior to the frame loss at TP1 (TP1-Tlfr) and the time of first frame received after the frame loss at TP1 (TP1-Tffr).

Measurement:

Forward Direction Path Re-Provisioning Time (FDRT)
$$= (TP2-Tffr - TP2-Tlfr)$$

Reverse Direction Path Re-Provisioning Time (RDRT)
$$= (TP1-Tffr - TP1-Tlfr)$$

Network Re-Provisioning Time = (FDRT+RDRT)/2

Forward Direction Packet Loss = Number of missing sequence frames at TP1

Reverse Direction Packet Loss = Number of missing sequence frames at TP2

Reporting Format:

The Network Re-Provisioning Time results MUST be tabulated with the following information.

- Number of nodes in the primary path
- Number of nodes in the alternate path
- Network Re-Provisioning Time

- Forward Direction Packet Loss
- Reverse Direction Packet Loss

6. References

6.1. Normative References

- [RFC2119] S. Bradner, "Key words for use in RFCs to Indicate Requirement Levels", [RFC 2119](#), March 1997.
- [RFC8174] B. Leiba, "Ambiguity of Uppercase vs Lowercase in [RFC 2119](#) Key Words", [RFC 8174](#), May 2017.
- [I-D.sdn-controller-benchmark-term] Bhuvaneshwaran.V, Anton Basil, Mark.T, Vishwas Manral, Sarah Banks, "Terminology for Benchmarking SDN Controller Performance", [draft-ietf-bmwg-sdn-controller-benchmark-term-10](#) (Work in progress), May 25, 2018

6.2. Informative References

- [OpenFlow Switch Specification] ONF, "OpenFlow Switch Specification" Version 1.4.0 (Wire Protocol 0x05), October 14, 2013.

7. IANA Considerations

This document does not have any IANA requests.

8. Security Considerations

Benchmarking tests described in this document are limited to the performance characterization of controllers in a lab environment with isolated network.

The benchmarking network topology will be an independent test setup and MUST NOT be connected to devices that may forward the test traffic into a production network, or misroute traffic to the test management network.

Further, benchmarking is performed on a "black-box" basis, relying solely on measurements observable external to the controller.

Special capabilities SHOULD NOT exist in the controller specifically for benchmarking purposes. Any implications for network security arising from the controller SHOULD be identical in the lab and in production networks.

9. Acknowledgments

The authors would like to thank the following individuals for providing their valuable comments to the earlier versions of this document: Al Morton (AT&T), Sandeep Gangadharan (HP), M. Georgescu (NAIST), Andrew McGregor (Google), Scott Bradner, Jay Karthik (Cisco), Ramakrishnan (Dell), Khasanov Boris (Huawei), Brian Castelli (Spirent)

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Appendix A Benchmarking Methodology using OpenFlow Controllers

This section gives an overview of OpenFlow protocol and provides test methodology to benchmark SDN controllers supporting OpenFlow southbound protocol. OpenFlow protocol is used as an example to illustrate the methodologies defined in this document.

[A.1. Protocol Overview](#)

OpenFlow is an open standard protocol defined by Open Networking Foundation (ONF) [OpenFlow Switch Specification], used for programming the forwarding plane of network switches or routers via a centralized controller.

[A.2. Messages Overview](#)

OpenFlow protocol supports three messages types namely controller-to-switch, asynchronous and symmetric.

Controller-to-switch messages are initiated by the controller and used to directly manage or inspect the state of the switch. These messages allow controllers to query/configure the switch (Features, Configuration messages), collect information from switch (Read-State message), send packets on specified port of switch (Packet-out message), and modify switch forwarding plane and state (Modify-State, Role-Request messages etc.).

Asynchronous messages are generated by the switch without a controller soliciting them. These messages allow switches to update controllers to denote an arrival of new flow (Packet-in), switch state change (Flow-Removed, Port-status) and error (Error).

Symmetric messages are generated in either direction without solicitation. These messages allow switches and controllers to set up connection (Hello), verify for liveness (Echo) and offer additional functionalities (Experimenter).

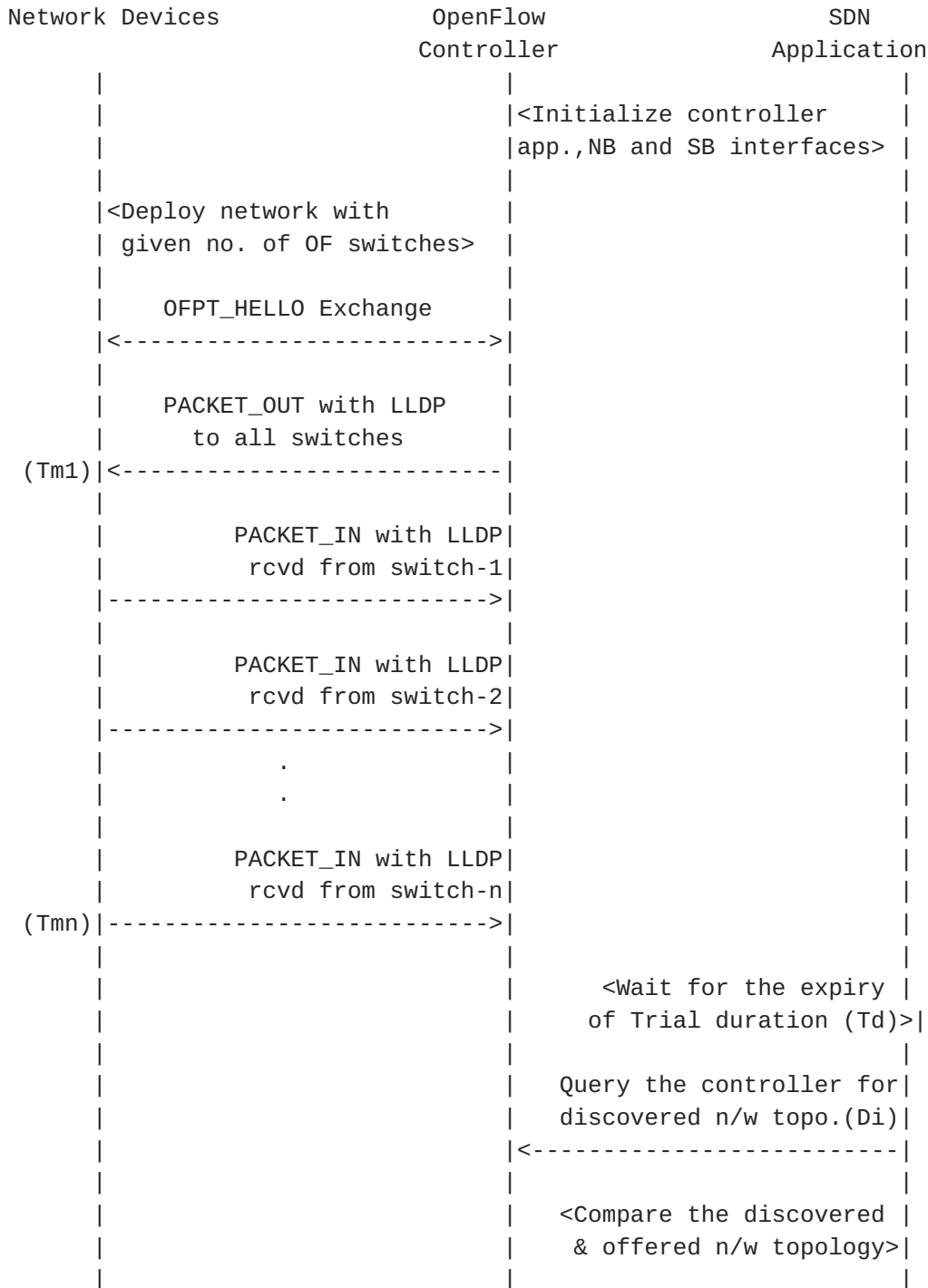
[A.3. Connection Overview](#)

OpenFlow channel is used to exchange OpenFlow message between an OpenFlow switch and an OpenFlow controller. The OpenFlow channel connection can be setup using plain TCP or TLS. By default, a switch establishes single connection with SDN controller. A switch may establish multiple parallel connections to single controller (auxiliary connection) or multiple controllers to handle controller failures and load balancing.

