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Benchmarking Methodology for SDN Controller Performance
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Abstract

This document defines the methodologies for benchmarking performance of SDN controllers. Terminology related to benchmarking SDN controllers is described in the companion terminology document. 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 standard mechanism 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. 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", "MAY", and "OPTIONAL" in this document are to be interpreted as described in RFC 2119.

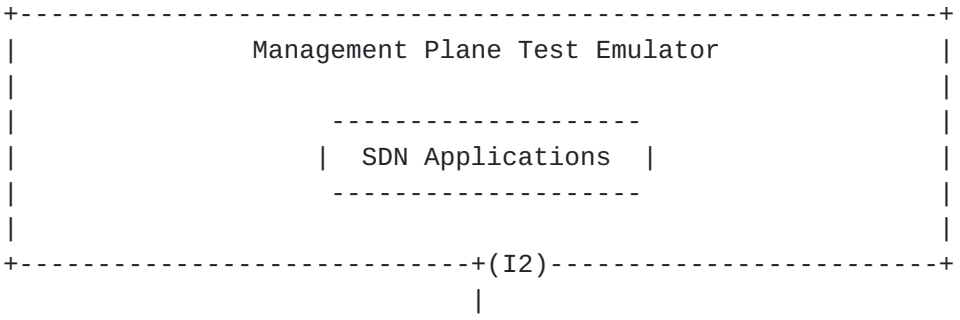
2. Scope

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 SDN nodes. 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 is beyond the scope of this document.

3. Test Setup

The tests defined in this document enable measurement of an SDN controllers 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



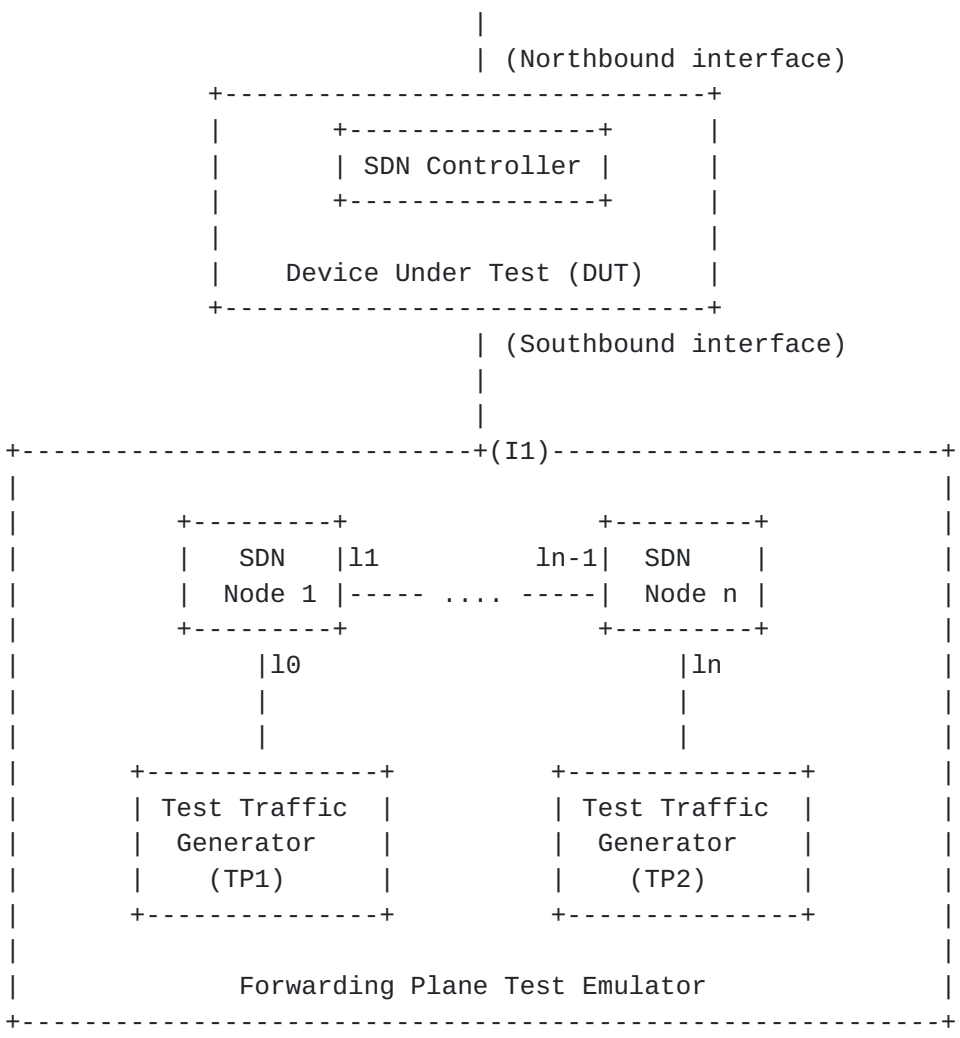
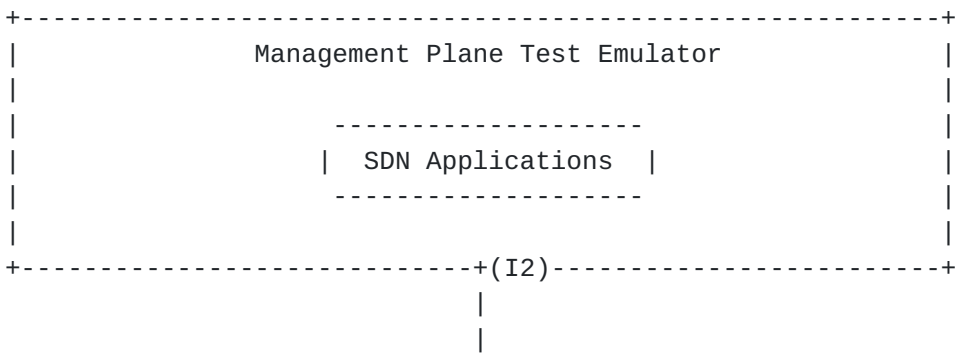


Figure 1

3.2. Test setup - Controller working in Cluster Mode



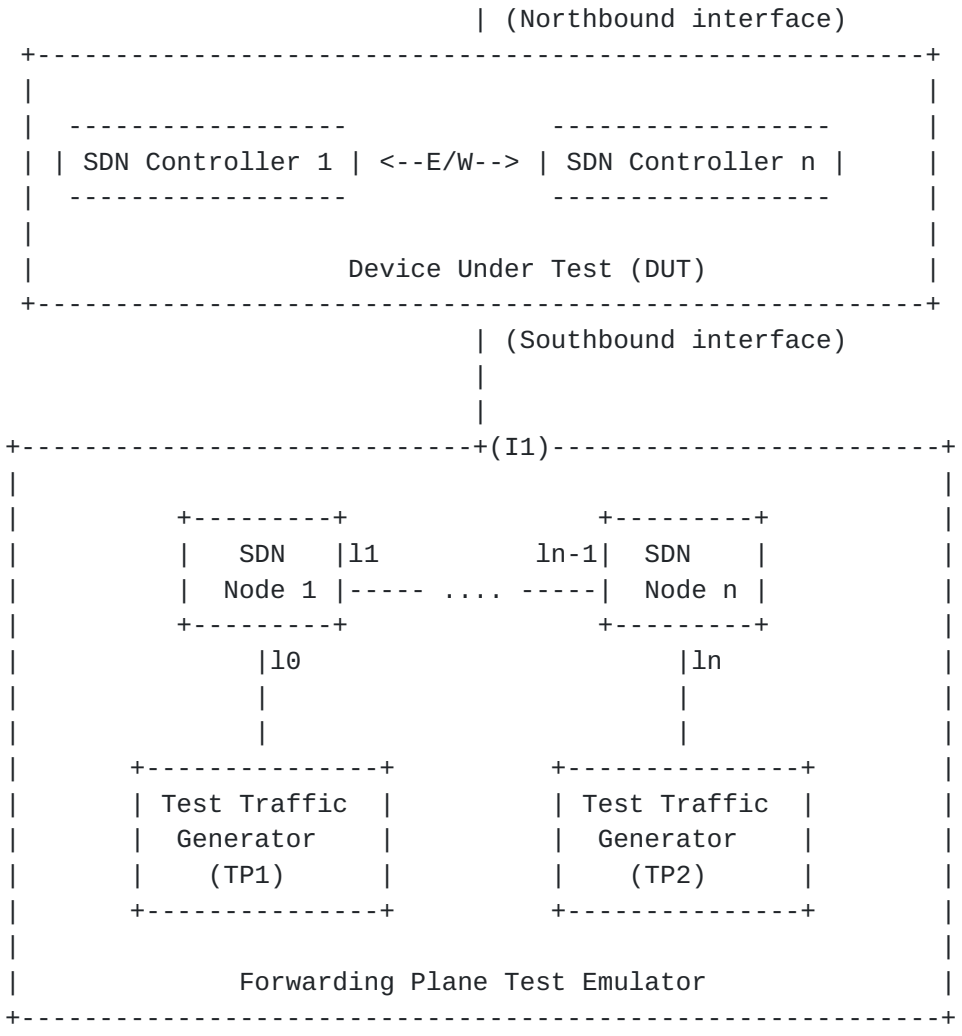


Figure 2

4. Test Considerations

4.1. Network Topology

The test cases SHOULD use Leaf-Spine topology with at least 1 SDN node in the topology for benchmarking. The test traffic generators TP1 and TP2 SHOULD be connected to the first and the last SDN leaf node. If a test case uses test topology with 1 SDN node, the test traffic generators TP1 and TP2 SHOULD be connected to the same node. However 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 SDN nodes. This document includes a few sample test topologies, defined in Section 10 - Appendix A for reference. 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 arrival of new flows. The test cases SHOULD use multiple frame sizes as recommended in RFC2544 for benchmarking.

4.3. Connection Setup

There may be controller implementations that support unencrypted and encrypted network connections with SDN nodes. Further, the controller may have backward compatibility with SDN nodes running older versions of southbound protocols. It is recommended that the controller performance be measured with one or more applicable connection setup methods defined below.

1. Unencrypted connection with SDN nodes, running same protocol version.
2. Unencrypted connection with SDN nodes, 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 SDN nodes, running same protocol version
4. Encrypted connection with SDN nodes, 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

4.4. 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.

4.5. 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.

4.6. Test Repeatability

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

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 Topology (Mesh or Tree or Linear)
7. SDN Node Type (Physical or Virtual or Emulated)
8. Number of Nodes
9. Number of Links
10. Test Traffic Type
11. Controller System Configuration (e.g., CPU, Memory, Operating System, Interface Speed etc.,)
12. 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.,)

5. Benchmarking Tests

5.1. Performance

5.1.1. Network Topology Discovery Time

Objective:

Measure the time taken by the SDN controller to discover the network topology (nodes and links), expressed in milliseconds.

