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White Box Performance Testing and Evaluation

Recommendations for NRENs

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Abstract
This document describes how NRENs can test the performance of white boxes, and specifically their control plane (i.e. number of routes) and forwarding performance.

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Executive Summary

When qualifying a white box for a given use case, on an NREN backbone or in other production scenarios, all operational parameters (e.g., the maintenance model) and financial, strategic and performance aspects have to be checked, in addition to the features specific to that use case. As white boxes can run different Network Operating Systems (NOSs), their evaluation should take into account the performance not only of the control plane and data plane but also of the specific combination of the chosen software (NOS) and white box hardware. This document lists the factors that should be considered related to white box performance testing.

A white box's performance cannot be validated simply based on what is stated on its datasheet but should be tested and measured in practice. Performance can be measured for specific features, such as the maximum capacity to forward IPv6 packets, or can be evaluated for a targeted use case. In production use cases, performance depends on all the features that consume the white box's resources (i.e., memory, chipset forwarding cycles, etc).

The evaluation presented is of a Multi-Protocol Label Switching (MPLS) Provider router use case, in particular the control plane performance testing for the Label Switching Router (LSR), including the number of MAC addresses, IP addresses, routes, router adjacencies, Label Switched Paths (LSPs) etc. and forwarding performance. Forwarding performance testing is based on RFC 2889 *Benchmarking Methodology for LAN Switching Devices* and includes tests to determine how the buffer size and the existence of bursts might impact data plane forwarding capability. The main goal of the RFC 2889 test is to verify whether 'head of line' blocking and back pressure appears on the tested white box platform.

While the evaluation is presented in the context of a white box validation for an LSR use case, it can be adapted to other use cases. Some general conclusions are drawn for network equipment benchmarking, especially for white box use cases, and examples of performance measurements conducted in the PSNC Lab provided.

1 Introduction

To validate a network device, network providers must evaluate hardware performance. While the features provided by a NOS can be validated both in a virtual environment and on hardware, control plane and data plane performance can only be tested on hardware.

White box performance is one of the areas explored in the Network Technologies and Service Development Work Package (WP6) of the GN4-3 project. Various factors must be taken into consideration when testing performance in a specific use case, which will depend on a combination of different elements (for instance data plane software performance, chipset forwarding performance and TCAM size). Additionally, when evaluating white box performance, the coupling of the control and data plane must be assessed on specific hardware. It appears that the most pragmatic and the safest approach is to test the hardware in the context of the use case in which it will be used, as the different use cases (CPE, campus router, PE, LSR/P, data centre switch, etc.) may require different hardware designs.

This document presents the different performance factors and an evaluation of control plane and data plane performance based on [RFC2544] and [RFC2889] in the context of a label switch router (LSR). These tests can be used not only for white boxes but also for traditional network hardware. The tests were performed on an Edgecore AS5912-54X-O-AC-F, Dell EMC S4248FBL-ON white box running the OcNOS system. This NOS was identified as the most advanced in terms of Multiprotocol Label Switching (MPLS) functionalities.

The initial tests performed by the WP6 team included verification of basic MPLS features of an LSR for transit LSP setup, Intermediate-System to Intermediate-System (IS-IS) adjacency establishment and switching performance.