[A.4. Performance Benchmarking Tests](#)

[A.4.1. Network Topology Discovery Time](#)

Procedure:



Legend:

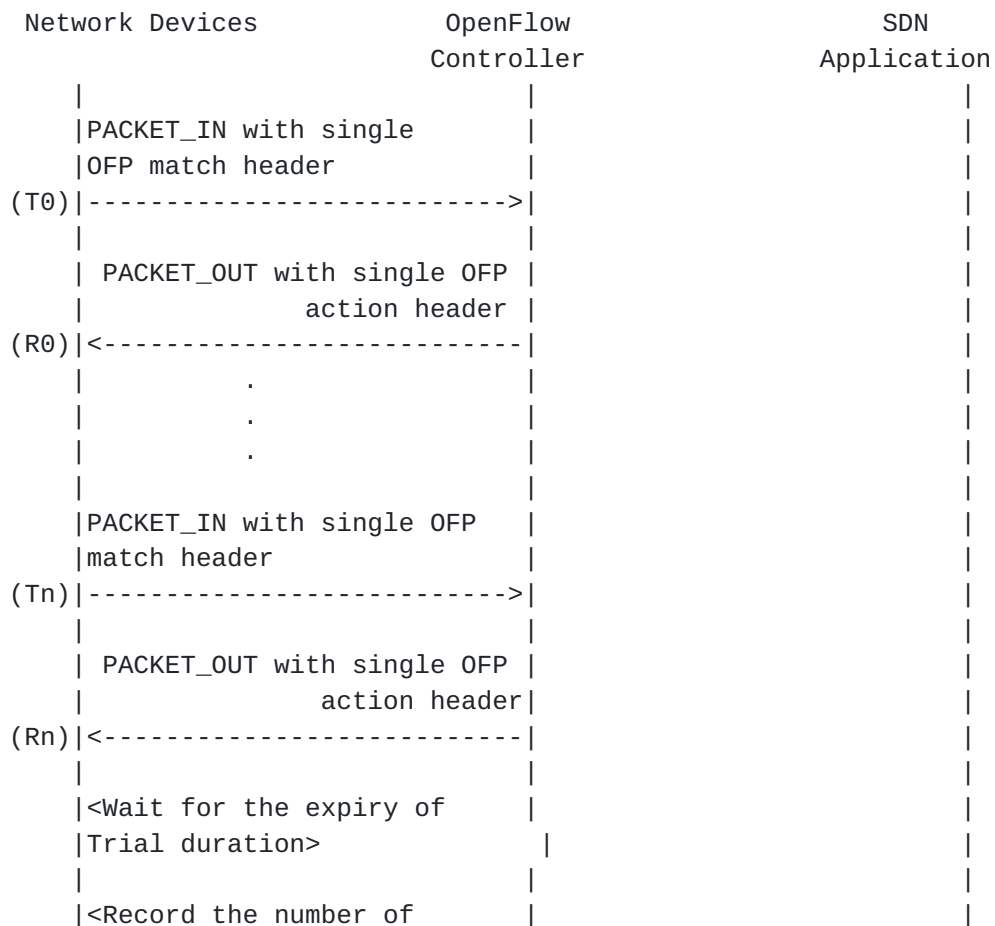
NB: Northbound
 SB: Southbound
 OF: OpenFlow
 Tm1: Time of reception of first LLDP message from controller
 Tmn: Time of last LLDP message sent to controller

Discussion:

The Network Topology Discovery Time can be obtained by calculating the time difference between the first PACKET_OUT with LLDP message received from the controller (Tm1) and the last PACKET_IN with LLDP message sent to the controller (Tmn) when the comparison is successful.

[A.4.2. Asynchronous Message Processing Time](#)

Procedure:



PACKET_INs/PACKET_OUTs		
Exchanged (Nrx)>		

Legend:

T0, T1, ..Tn are PACKET_IN messages transmit timestamps.
R0, R1, ..Rn are PACKET_OUT messages receive timestamps.
Nrx : Number of successful PACKET_IN/PACKET_OUT message exchanges

Discussion:

The Asynchronous Message Processing Time will be obtained by sum of $((R0-T0), (R1-T1) .. (Rn - Tn)) / Nrx$.

A.4.3. Asynchronous Message Processing Rate**Procedure:**

Network Devices	OpenFlow Controller	SDN Application
PACKET_IN with single OFP		
match headers		
----->		
PACKET_OUT with single		
OFP action headers		
<-----		
.		
.		
.		
PACKET_IN with single OFP		
match headers		
----->		
PACKET_OUT with single		
OFP action headers		
<-----		
<Repeat the steps until the		
expiry of Trial Duration>		

(Ntx1)	<Record the number of OFP match headers sent>	
(Nrx1)	<Record the number of OFP action headers rcvd>	

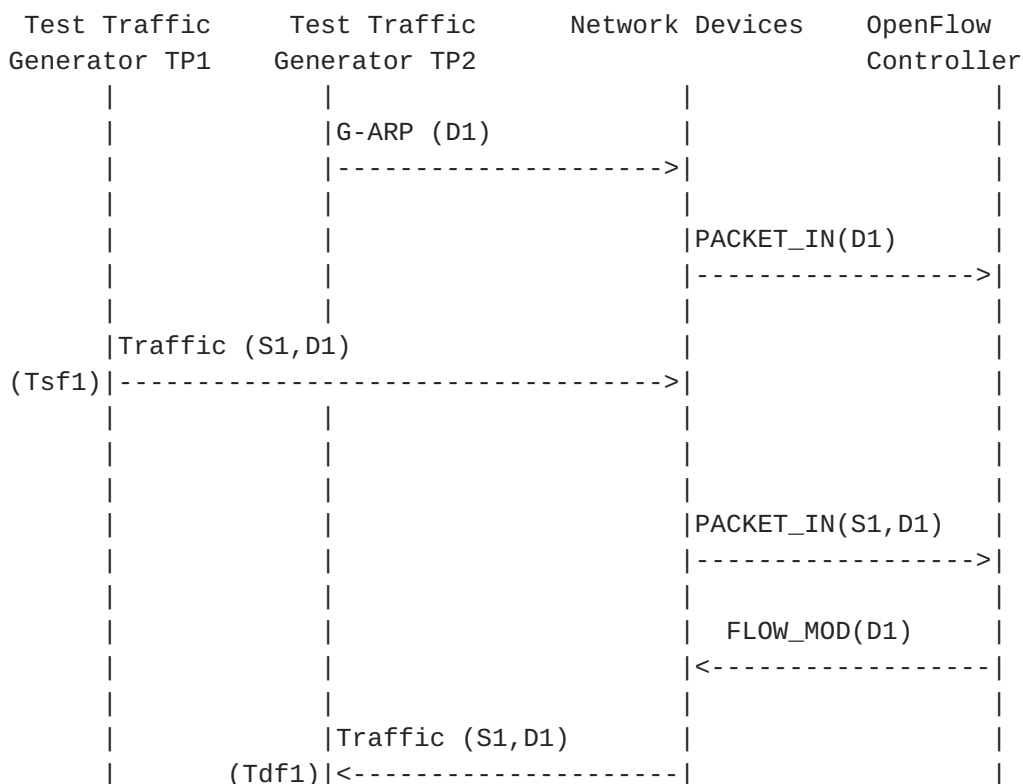
Note: The Ntx1 on initial trials should be greater than Nrx1 and repeat the trials until the Nrxn for two consecutive trials equal to (+/-P%).