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 SDN nodes.
3. Record the time for the first discovery message (Tm1) received from the controller at forwarding plane test emulator interface I1.
4. Query the controller every 3 seconds 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 test when the discovered topology information matches the deployed network topology, or when the discovered topology information for 3 consecutive queries return the same details.
6. Record the time last discovery message (Tmn) sent to controller from the forwarding plane test emulator interface (I1) when the test completed successfully. (e.g., the topology matches).

Measurement:

Topology Discovery Time Tr1 = Tmn-Tm1.

$$\text{Average Topology Discovery Time} = \frac{Tr1 + Tr2 + Tr3 .. Trn}{\text{Total Test Iterations}}$$

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 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.

If this test is repeated with same number of nodes over different topologies, the results SHOULD be reported in the form of a graph. The X coordinate SHOULD be the Topology Type, the Y coordinate SHOULD be the average Topology Discovery Time.

5.1.2. Asynchronous Message Processing Time

Objective:

Measure the time taken by the SDN controller to process an asynchronous message, expressed in milliseconds.

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 completed the network topology discovery for the connected SDN nodes.

Procedure:

1. Generate asynchronous messages from every connected SDN node, to the SDN controller, one at a time in series from the forwarding plane test emulator for the test duration.

2. Record every request transmit (T1) timestamp and the corresponding response (R1) received timestamp at the forwarding plane test emulator interface (I1) for every successful message exchange.

Measurement:

$$\text{Asynchronous Message Processing Time } Tr1 = \frac{(R1-T1) + (R2-T2)..(Rn-Tn)}{Nrx}$$

Where Nrx is the total number of successful messages exchanged

$$\text{Average Asynchronous Message Processing Time} = \frac{Tr1 + Tr2 + Tr3..Trn}{\text{Total Test Iterations}}$$

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 average Asynchronous Message Processing Time.

The report should capture the following information in addition to the configuration parameters captured in section 5. - Successful messages exchanged (Nrx)

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.

If this test is repeated with same number of nodes using different topologies, the results SHOULD be reported in the form of a graph. The X coordinate SHOULD be the Topology Type, the Y coordinate SHOULD be the average Asynchronous Message Processing Time.

5.1.3. Asynchronous Message Processing Rate

Objective:

To measure the maximum rate of asynchronous messages (session aliveness check message, new flow arrival notification message etc.)

a controller can process within the test duration, expressed in messages processed per second.

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 completed the network topology discovery for the connected SDN nodes.

Procedure:

1. Generate asynchronous messages continuously at the maximum possible rate on the established connections from all the connected SDN nodes in the forwarding plane test emulator for the Test Duration (Td).
2. Record the total number of responses received from the controller (Nrx) as well as the number of messages sent(Ntx) to the controller within the test duration(Td) at the forwarding plane test emulator interface (I1).

Measurement:

$$\text{Asynchronous Message Processing Rate Tr1} = \frac{Nrx}{Td}$$

$$\text{Average Asynchronous Message Processing Rate} = \frac{Tr1 + Tr2 + Tr3..Trn}{\text{Total Test Iterations}}$$

$$\text{Loss Ratio} = (Ntx-Nrx)/100.$$

Reporting Format:

The Asynchronous Message Processing 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 average Asynchronous Message Processing Rate.

The report should capture the following information in addition to the configuration parameters captured in section 5.

- Offered rate (Ntx)

- Loss Ratio

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 coordinate SHOULD be the Number of nodes (N), the Y coordinate SHOULD be the average Asynchronous Message Processing Rate.

If this test is repeated with same number of nodes over different topologies, the results SHOULD be reported in the form of a graph. The X coordinate SHOULD be the Topology Type, the Y coordinate SHOULD be the average Asynchronous Message Processing Rate.

5.1.4. Reactive Path Provisioning Time

Objective:

To measure the time taken by the controller to setup a path reactively between source and destination node, expressed in milliseconds.

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 SDN node is configured to 'send to controller'.
4. Ensure that each SDN node 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 SDN node 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 test duration (Td).
4. Record the time of the last flow provisioning response message received from the controller (Tdf1) to the SDN node at the forwarding plane test emulator interface (I1).

Measurement:

Reactive Path Provisioning Time Tr1 = Tdf1-Tsf1.

$$\text{Average Reactive Path Provisioning Time} = \frac{Tr1 + Tr2 + Tr3 \,..\, Trn}{\text{Total Test Iterations}}$$

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 Average Reactive Path Provisioning Time

The report should capture the following information in addition to the configuration parameters captured in section 5.

- Number of SDN nodes in the path

5.1.5. Proactive Path Provisioning Time

Objective:

To measure the time taken by the controller to setup a path proactively between source and destination node, expressed in milliseconds.

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 SDN node 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 test 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.

$$\text{Average Proactive Path Provisioning Time} = \frac{Tr1 + Tr2 + Tr3 \,..\, Trn}{\text{Total Test Iterations}}$$

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 Average Proactive Path Provisioning Time.

The report should capture the following information in addition to the configuration parameters captured in section 5.

- Number of SDN nodes in the path

5.1.6. Reactive Path Provisioning Rate

Objective:

Measure the maximum number of independent paths a controller can concurrently establish between source and destination nodes reactively within the test duration, expressed in paths per second.

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 SDN node is configured to 'send to controller'.
4. Ensure that each SDN node 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 test duration (Td).

Measurement:

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

$$\text{Average Reactive Path Provisioning Rate} = \frac{Tr1 + Tr2 + Tr3 \,..\, Trn}{\text{Total Test Iterations}}$$

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 Average Reactive Path Provisioning Rate.

The report should capture the following information in addition to the configuration parameters captured in section 5.

- Number of SDN nodes 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 between source and destination nodes proactively within the test duration, expressed in paths per second.

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 SDN node 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 test duration (Td).

Measurement:

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

$$\text{Average Proactive Path Provisioning Rate} = \frac{\text{Tr1 + Tr2 + Tr3 .. Trn}}{\text{Total Test Iterations}}$$

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 Average Proactive Path Provisioning Rate.

The report should capture the following information in addition to the configuration parameters captured in section 5.

- Number of SDN nodes in the path

- Offered rate

5.1.8. Network Topology Change Detection Time

Objective:

Measure the time taken by the controller to detect any changes in the network topology, expressed in milliseconds.

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 discovered the network topology information for the deployed network topology.

2. The periodic network discovery operation should be configured to twice the Test duration (Td) value.

Procedure:

1. Trigger a topology change event by bringing down an active SDN node 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 test when the controller sends the first topology re-discovery message to the SDN node or the expiry of test interval (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.

$$\text{Average Network Topology Change Detection Time} = \frac{Tr1 + Tr2 + Tr3 \,..\, Trn}{\text{Total Test Iterations}}$$

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 average Network Topology Change Time.

5.2. 6.2 Scalability

5.2.1. Control Session Capacity

Objective:

Measure the maximum number of control sessions that the controller can maintain.

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 SDN node emulated in the forwarding plane test emulator.
2. Stop the test when the controller starts dropping the control connection.
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 5.

5.2.2. Network Discovery Size

Objective:

Measure the network size (number of nodes, links, and hosts) that a controller can 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 for the discovered network topology information and compare it with the deployed network topology information.
3. 3a. Increase the number of nodes by 1 when the comparison is successful and repeat the test.
4. 3b. Decrease the number of nodes by 1 when the comparison fails and repeat the test.
5. Continue the test until the comparison of step 3b is successful.
6. Record the number of nodes for the last iteration (Ns) where the topology comparison was successful.

Measurement:

Network Discovery Size = Ns.

Reporting Format:

The Network Discovery Size results MUST be reported in addition to the configuration parameters captured in section 5.

5.2.3. 6.2.3 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 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/or 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 learnt flow entries from its northbound interface.
3. Stop the test 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 learnt 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 5.

- Provisioning Type (Proactive/Reactive)

5.3. 6.3 Security

5.3.1. 6.3.1 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 SDN nodes.

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 SDN nodes 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 SDN nodes 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 test is running.

Note:

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

a. Northbound (e.g., Sending a huge number of requests on northbound interface)
b. Management (e.g., Ping requests to controller's management interface)
c. Southbound (e.g., TCP SYNC 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:

Measure 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.

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 completed the network topology discovery.
4. The SDN Node MUST send all new flows to the controller when it receives from the test traffic generator.
5. Controller should have learnt the location of destination (D1) at test traffic generator 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 the test traffic generator TP2.
3. Bring down the active controller.
4. Stop the test 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:

Compute the time taken to re-route the traffic by the controller when there is a failure in existing traffic paths.

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 SDN nodes 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 test 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).
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

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[RFC6020] M. Bjorklund, "YANG - A Data Modeling Language for the Network Configuration Protocol (NETCONF)", RFC 6020, October 2010

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

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6.2. Informative References

[I-D.i2rs-architecture] A. Atlas, J. Halpern, S. Hares, D. Ward, T. Nadeau, "An Architecture for the Interface to the Routing System", draft-ietf-i2rs-architecture-09 (Work in progress), March 6, 2015

[OpenContrail] Ankur Singla, Bruno Rijsman, "OpenContrail Architecture Documentation", http://opencontrail.org/opencontrail-architecture-documentation

[OpenDaylight] OpenDaylight Controller:Architectural Framework, https://wiki.opendaylight.org/view/OpenDaylight_Controller

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 controller in lab environment with isolated network.

9. Acknowledgments

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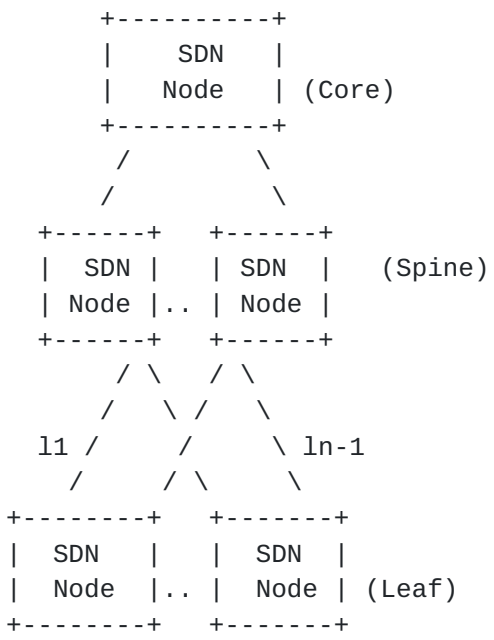
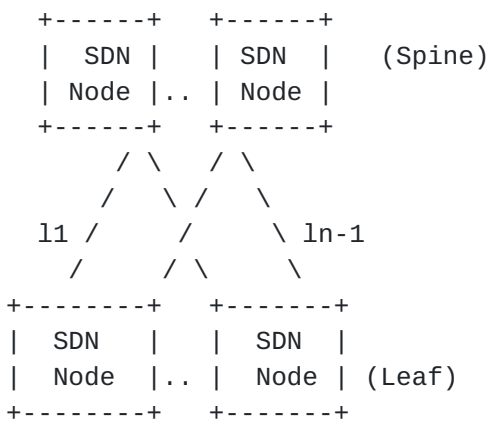
Appendix A. Example Test Topologies

A.1. Leaf-Spine Topology - Three Tier Network Architecture



A.2. Leaf-Spine Topology - Two Tier Network Architecture



Appendix B. 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.