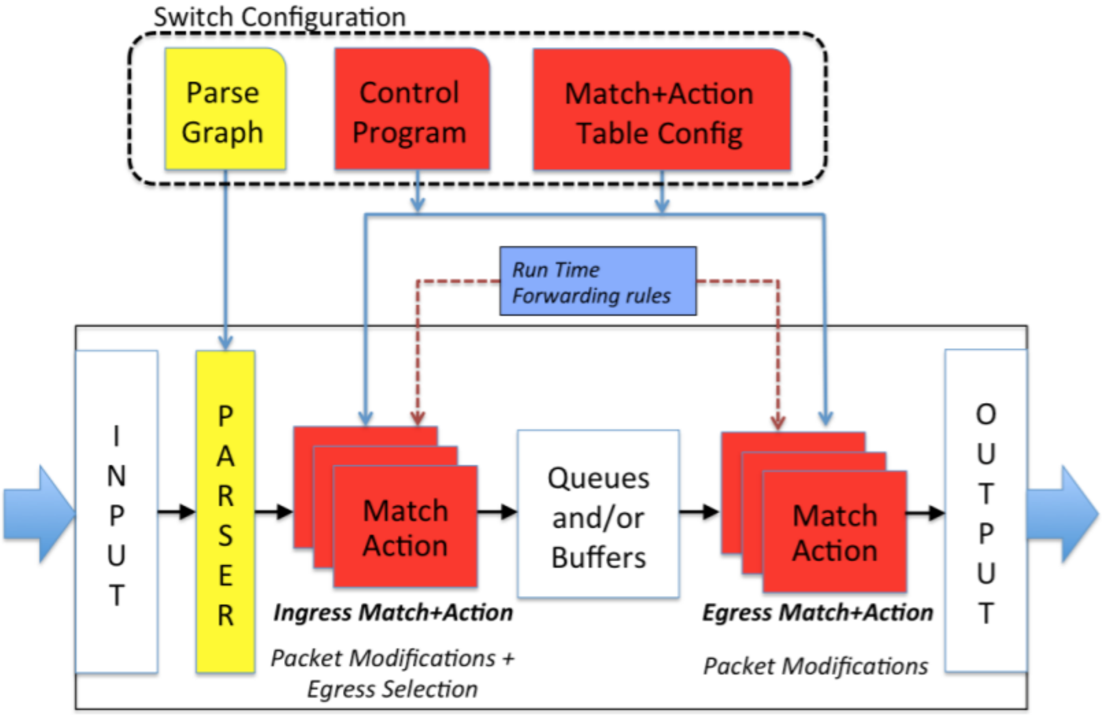
2 Performance Factors

The performance of a white box is determined by both the chosen hardware and software. Some parts of the software platform could require optimisation depending on the selected hardware. The performance factors that depend on the selected hardware are described in Table 2.1.

Hardware element	**Performance factor**
Forwarding chipset	Number of match/action stages in the pipeline
	Static Random Access Memory (SRAM)
	Ternary content addressable memory (TCAM)
	Packet buffer size
	Cryptography capabilities
CPU	Classical CPU performance

Table 2.1: Performance evaluation factors for hardware elements

The first piece of hardware is the forwarding chipset. The typical architecture of a forwarding chipset is presented in Figure 2.1. Some traditional vendors still continue to develop their own chipsets (e.g. ASICs) whereas white boxes use commodity hardware. While FPGA cards can be found in some routers, router manufacturers tend to try to and avoid integrating expensive FPGA cards in their hardware solutions.



Source: https://p4.org/p4-spec/p4-14/v1.0.5/tex/p4.pdf

Figure 2.1: Abstract Forwarding Model

TCAM can limit the number of routes the router can manage which also limits its applications. On some forwarding chipsets, one can plug an additional TCAM chipset (for instance TCAM: BCM52311) to solve this shortcoming.

Static Random Access Memory (SRAM) is used for various purposes (store table, variable, etc.), so this factor can limit the number of features that a forwarding chipset can provide.

The number of stages in the pipeline defines how powerful a device is, and varies depending on the chipset. In general, the more stages that are available, the more powerful the chipset is. Figure 2.2 shows the “stage units” within the ingress pipeline of a forwarding chipset according to the PISA architecture. With more stages, the chipset can manage more protocols and features. If there are not enough stages to manage a specific packet, a mechanism that allows reinjecting the packet within the pipeline for new packet processing may be available. Unfortunately, this process degrades the performance.

Traditional vendors continue to develop their own chipsets that provide specific features especially for MPLS and segment routing. For instance, these chipsets may support more MPLS labels that can be processed in a single lookup than is the case with commodity forwarding chipsets. The exact difference in terms of available features with commodity chipsets is not easy to identify. The network market seems to be divided into two sectors, with vendors either catering to data centres (Layer 2 network, VXLAN and shallow buffer) or to the MPLS market for telecommunication operators. Telecommunication operators often use MPLS for network transport and additional carrier grade services such as CGNAT, BRAS or PPPoE and are therefore strongly bound to traditional vendors. Nevertheless, manufacturers of commodity chipsets tend to narrow the gap in supported functions compared to legacy manufacturers. At the same time, traditional vendors widely use commodity hardware to reduce their costs.