Discussion:

This test will measure two benchmarks using single procedure. 1) The Maximum Asynchronous Message Processing Rate will be obtained by calculating the maximum PACKET OUTs (Nrxn) received from the controller(s) across n trials. 2) The Loss-free Asynchronous Message Processing Rate will be obtained by calculating the maximum PACKET OUTs received from controller (s) when Loss Ratio equals zero. The loss ratio is obtained by $1 - \text{Nrxn}/\text{Ntxn}$

A.4.4. Reactive Path Provisioning Time

Procedure:

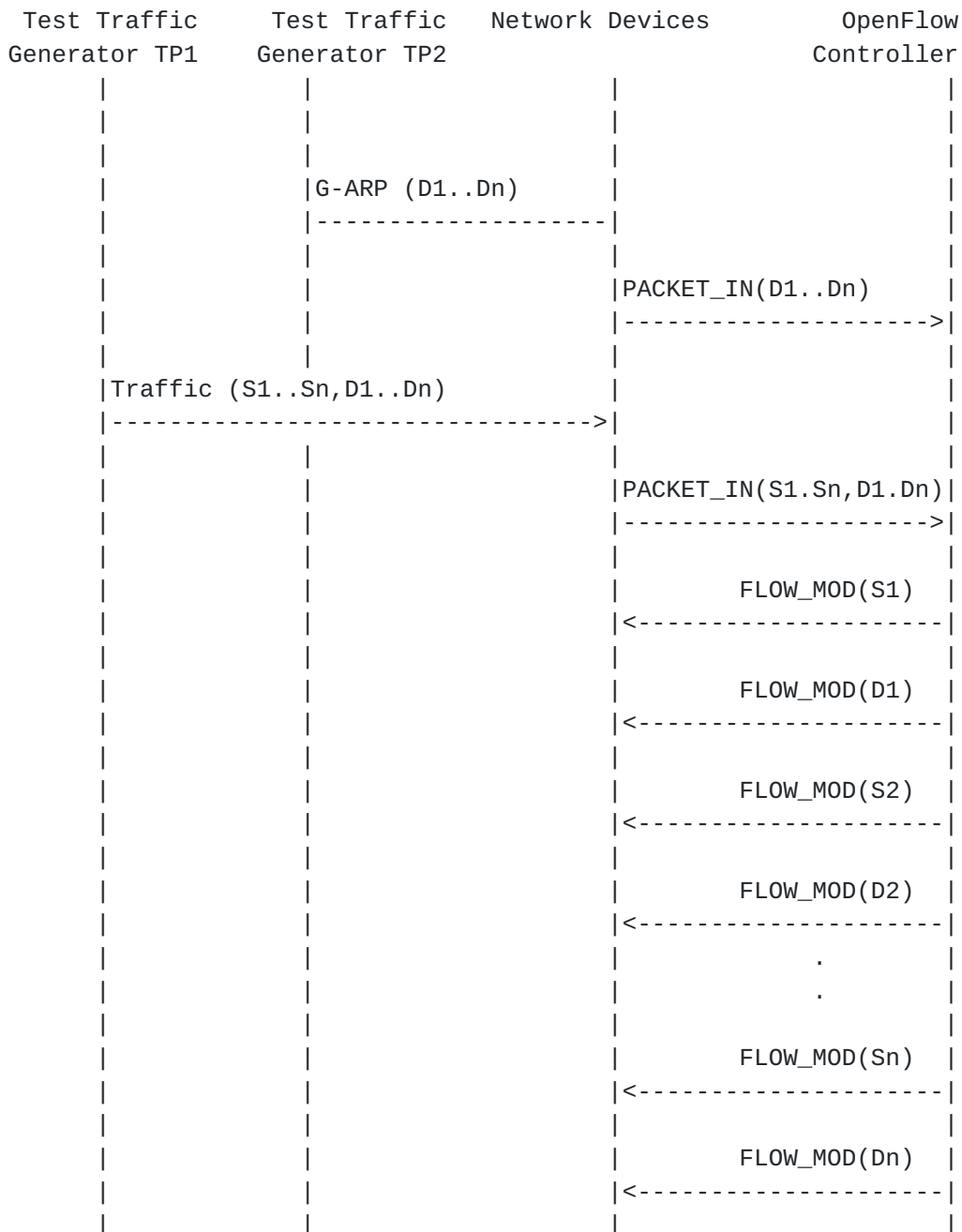


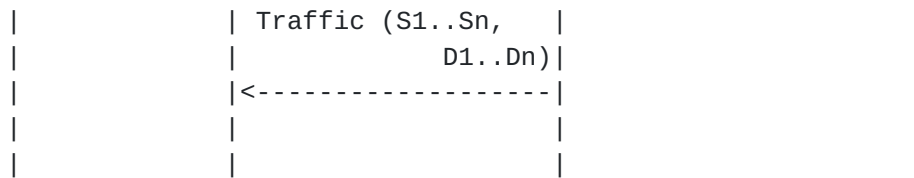
Discussion:

The Proactive Path Provisioning Time can be obtained by finding the time difference between the transmit and receive time of the traffic (Tsf1-Tdf1).

A.4.6. Reactive Path Provisioning Rate

Procedure:





Legend:

G-ARP: Gratuitous ARP

D1..Dn: Destination Endpoint 1, Destination Endpoint 2
Destination Endpoint n

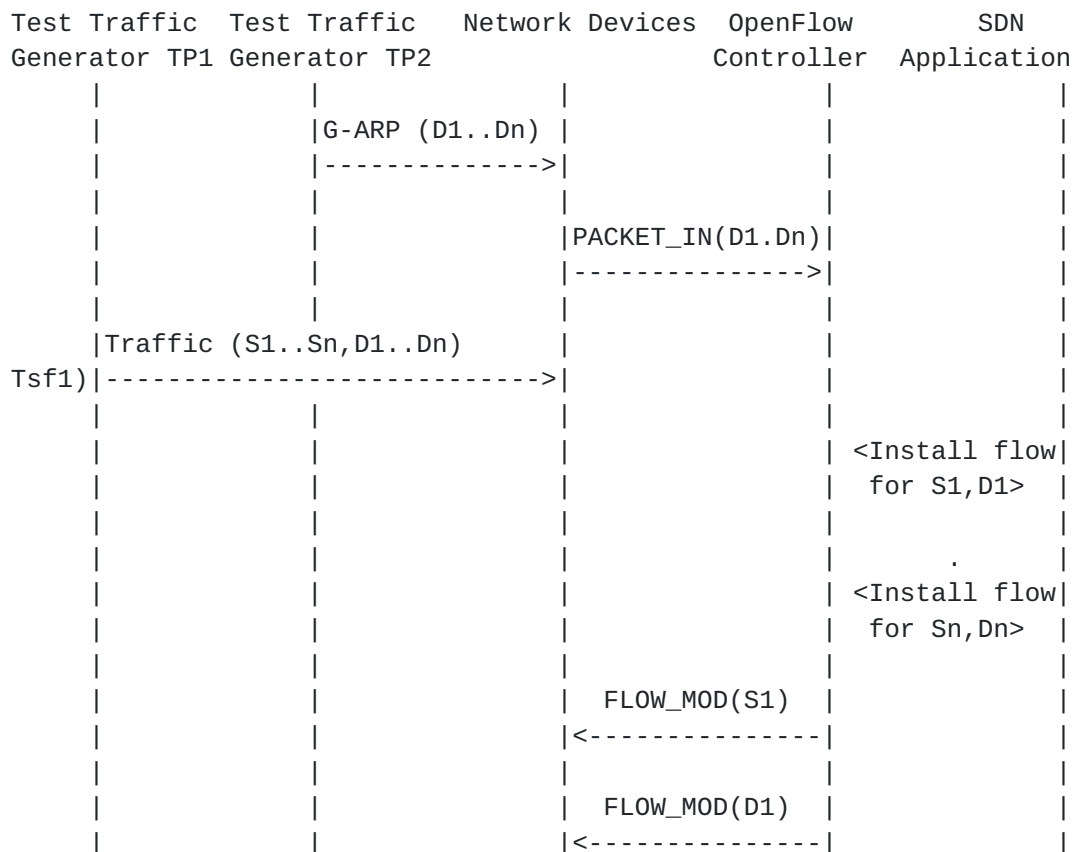
S1..Sn: Source Endpoint 1, Source Endpoint 2 ..., Source
Endpoint n