B.1. Protocol Overview

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

B.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).

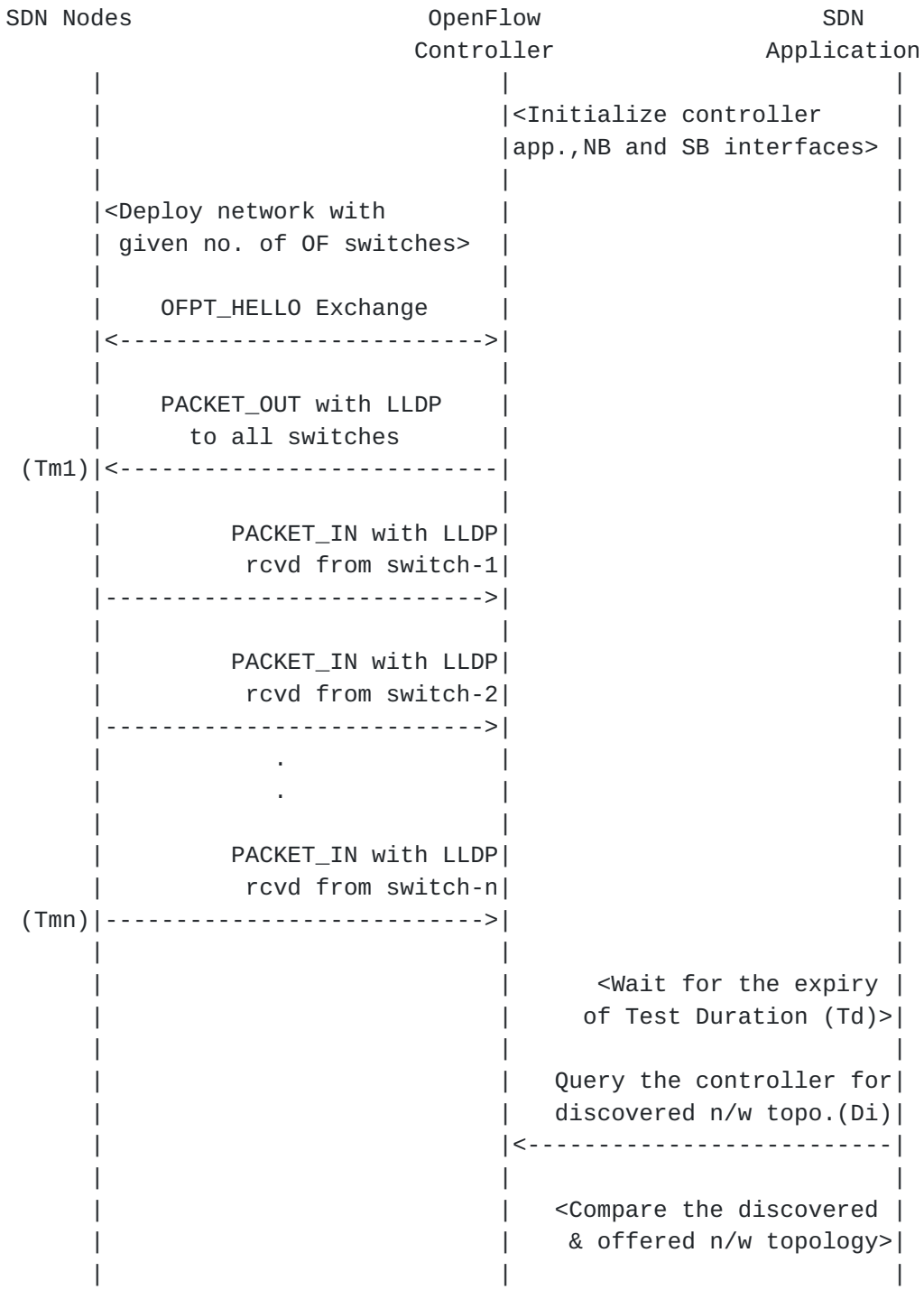
B.3. Connection Overview

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.

B.4. Performance Benchmarking Tests

B.4.1. Network Topology Discovery Time

Procedure:



Legend:

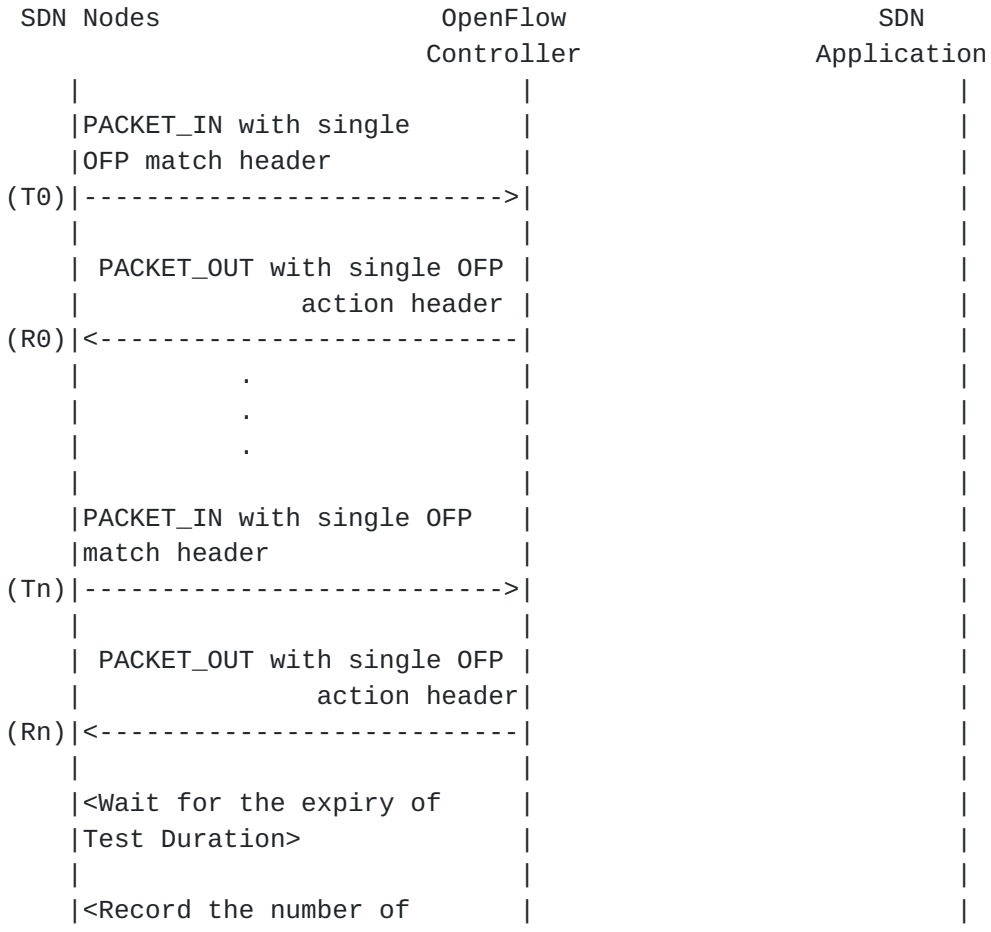
NB: Northbound
SB: Southbound
OF: OpenFlow
Tm1: Time of reception of first LLDP message from controller
Tmn: Time of last LLDP message sent to controller

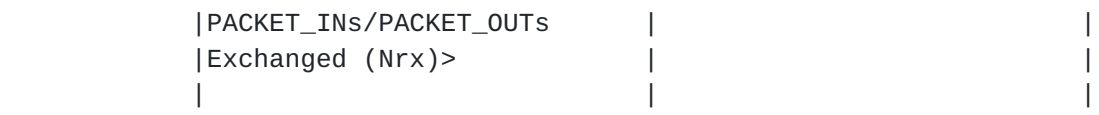
Discussion:

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.

B.4.2. Asynchronous Message Processing Time

Procedure:





Legend:

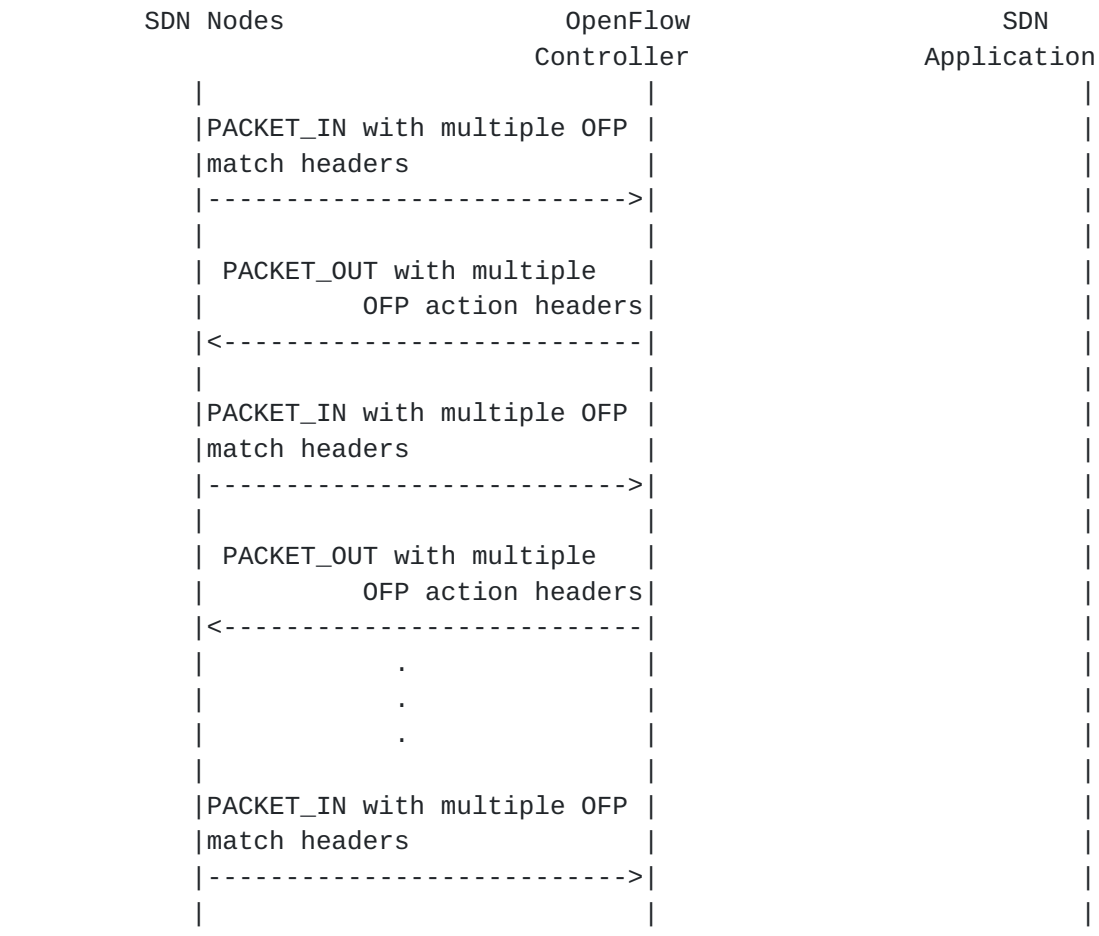
T0,T1, ..Tn are PACKET_IN messages transmit timestamps.
R0,R1, ..Rn are PACKET_OUT messages receive timestamps.
Nrx : Number of successful PACKET_IN/PACKET_OUT message exchanges