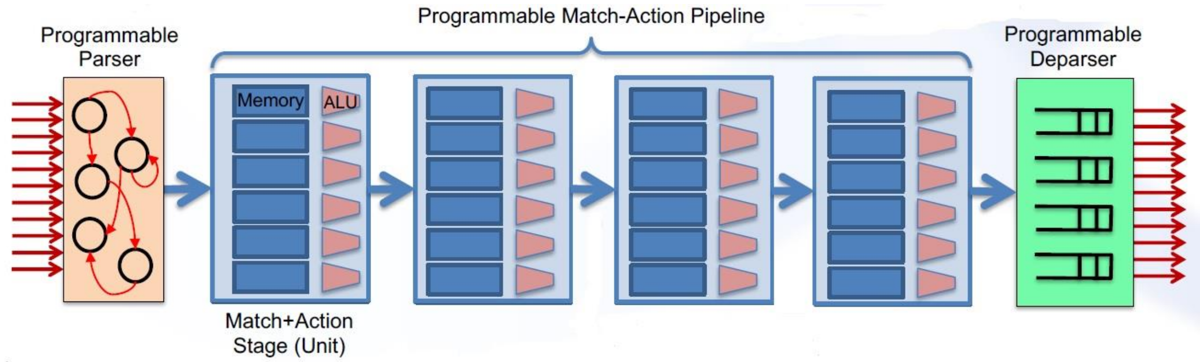


Figure 2.2: Internal architecture of ingress pipeline chipset

The packet buffer is mainly used for QoS or when the chipset needs to store a packet in memory for a short time because for instance the egress port is not available (congestion).

Some forwarding chipsets could also embed cryptography capabilities allowing for instance MACSec and IPSec support at line rate (BCM88850 Jericho2c+).

A last point of caution is that different versions of the same chipset exist that do not provide the same capabilities and features.

The router's CPU power is also an important aspect of the hardware, as the CPU could be used intensively for some processes. Therefore, typical processor performance tests should be carried out, including under conditions where the processor load is increased to the maximum to verify normal operation of the hardware under these conditions.

Some chipset manufacturers also provide additional features that could be considered important depending on the use case in question, for example: power consumption control, remote access, fan control.

An additional key factor that should be taken into consideration is the quality and performance of the software. The quality both of the control plane that handles network protocols and monitoring and of the data plane are crucial for performance. Some vendors are able to better exploit the functions provided by the software development kit (SDK) associated with the forwarding chipset. Some programming can be done to offload the execution of pieces of software from a CPU (control plane) and process them in the data plane. For instance, Bidirectional Forwarding Detection (BFD) can be offloaded to the data plane rather than being processed by the control plane. But this leads to a problem in terms of the capacity of the forwarding chipset (number of stages, memory etc.) in running several protocols. The software component that we have to mention is the one that enables the communication between the data plane and control plane.

3 Testbed Requirements

White box evaluation can be performed in two different stages. Functional tests may be performed even in a virtual environment (for instance with a GNS3 emulator) while performance tests should be conducted in real hardware testbeds with traffic generators such as Spirent Test Center, Ixia IxNetwork platforms or through homemade scripts. Depending on the use case, the testbed may consist of a single box or set of devices.

4 Control Plane Performance Test

Control plane performance tests should be adjusted to the targeted use case, which also identifies the key protocols that will be enabled. It is quite common for device or NOS vendors to provide performance values for a given protocol or mechanism. What is crucial for performance evaluation in that case is the verification of a complete set of protocols and technologies enabled simultaneously on the device. This means that the tester should measure a box's performance with a given number of prefixes in memory, a list of established protocol sessions or adjacencies, a list of enabled services, and so on.

Control plane performance testing includes verification not only of how many prefixes can be handled by the platform, but also of whether the device switches the traffic correctly in a given setup.