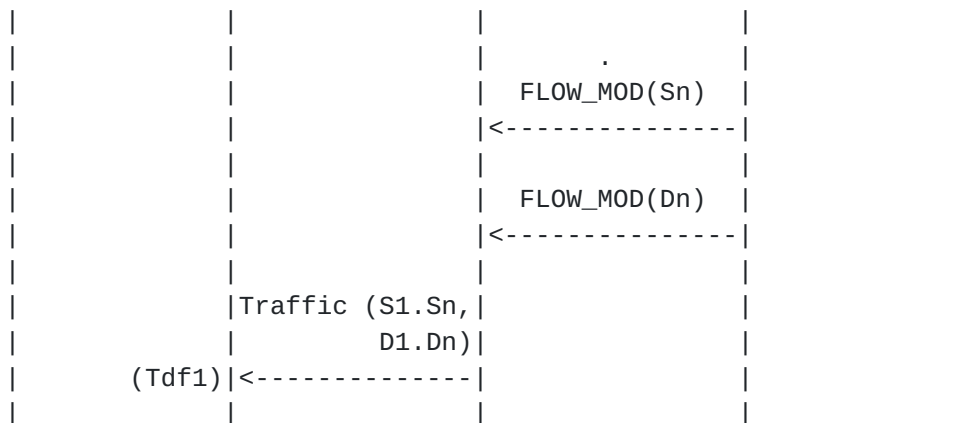
Discussion:

The Reactive Path Provisioning Rate can be obtained by finding the total number of frames received at TP2 after the trial duration.

[A.4.7. Proactive Path Provisioning Rate](#)

Procedure:





Legend:

G-ARP: Gratuitous ARP

D1..Dn: Destination Endpoint 1, Destination Endpoint 2
Destination Endpoint n

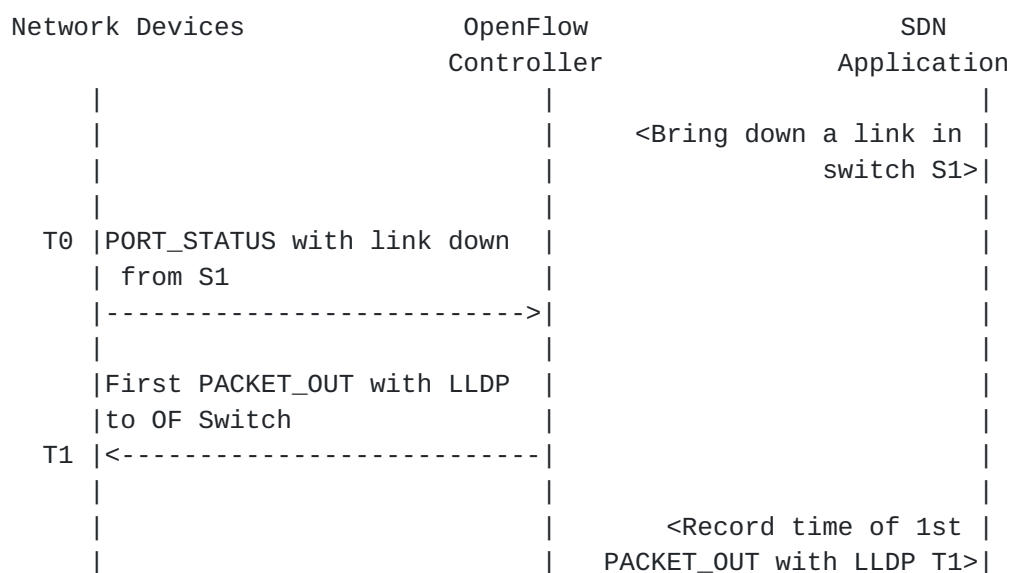
S1..Sn: Source Endpoint 1, Source Endpoint 2 .., Source
Endpoint n

Discussion:

The Proactive Path Provisioning Rate can be obtained by finding the total number of frames received at TP2 after the trial duration

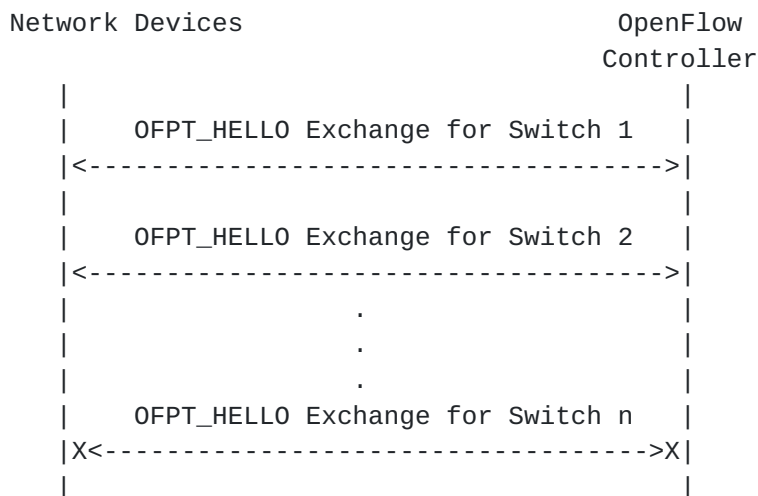
[A.4.8. Network Topology Change Detection Time](#)

Procedure:

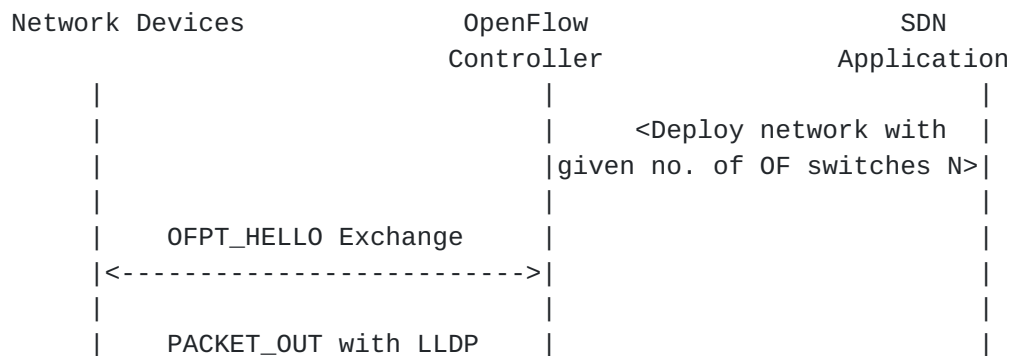


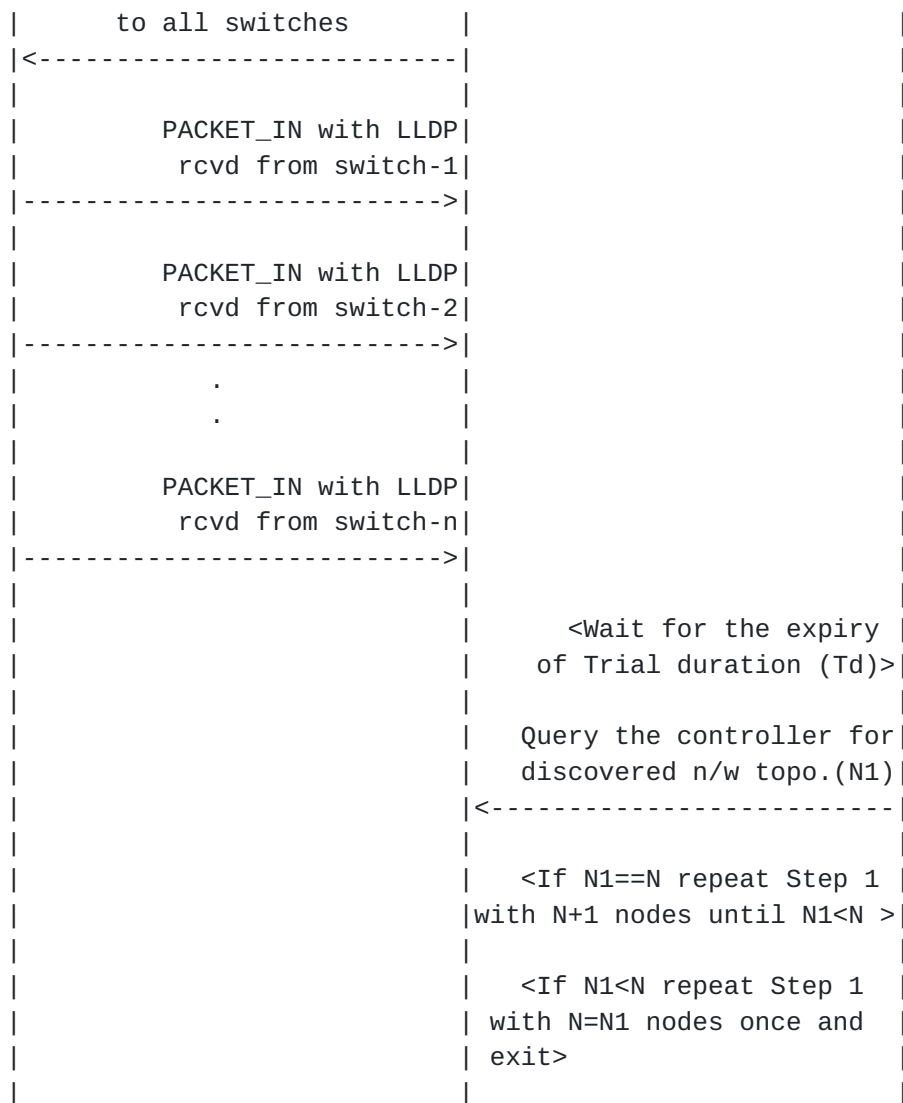
Discussion:

The Network Topology Change Detection Time can be obtained by finding the difference between the time the OpenFlow switch S1 sends the PORT_STATUS message (T0) and the time that the OpenFlow controller sends the first topology re-discovery message (T1) to OpenFlow switches.

[A.5. Scalability](#)**[A.5.1. Control Sessions Capacity](#)****Procedure:****Discussion:**

The value of Switch n-1 will provide Control Sessions Capacity.

[A.5.2. Network Discovery Size](#)**Procedure:**



Legend:

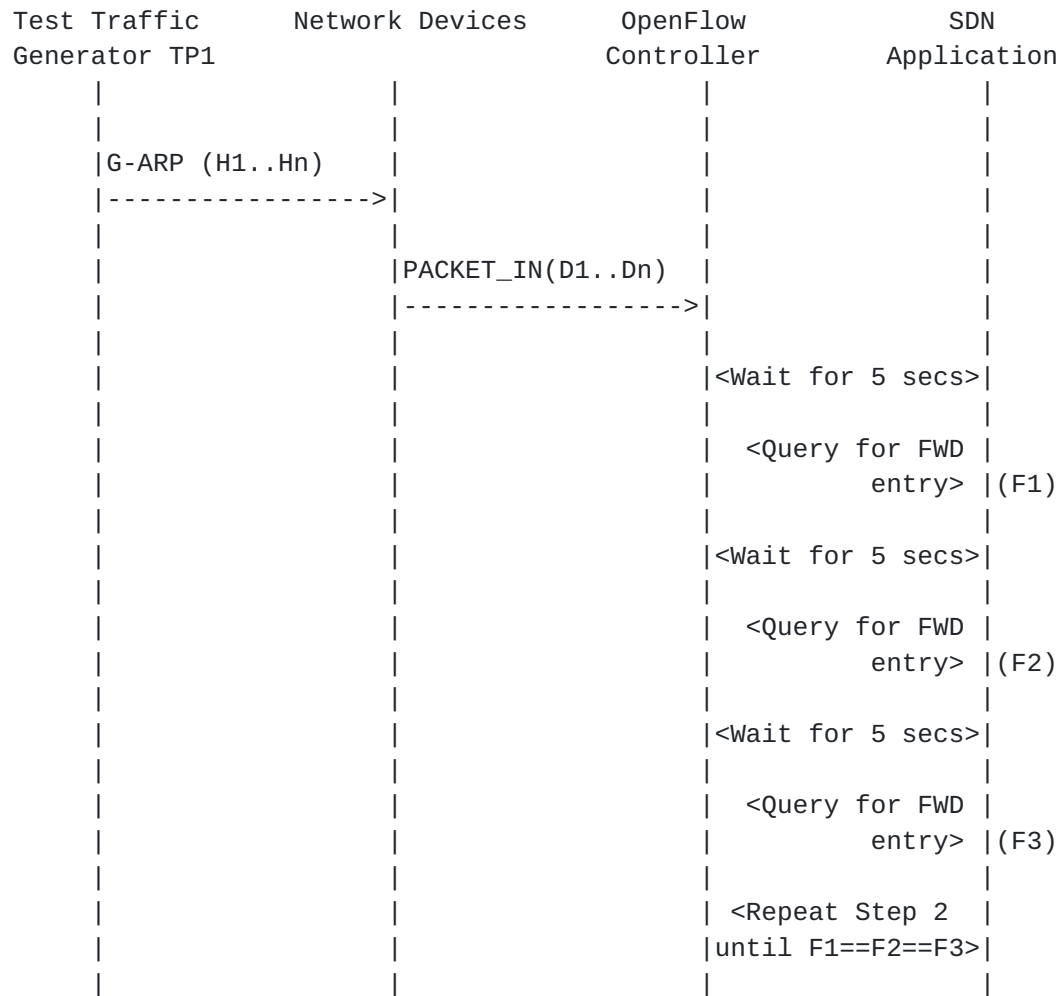
n/w topo: Network Topology
OF: OpenFlow

Discussion:

The value of N1 provides the Network Discovery Size value. The trial duration can be set to the stipulated time within which the user expects the controller to complete the discovery process.