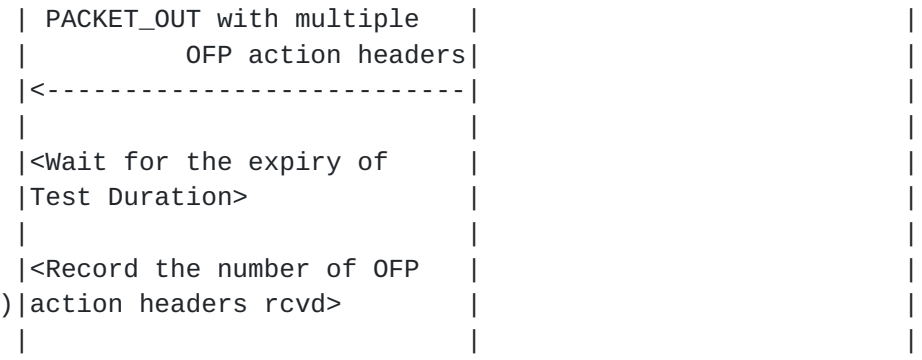
Discussion:

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

B.4.3. Asynchronous Message Processing Rate

Procedure:



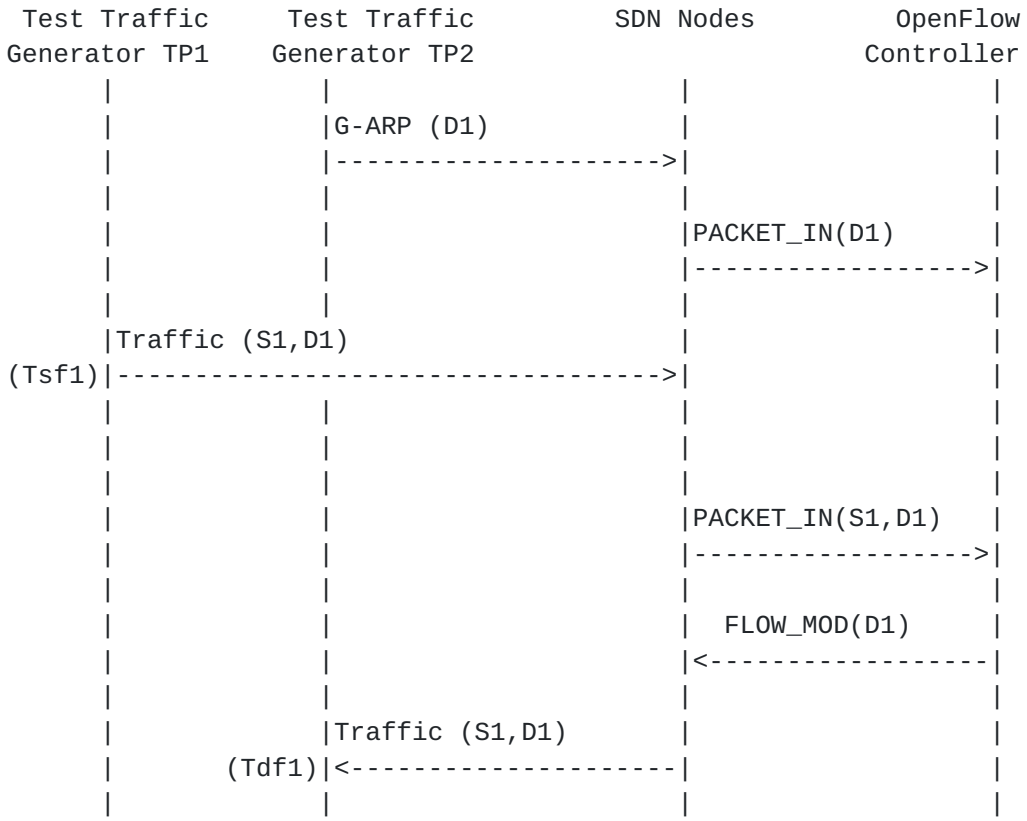


Discussion:

The Asynchronous Message Processing Rate will be obtained by calculating the number of OFP action headers received in all PACKET_OUT messages during the test duration.

B.4.4. Reactive Path Provisioning Time

Procedure:



Legend:

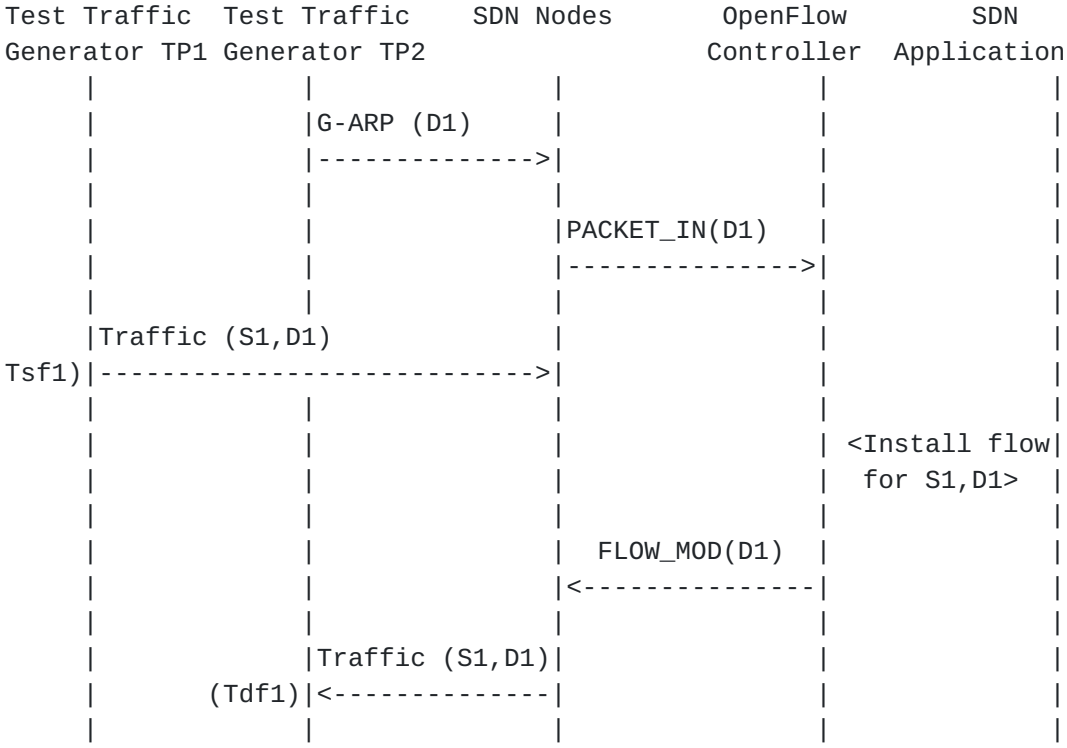
G-ARP: Gratuitous ARP message.
Tsf1: Time of first frame sent from TP1
Tdf1: Time of first frame received from TP2

Discussion:

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

B.4.5. Proactive Path Provisioning Time

Procedure:



Legend:

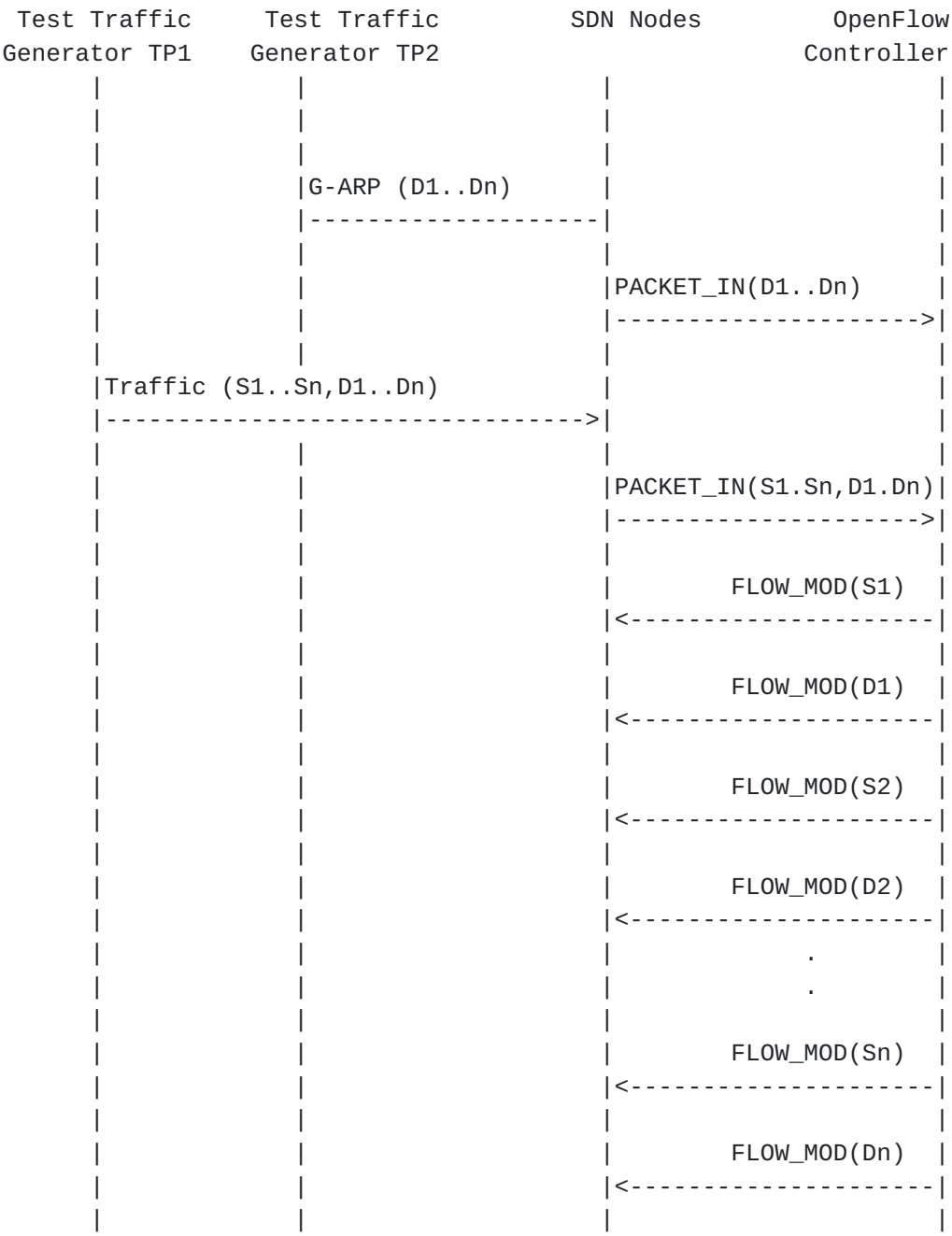
G-ARP: Gratuitous ARP message.
Tsf1: Time of first frame sent from TP1
Tdf1: Time of first frame received from TP2