In order to properly evaluate the control plane of a networking device, the signalling of particular protocols should be evaluated both separately and together as a complete solution.

The first test gives an overview of a platform's capability to handle a given protocol at the required level, especially the number of accepted prefixes, peers, and established adjacencies which should be estimated together with network resiliency (recovery) time after failures (switchover).

The second test provides verification of a platform's ability to handle all the required mechanisms together.

As an example, let us consider the test scenario presented in Figure 4.1. The device under test (DUT) should be connected by a number of interfaces to the measurement equipment (network tester). On the tester platform, a set of protocols should be emulated reflecting conditions close to the desired real use case. The grey rectangles in Figure 4.1 represent the interfaces of the network tester that emulate the network connected to the DUT.

In the scenario presented in Figure 4.1, a set of IGP adjacencies is configured together with a number of transit LSPs. In this case, an LSR use case can be verified.

Once all protocol parameters are defined, the tester can analyse the status of the DUT control plane. Additionally, some traffic can be generated to verify whether the forwarding information database (FIB) was programmed properly.

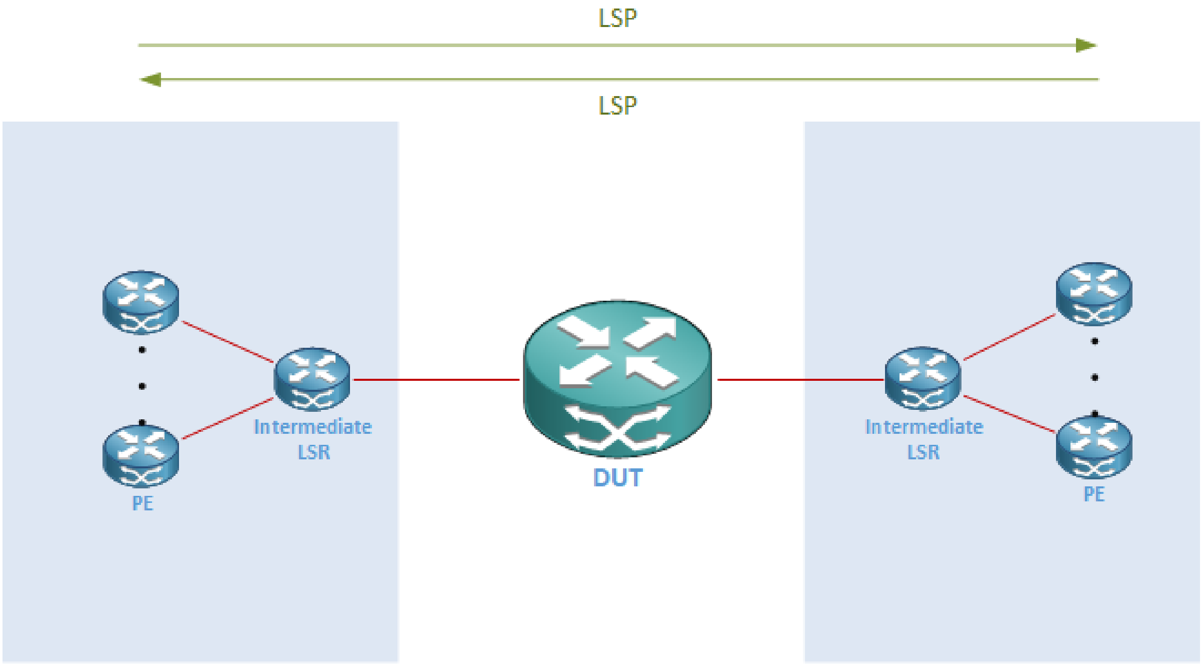


Figure 4.1: Control plane performance testbed architecture

5 Data Plane Performance

A set of data plane benchmarking methodologies has already been defined. [RFC2544] discusses and defines a number of tests that may be used to describe the performance characteristics of a network device and the set-up of the DUT (number of routes, filters, protocols configured). [RFC2889] provides the methodology for the benchmarking of local area network (LAN) switching devices and focuses on switching performance tests.

The test methodologies described in the RFCs are quite complex, so it is recommended to use any of the other automated test scenarios available for advanced testing platforms.