[A.5.3. Forwarding Table Capacity](#)

Procedure:



Legend:

G-ARP: Gratuitous ARP
H1..Hn: Host 1 .. Host n
FWD: Forwarding Table

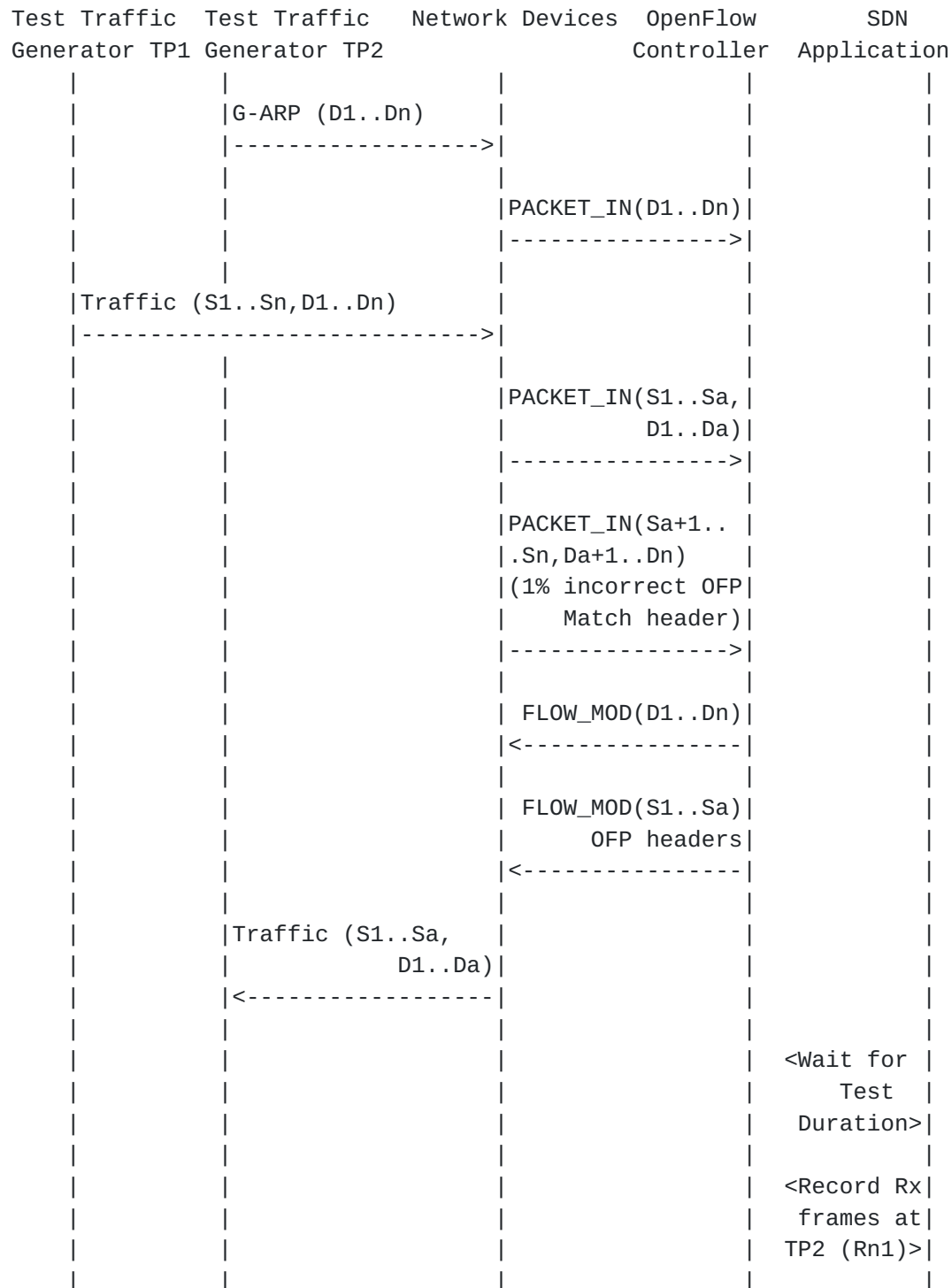
Discussion:

Query the controller forwarding table entries for multiple times until the three consecutive queries return the same value. The last value retrieved from the controller will provide the Forwarding Table Capacity value. The query interval is user configurable. The 5 seconds shown in this example is for representational purpose.

A.6. Security

A.6.1. Exception Handling

Procedure:



				<Repeat	
				Step1 with	
				2% incorrect	
				PACKET_INS>	
				<Record Rx	
				frames at	
				TP2 (Rn2)>	

Legend:

G-ARP: Gratuitous ARP

PACKET_IN(Sa+1..Sn,Da+1..Dn): OpenFlow PACKET_IN with wrong version number

Rn1: Total number of frames received at Test Port 2 with 1% incorrect frames

Rn2: Total number of frames received at Test Port 2 with 2% incorrect frames

Discussion:

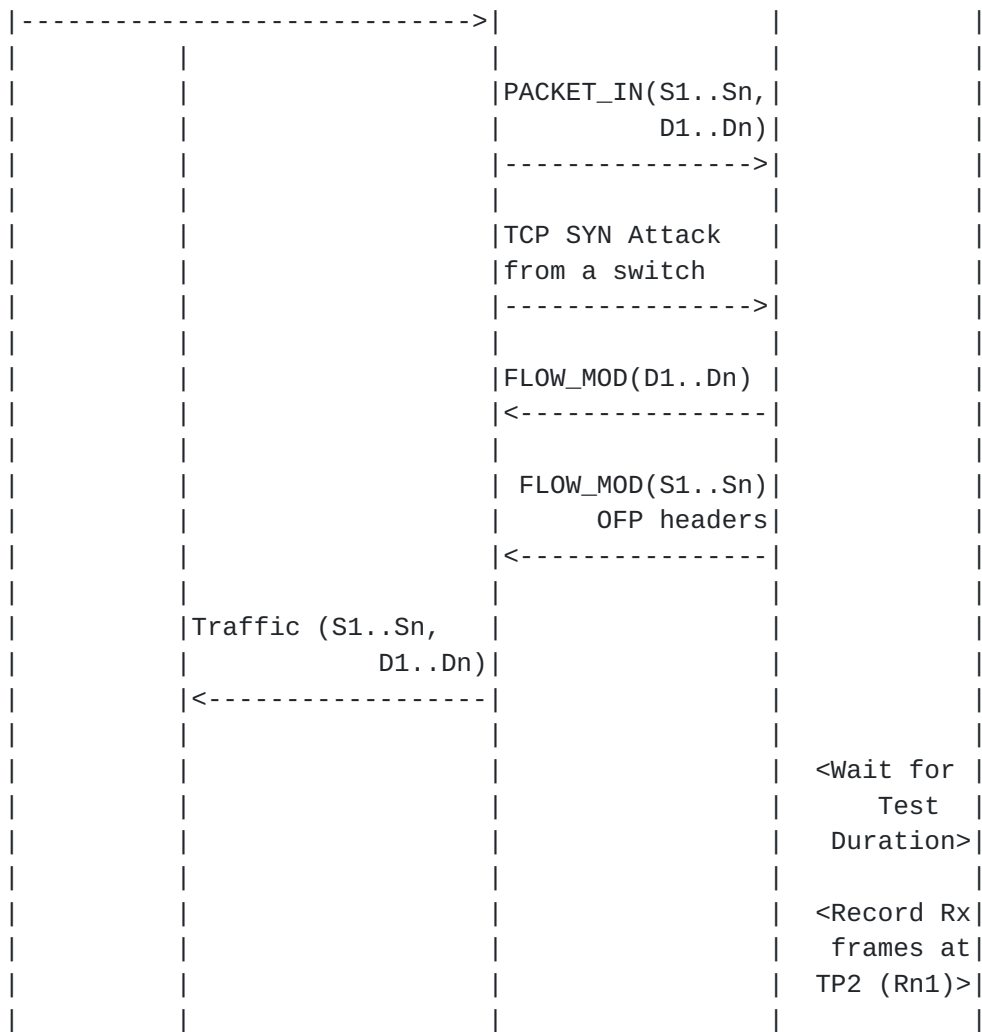
The traffic rate sent towards OpenFlow switch from Test Port 1 should be 1% higher than the Path Programming Rate. Rn1 will provide the Path Provisioning Rate of controller at 1% of incorrect frames handling and Rn2 will provide the Path Provisioning Rate of controller at 2% of incorrect frames handling.

The procedure defined above provides test steps to determine the effect of handling error packets on Path Programming Rate. Same procedure can be adopted to determine the effects on other performance tests listed in this benchmarking tests.