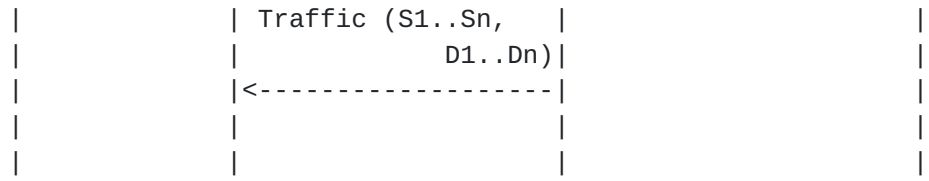
Discussion:

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

B.4.6. Reactive Path Provisioning Rate

Procedure:





Legend:

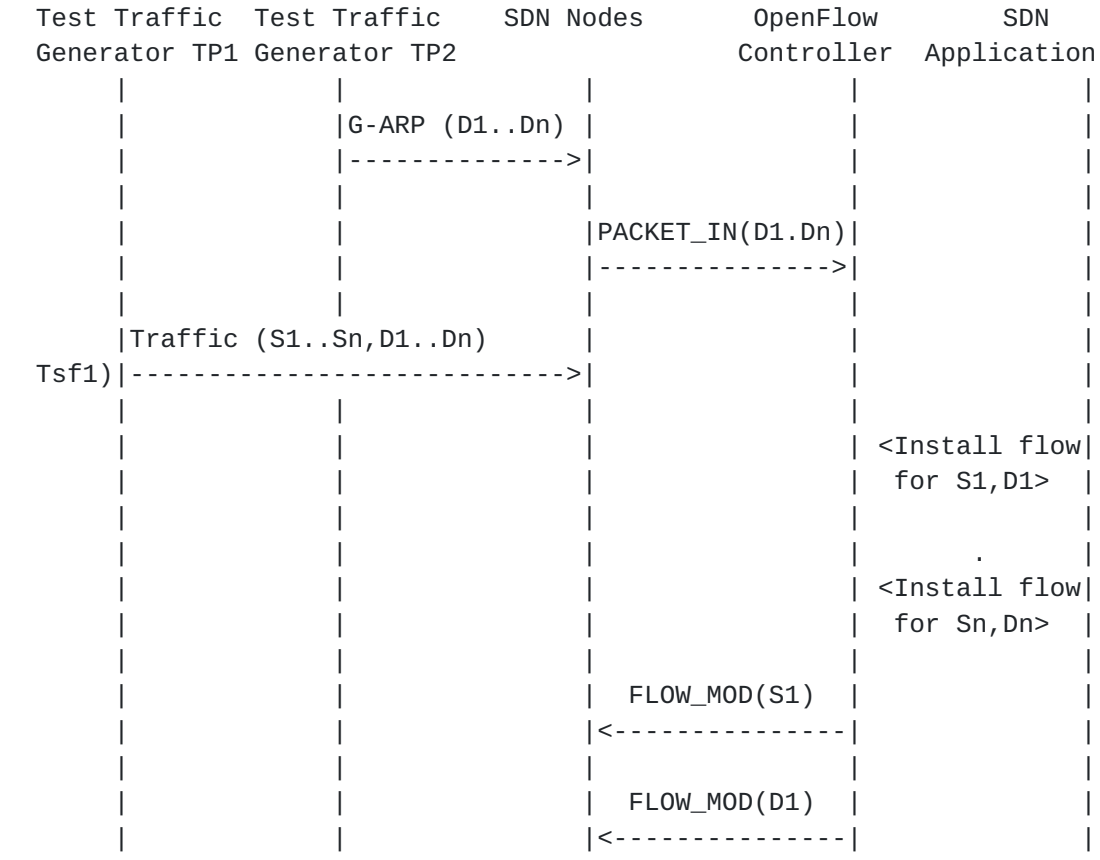
G-ARP: Gratuitous ARP
D1..Dn: Destination Endpoint 1, Destination Endpoint 2 ....
Destination Endpoint n
S1..Sn: Source Endpoint 1, Source Endpoint 2 .., Source Endpoint n

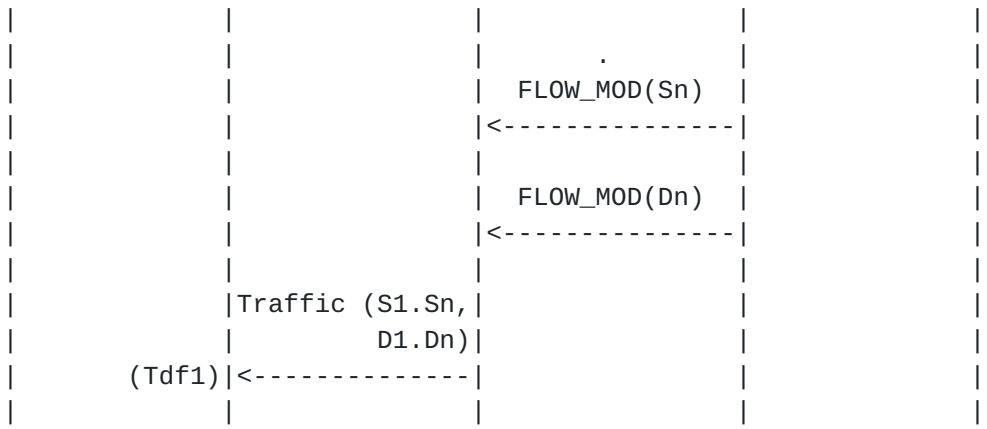
Discussion:

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

B.4.7. Proactive Path Provisioning Rate

Procedure:





Legend:

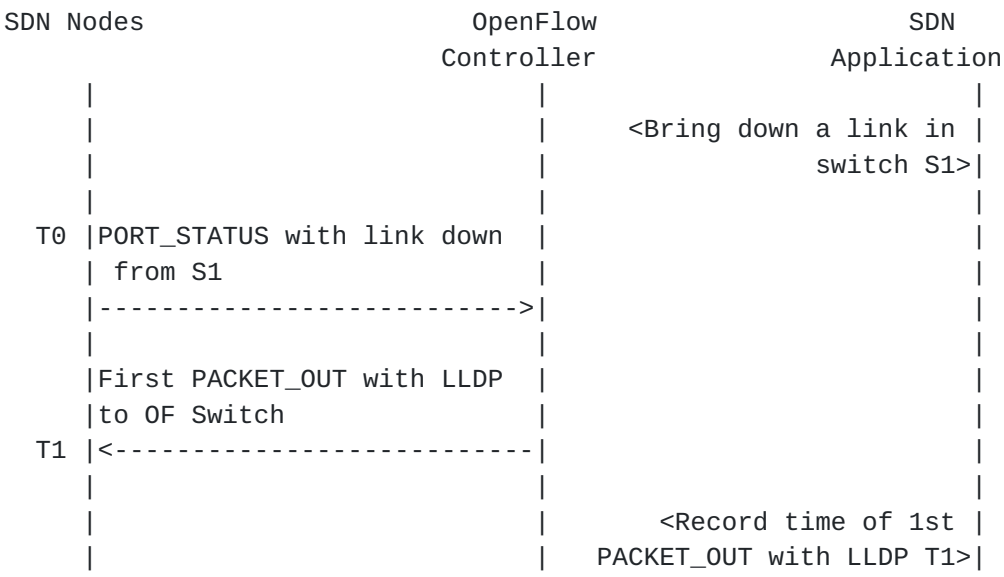
G-ARP: Gratuitous ARP
D1..Dn: Destination Endpoint 1, Destination Endpoint 2 ....
Destination Endpoint n
S1..Sn: Source Endpoint 1, Source Endpoint 2 .., Source Endpoint n

Discussion:

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

B.4.8. Network Topology Change Detection Time

Procedure:



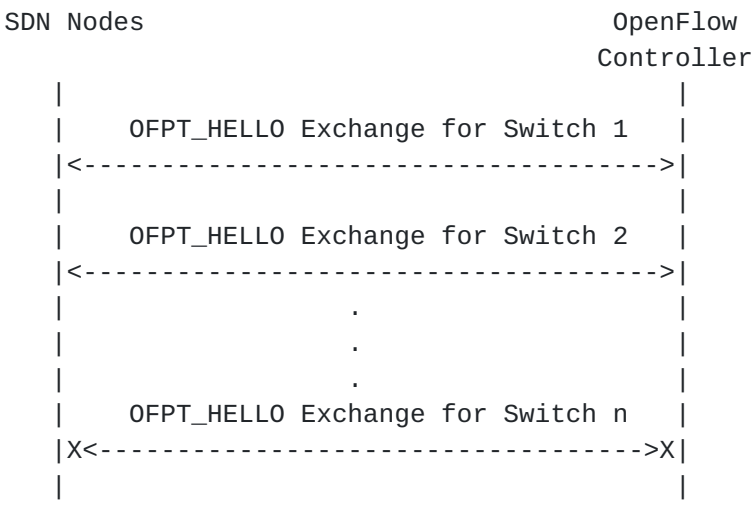
Discussion:

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.