5.1 Performance Tests

The list of tests defined in [RFC2889] and based on Spirent Test Center [STC] documentation is provided in Table 5.1. Most of the tests are specific to Layer 2 switching but some of them can be used in other switching environments such as an MPLS backbone network. For example, a congestion control test can be used to validate MPLS P/PE devices.

The performance tests may require advanced measurement equipment. In the case of the STC tool, some pre-prepared tests aligned with RFC 2889 are provided (e.g. the RFC 2889 test suite). These tests were conducted using devices available in the PSNC lab.

Test case	Objective
Address Caching Capacity	This test determines the address caching capacity of a LAN switching device.
Address Learning Rate	This test determines the rate of address learning of a LAN switching device.
Broadcast Frame Forwarding	This test determines the throughput of the DUT when forwarding broadcast traffic.
Broadcast Frame Latency	This test determines the latency of the DUT when forwarding broadcast traffic.
Congestion Control	This test determines how a DUT handles congestion, specifically whether the device implements congestion control and whether congestion on one port affects an uncongested port.
Errored Frames Filtering	This test determines the behaviour of the DUT under error or abnormal

Test case	Objective
	frame conditions. The results of the test indicate whether the DUT filters or forwards the errored frames.
Forward Pressure Rate	This test overloads a DUT port by sending traffic with an interframe gap of 88 bits. If the DUT egress port transmits frames with an interframe gap that is less than 96 bits, then forward pressure is detected.
Forwarding Test	This test determines the throughput, frame loss, and forwarding rates of the DUT offered fully meshed, one-to-many, many-to-one, or one-to-one traffic as defined in RFC 2285. This wizard is used to run the tests in sections 5.1, 5.2, 5.3, and 5.4 of RFC 2889.
Maximum Forwarding Rate	This test measures the maximum forwarding rate of the DUT when the load is varied between the throughput value derived from the Throughput test and the maximum load (100%).

Table 5.1: RFC 2889 test cases

The congestion state on an interface has a negative impact on a wide set of applications relying on network transmission. Despite the existence of many technologies designed to avoid this, it is still a fairly common property of packet networks and should be evaluated on switching platforms and new network setups.

As shown in Figure 5.1, during the test two of the four ports are transmitters, while the other two are receivers. Ingress interfaces send traffic at 100% load. One of the two receiver ports is not congested; it receives 50% traffic from one transmitter and no traffic from the other port. The other receiver port, which is intentionally congested, receives the remaining traffic, for a total of 150% of its maximum capacity. If the results show frame loss at the uncongested port, then Head of Line Blocking (HOLB) is present. If there is no frame loss at the congested port, then Back Pressure is present. The results of the relevant tests for the LSR use case are presented in section 6.2.2.