[A.6.2. Denial of Service Handling](#)

Procedure:

Test Traffic Generator TP1	Test Traffic Generator TP2	Network Devic	OpenFlow Controller	SDN Application
	G-ARP (D1..Dn)			
	----->			
		PACKET_IN(D1..Dn)		
		----->		
Traffic (S1..Sn,D1..Dn)				



Legend:

G-ARP: Gratuitous ARP

Discussion:

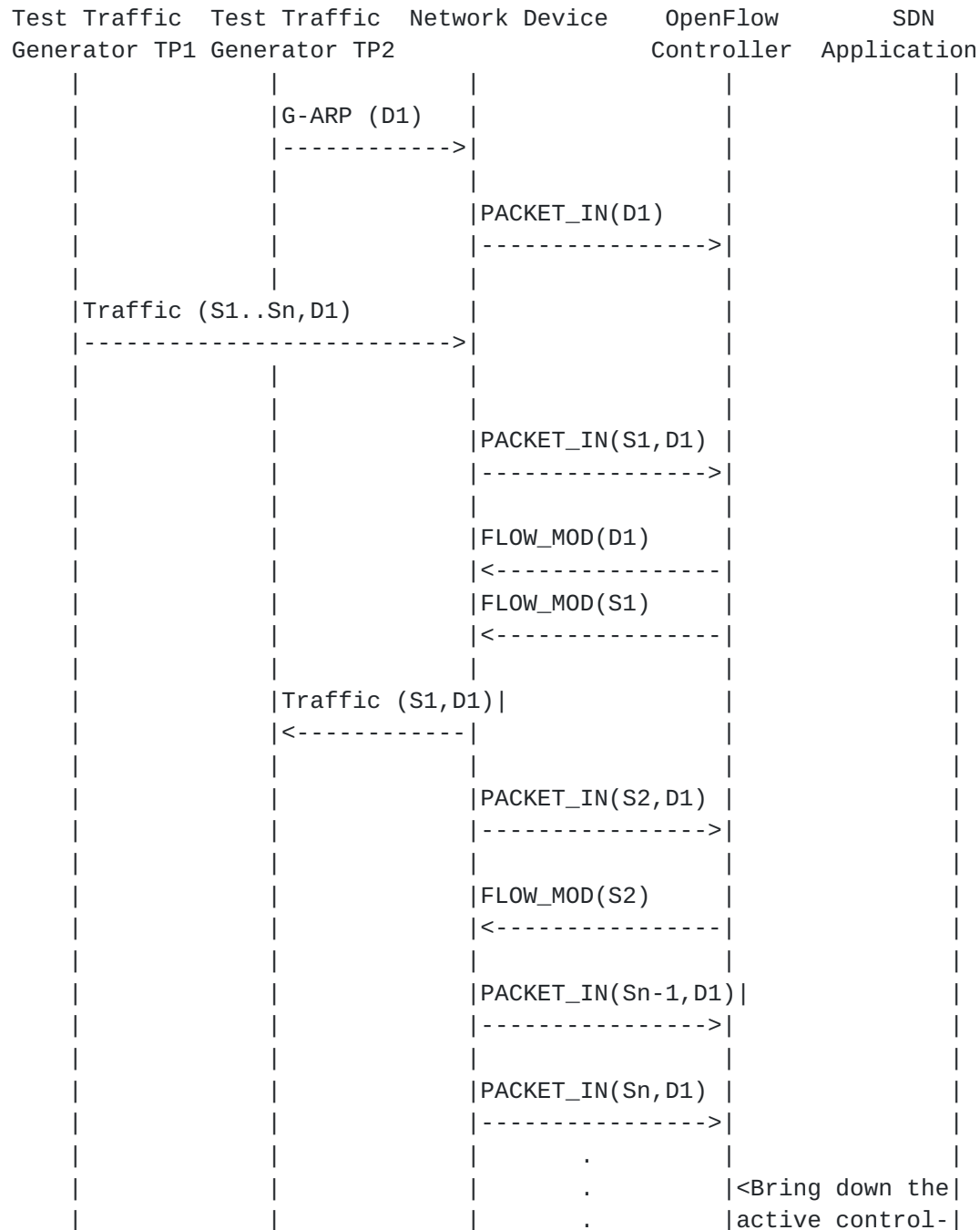
TCP SYN attack should be launched from one of the emulated/simulated OpenFlow Switch. Rn1 provides the Path Programming Rate of controller uponhandling denial of service attack.

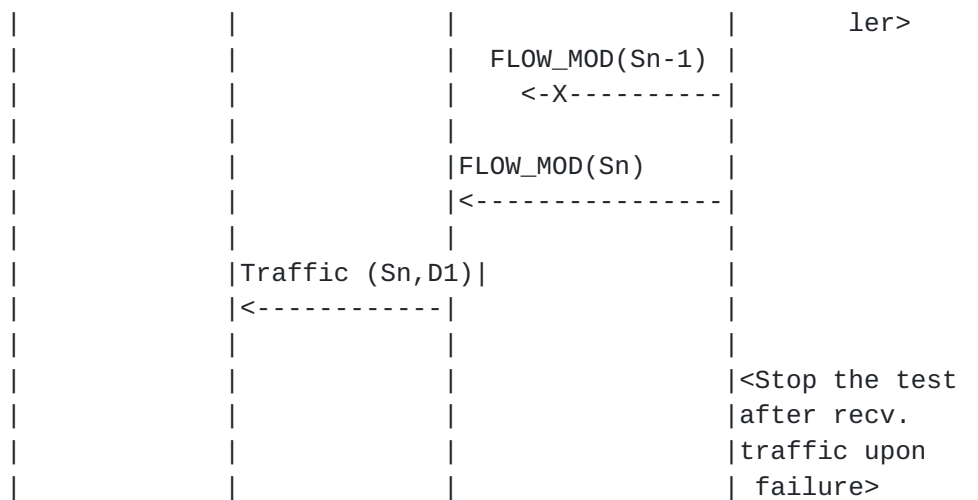
The procedure defined above provides test steps to determine the effect of handling denial of service on Path Programming Rate. Same procedure can be adopted to determine the effects on other performance tests listed in this benchmarking tests.

A.7. Reliability

A.7.1. Controller Failover Time

Procedure:





Legend:

G-ARP: Gratuitous ARP.

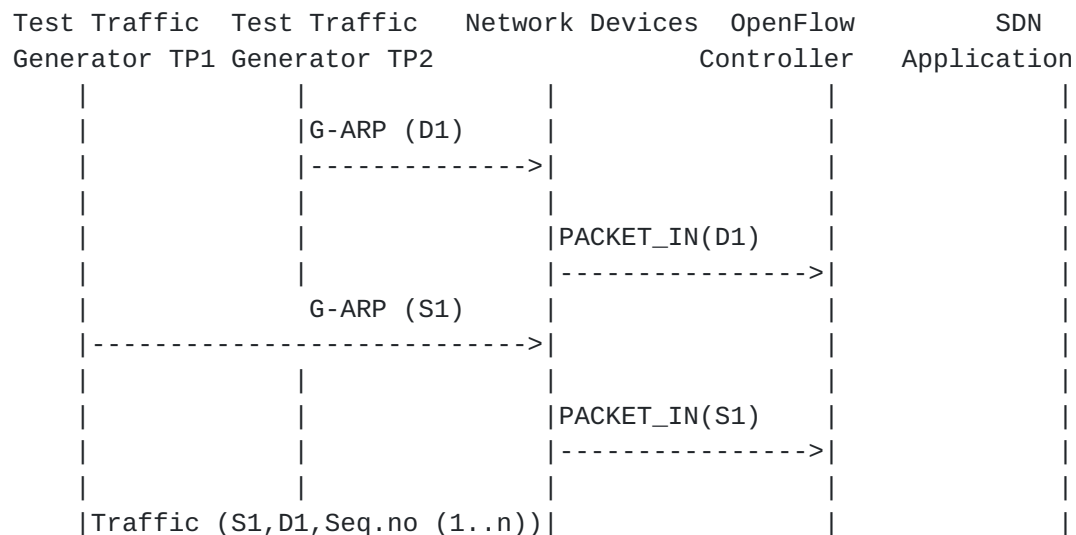
Discussion:

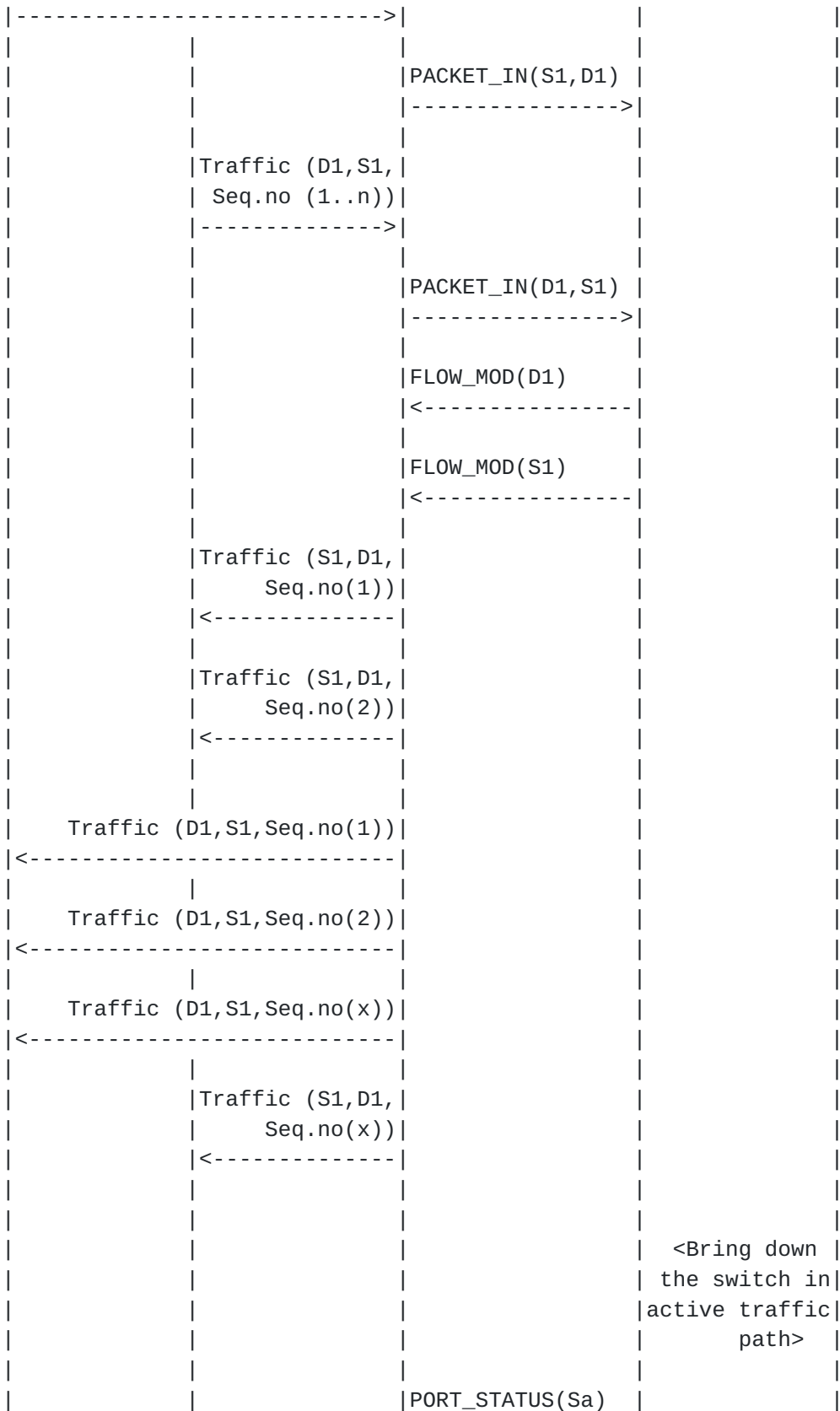
The time difference between the last valid frame received before the traffic loss and the first frame received after the traffic loss will provide the controller failover time.

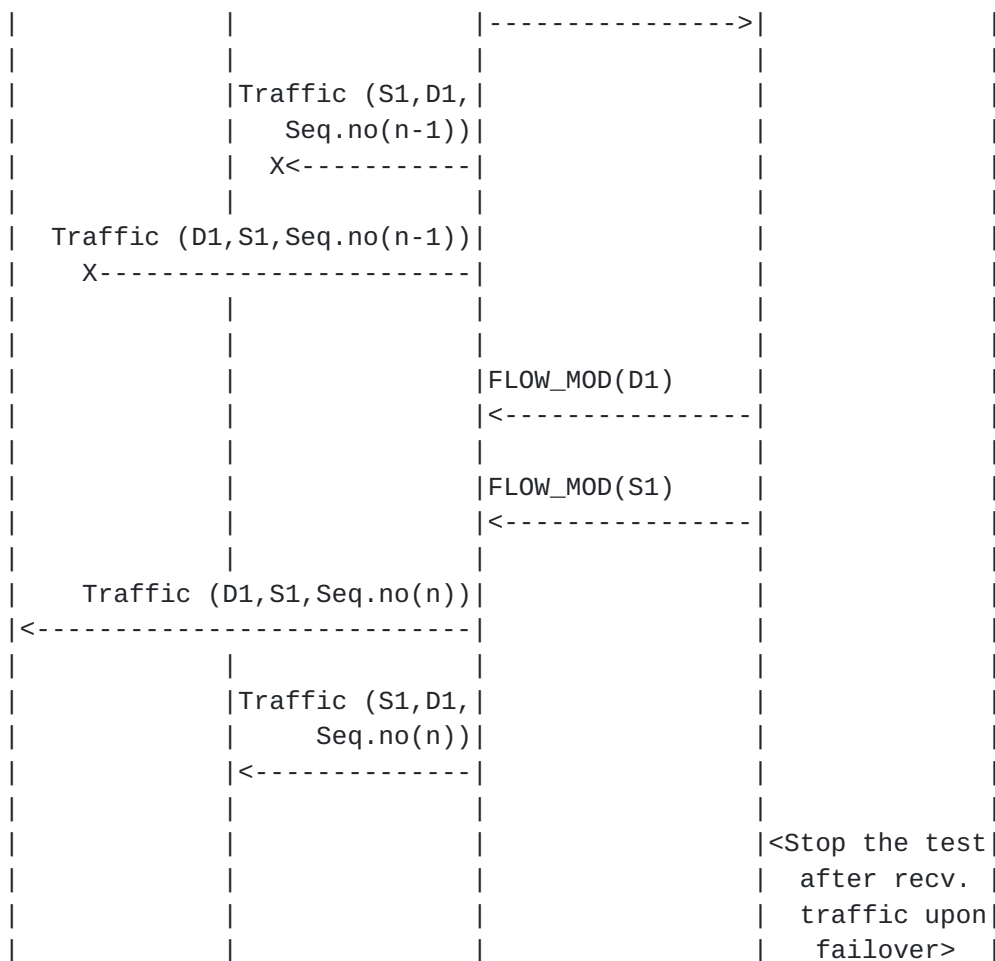
If there is no frame loss during controller failover time, the controller failover time can be deemed negligible.

[A.7.2. Network Re-Provisioning Time](#)

Procedure:







Legend:

G-ARP: Gratuitous ARP message.

Seq.no: Sequence number.

Sa: Neighbor switch of the switch that was brought down.

Discussion:

The time difference between the last valid frame received before the traffic loss (Packet number with sequence number x) and the first frame received after the traffic loss (packet with sequence number n) will provide the network path re-provisioning time.

Note that the trial is valid only when the controller provisions the alternate path upon network failure.

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