B.5. Scalability

B.5.1. Control Sessions Capacity

Procedure:

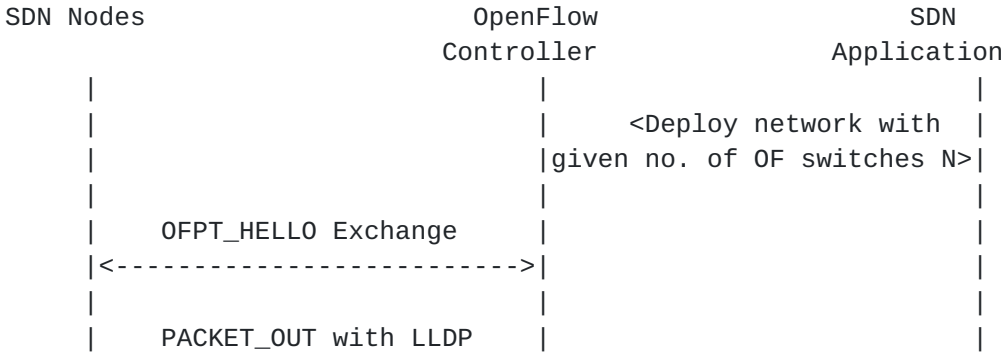


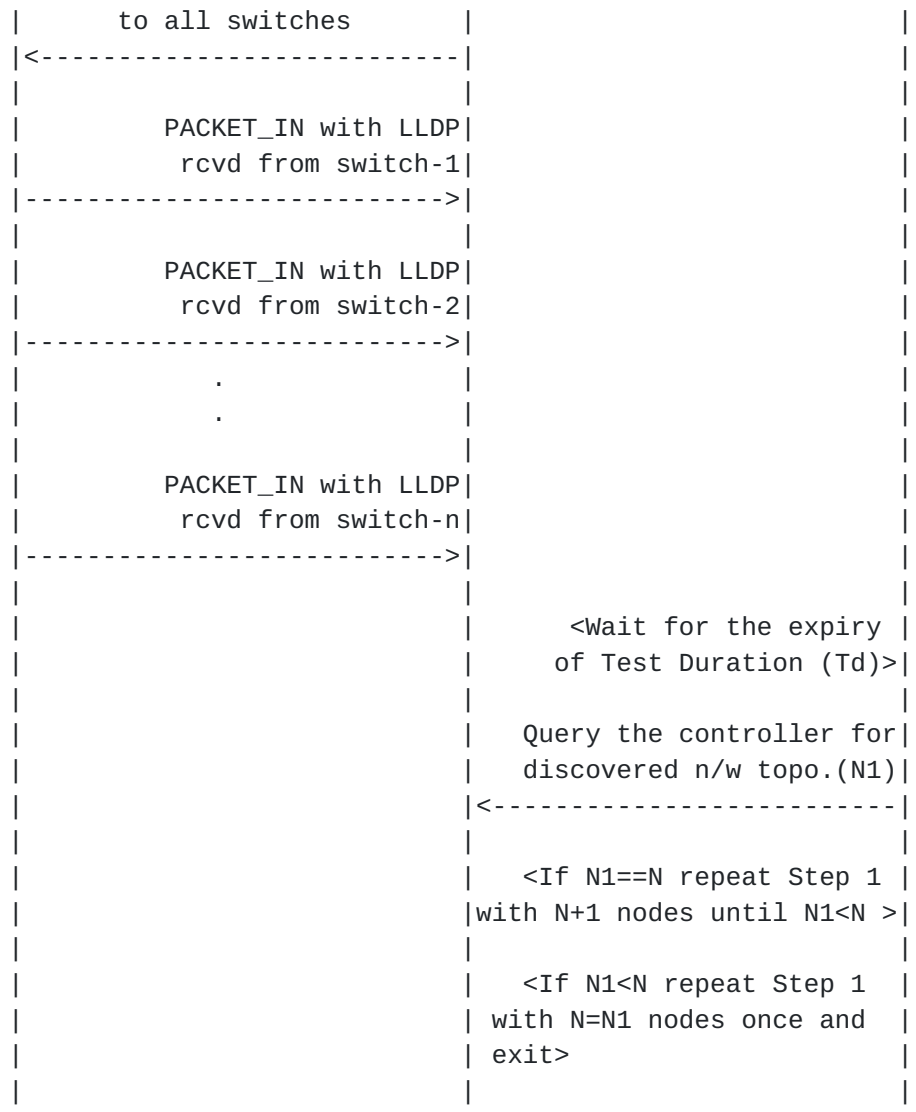
Discussion:

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

B.5.2. Network Discovery Size

Procedure:





Legend:

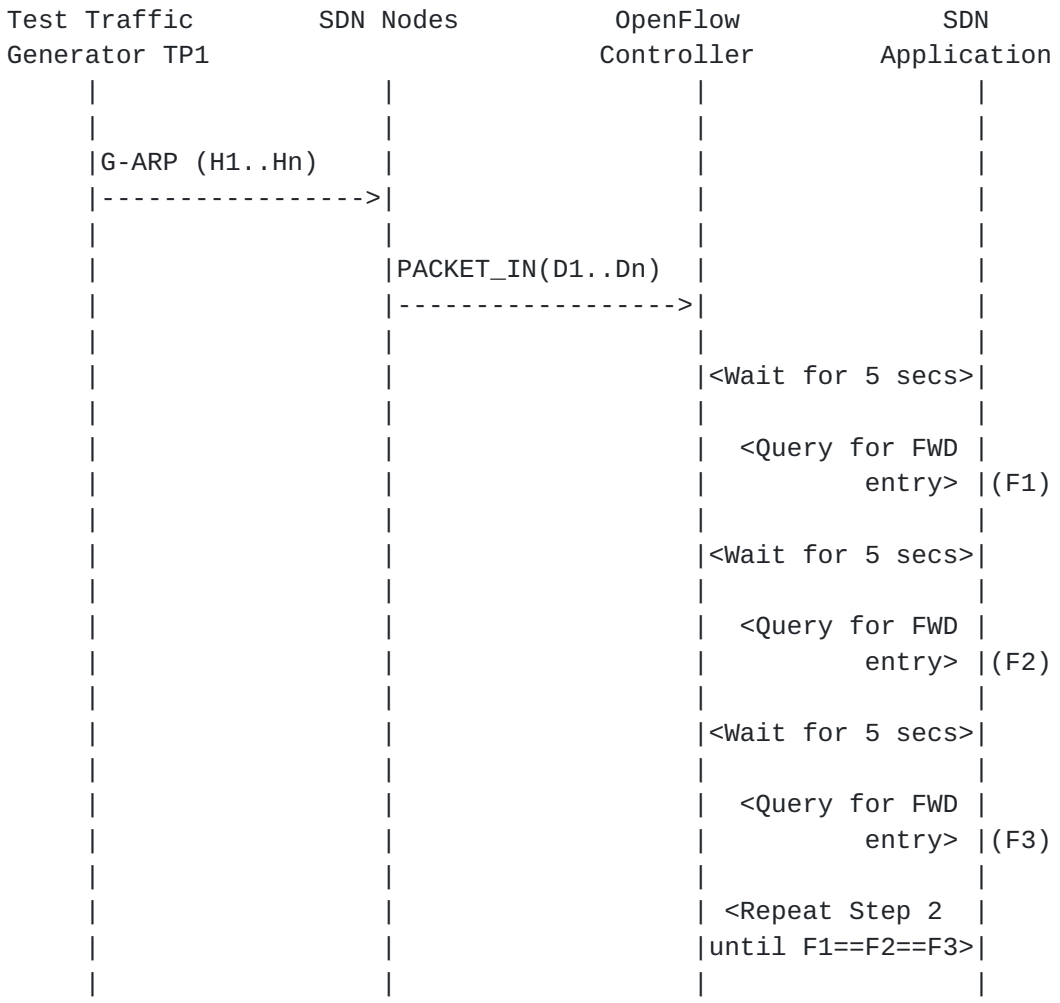
n/w topo: Network Topology
OF: OpenFlow

Discussion:

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

B.5.3. Forwarding Table Capacity

Procedure:



Legend:

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

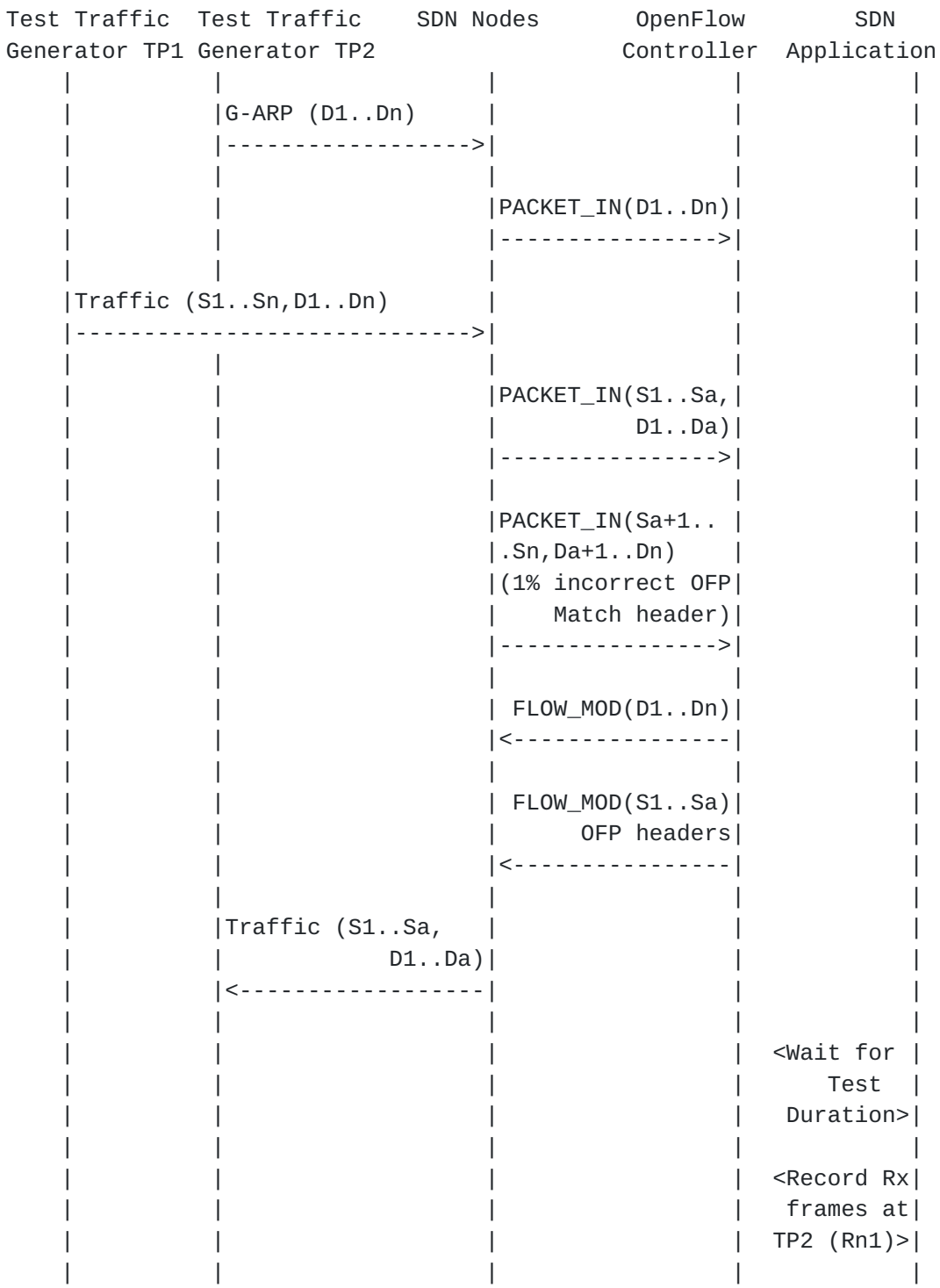
Discussion:

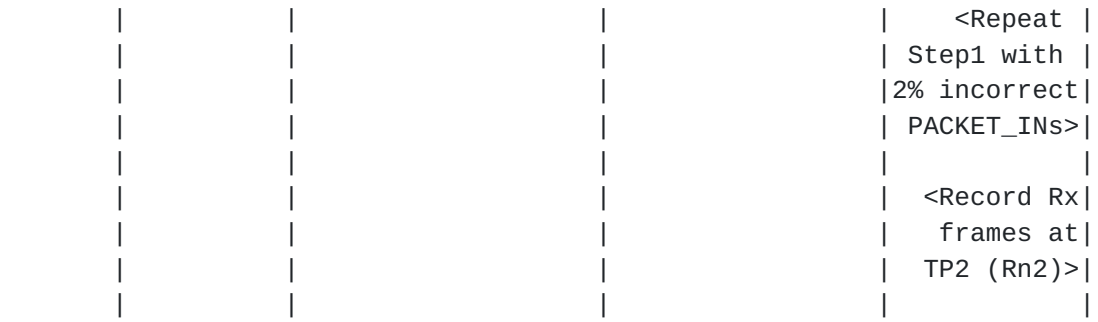
Query the controller forwarding table entries for multiple times until the three consecutive queries return the same value. The last value retrieved from the controller will provide the Forwarding Table Capacity value. The query interval is user configurable. The 5 seconds shown in this example is for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

B.6. Security

B.6.1. Exception Handling

Procedure:





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

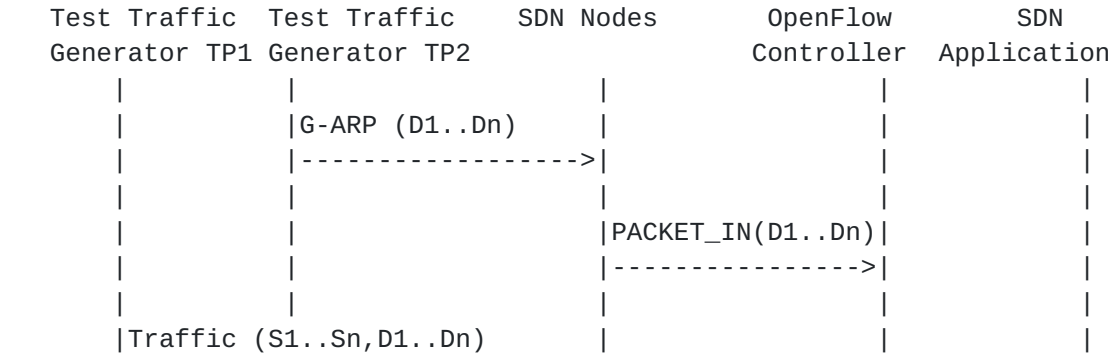
Discussion:

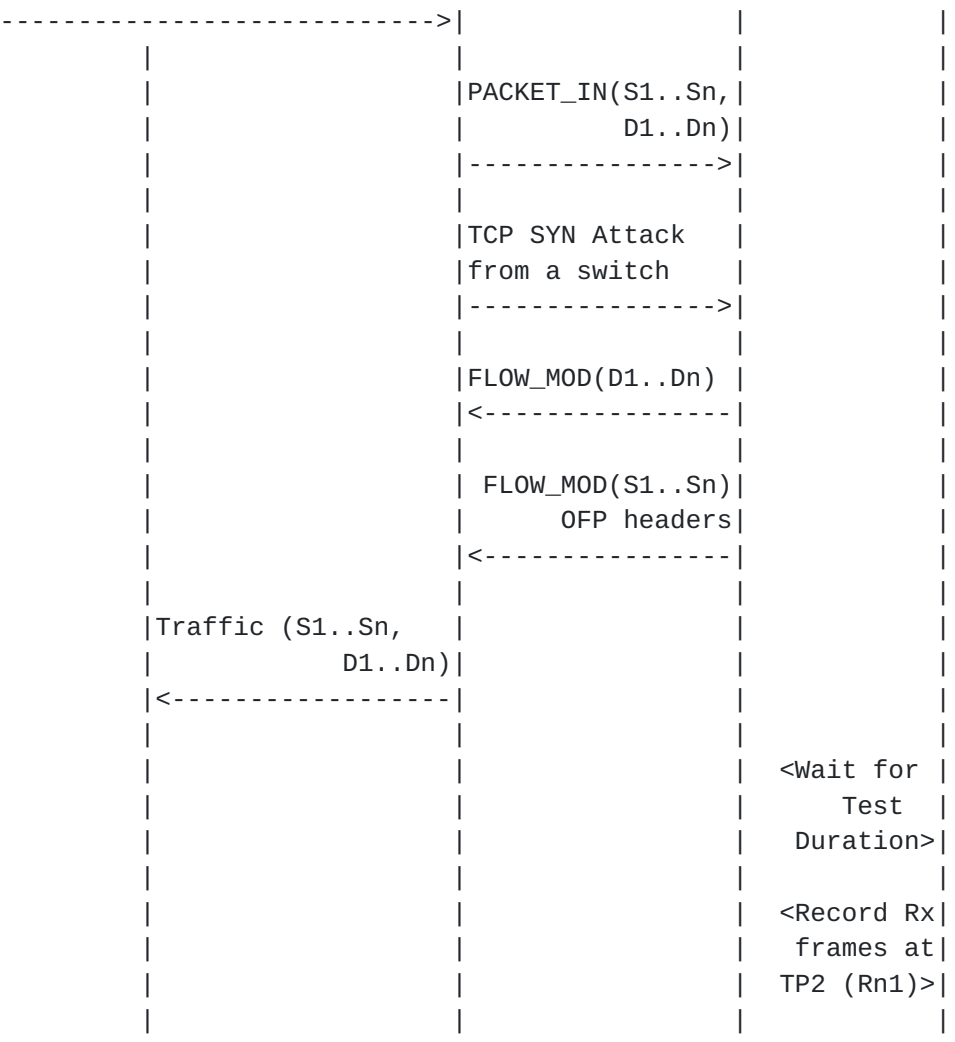
The traffic rate sent towards OpenFlow switch from Test Port 1 should be 1% higher than the Path Programming Rate. Rn1 will provide the Path Provisioning Rate of controller at 1% of incorrect frames handling and Rn2 will provide the Path Provisioning Rate of controller at 2% of incorrect frames handling.

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.

B.6.2. Denial of Service Handling

Procedure:





Legend:

G-ARP: Gratuitous ARP

Discussion:

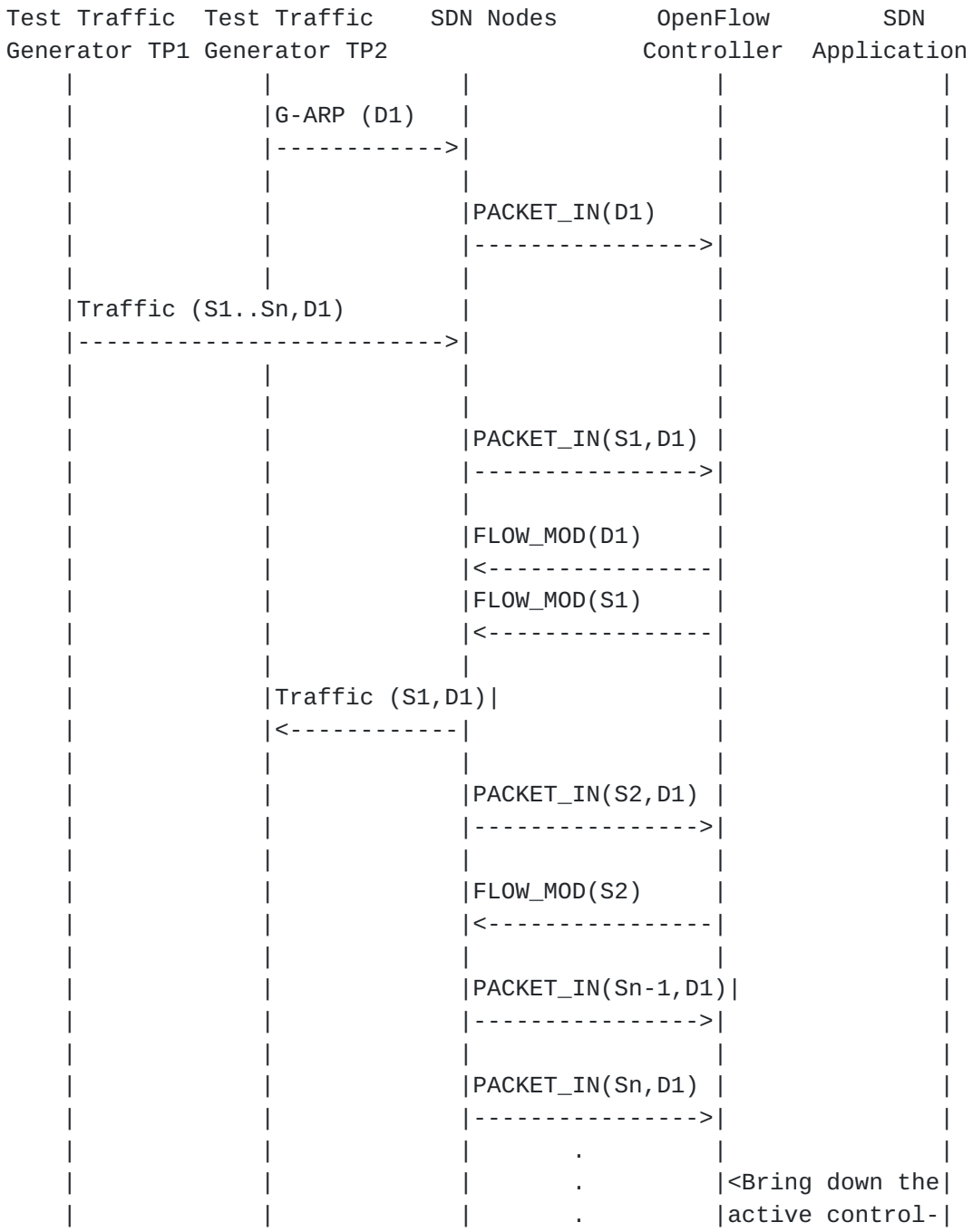
TCP SYN attack should be launched from one of the emulated/simulated OpenFlow Switch. Rn1 provides the Path Programming Rate of controller uponhandling denial of service attack.

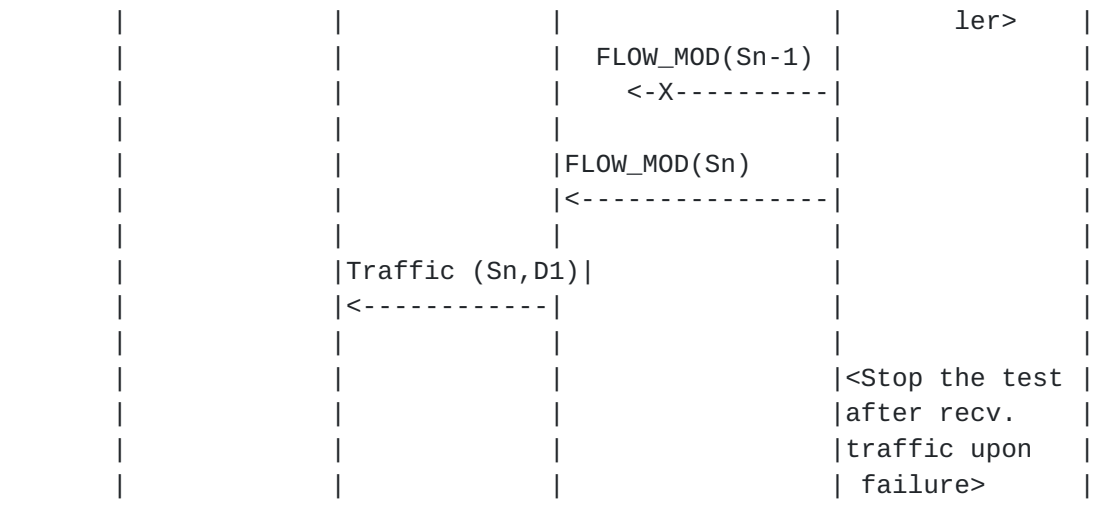
The procedure defined above provides test steps to determine the effect of handling denial of service on Path Programming Rate. Same procedure can be adopted to determine the effects on other performance tests listed in this benchmarking tests.

B.7. Reliability

B.7.1. Controller Failover Time

Procedure:





Legend:

G-ARP: Gratuitous ARP.

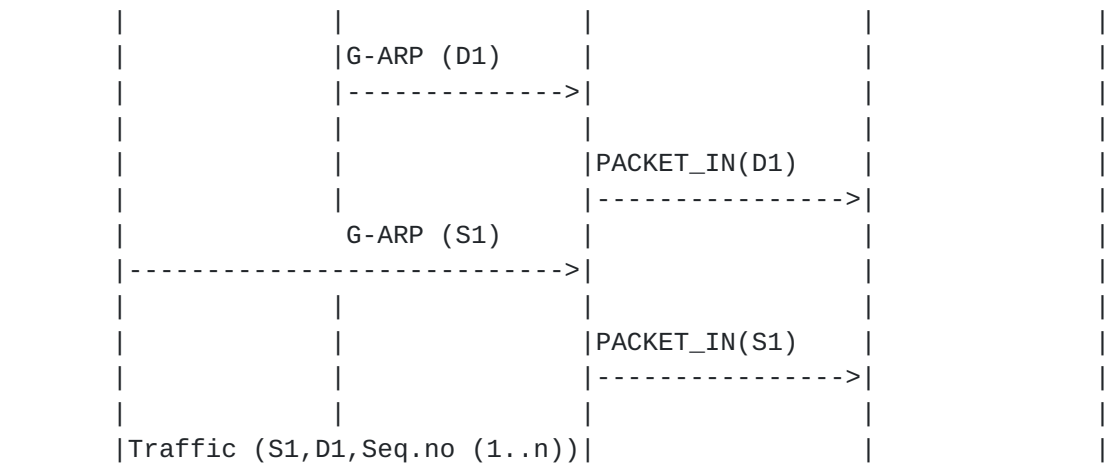
Discussion:

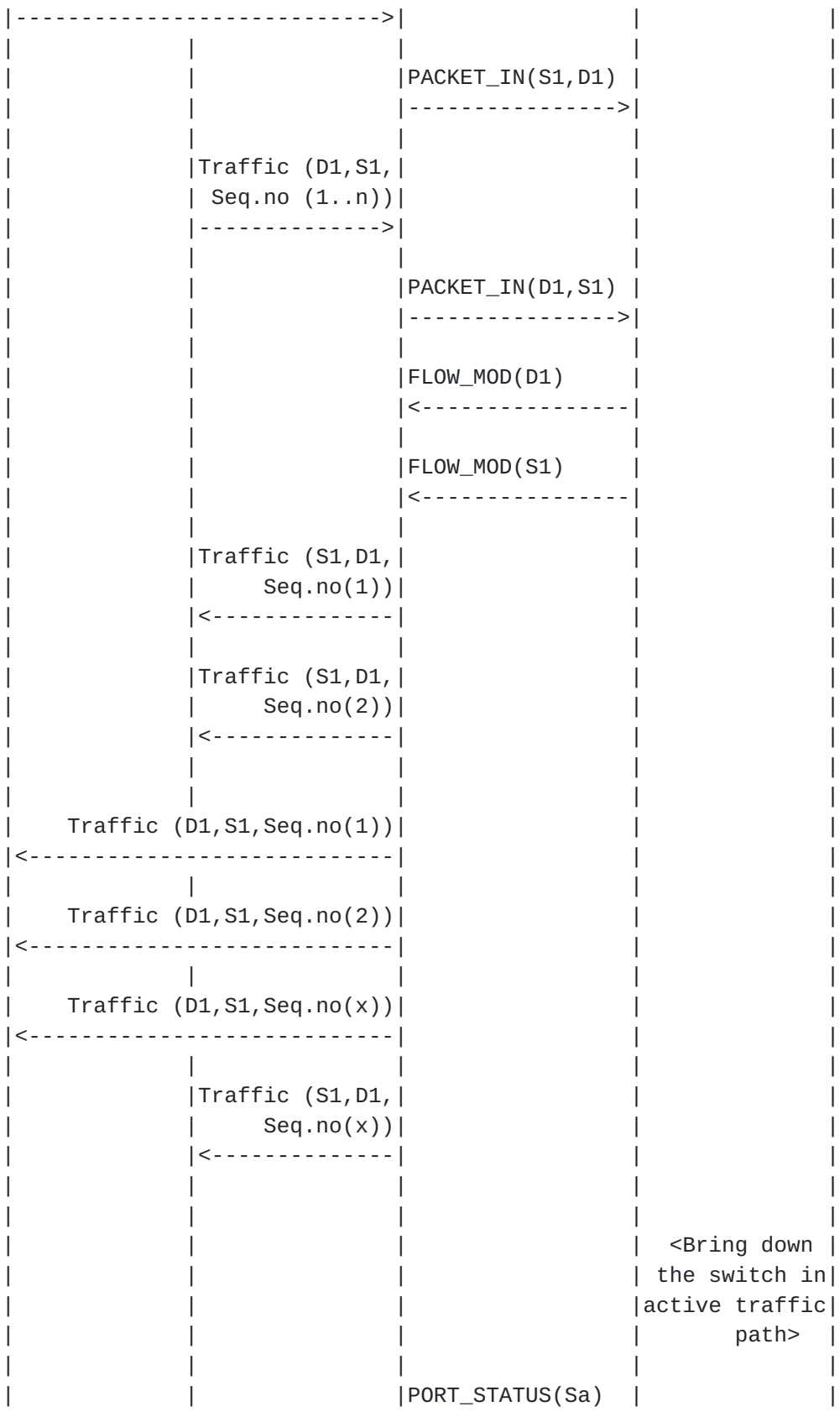
The time difference between the last valid frame received before the traffic loss and the first frame received after the traffic loss will provide the controller failover time.

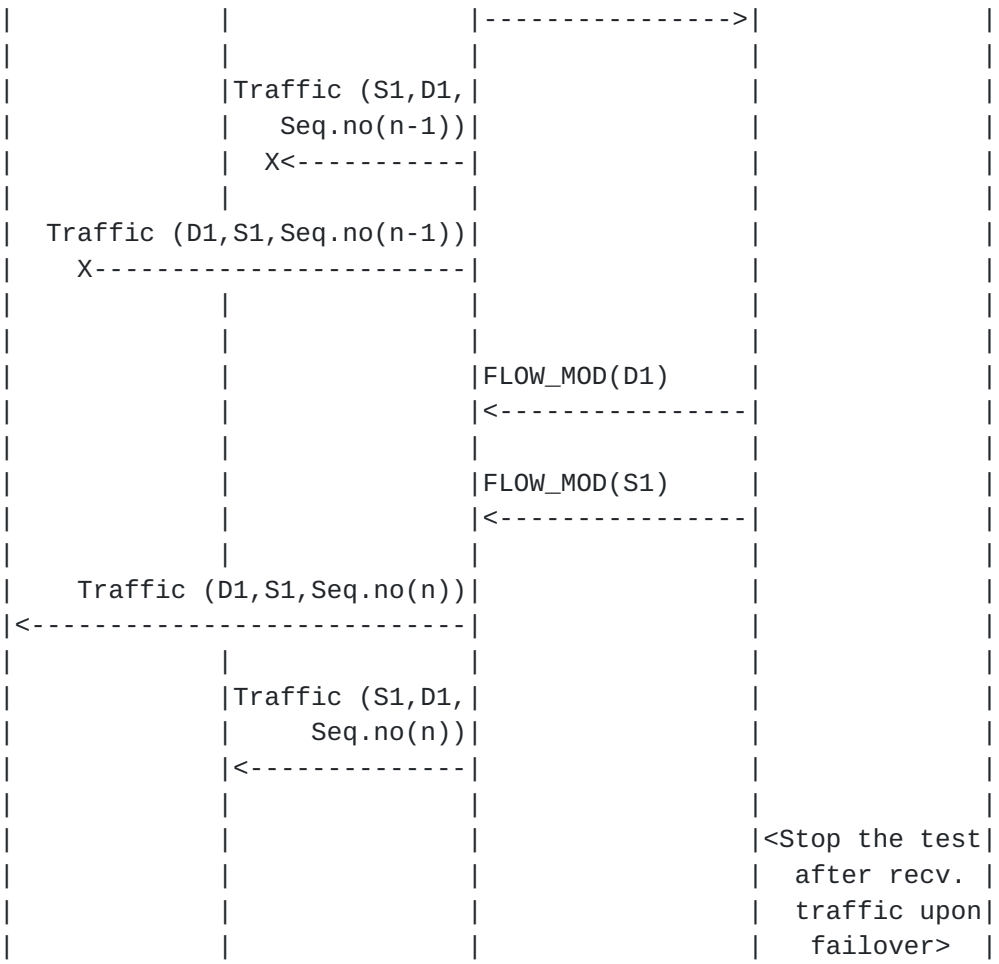
If there is no frame loss during controller failover time, the controller failover time can be deemed negligible.

B.7.2. Network Re-Provisioning Time

Procedure:




Traffic (D1,S1,
Seq.no (1..n))
PACKET_IN(S1,D1)
PACKET_IN(D1,S1)
FLOW_MOD(D1)
FLOW_MOD(S1)
Traffic (S1,D1,
Seq.no(1))
Traffic (S1,D1,
Seq.no(2))
Traffic (D1,S1,Seq.no(1))
Traffic (D1,S1,Seq.no(2))
Traffic (D1,S1,Seq.no(x))
Traffic (S1,D1,
Seq.no(x))
<Bring down
the switch in
active traffic
path>
PORT_STATUS(Sa)



Legend:

G-ARP: Gratuitous ARP message.
Seq.no: Sequence number.
Sa: Neighbour 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 test is valid only when the controller provisions the alternate path upon network failure.

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