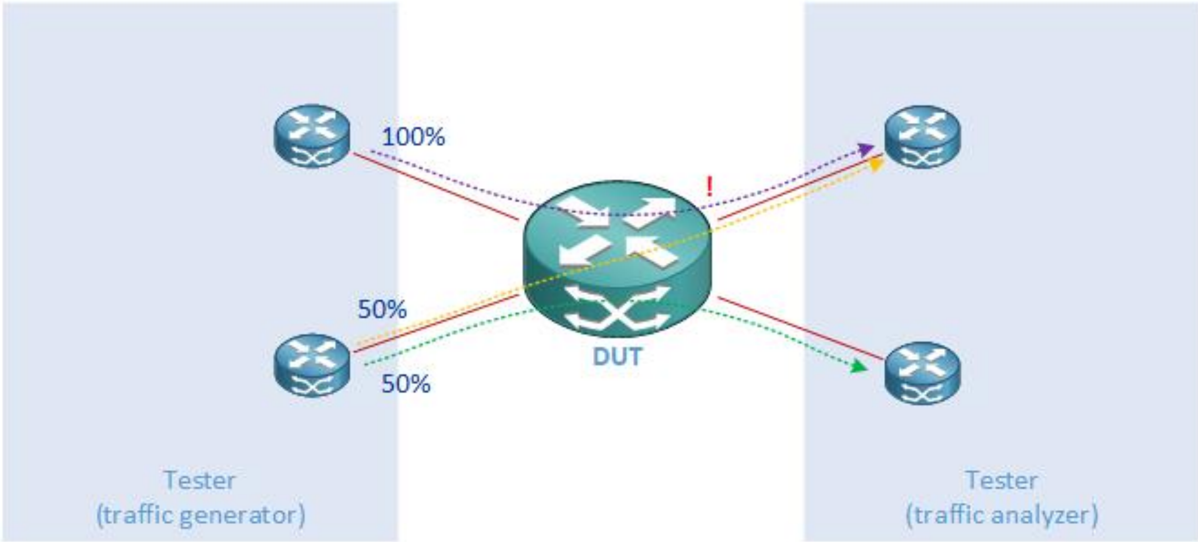


Figure 5.1: Congestion test set-up

5.2 Buffer Size Impact on Performance

After analysing the RFC 2889 results, the WP6 test team found that even with line-rate switching performance and without head-of-line blocking results differed between various hardware platforms – Edgecore AS5912-54X-O-AC-F, Dell EMC S4248FBL-ON, Arista 7280SR and Juniper PTX (see Appendix A for results).

The conclusion drawn from this was that the size of interface buffers is an important parameter of the switching platform. Therefore, it should be crucial for NRENs to also evaluate the switch in this respect.

The WP6 team designed a test setup that enables the buffer size of the given switch to be determined. The tests were performed using the Spirent Test Center platform. The key element of this test is overloading of the egress interface (Figure 5.2). This was achieved by generating two packet streams from two ingress interfaces to a single egress interface. Each stream kept the same mean transmission speed in bits per second. However, each stream also contained a number of burst packets in order to reproduce a “real network traffic” profile according to [RFC2544]. Burst packets are generated with maximum link speed (therefore with a minimum Inter Frame Gap). As a result, such bursts cannot be transmitted simultaneously on the egress interface and need to be buffered for a period of time. The goal of the test is to determine a packet per second value at which the DUT can successfully buffer without packet loss.

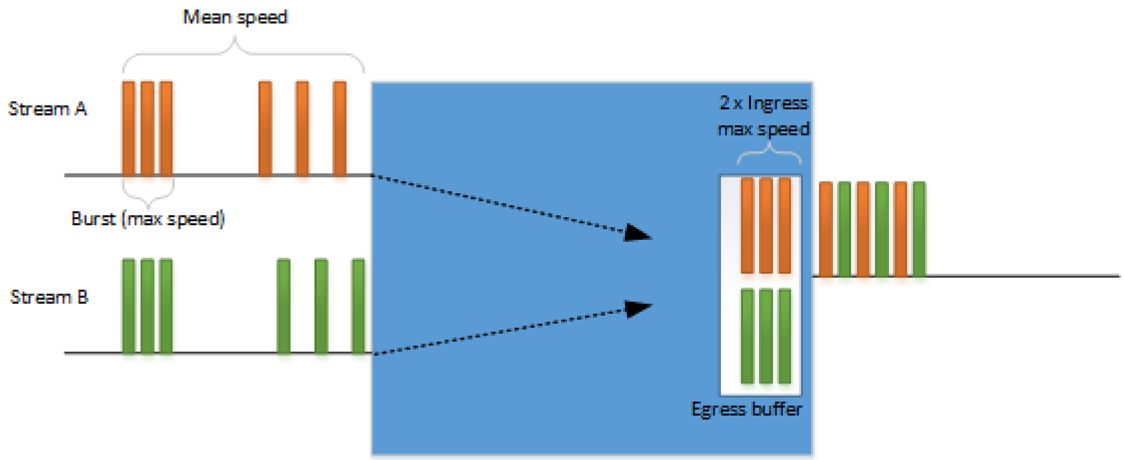


Figure 5.2: Egress traffic buffering

Figure 5.3 shows the basic test steps defined for buffer size estimation tests. The test is focused on the MPLS functionality of an LSR router, therefor MPLS signalling is activated first. However, for this type of test, it is not necessary to use MPLS traffic.

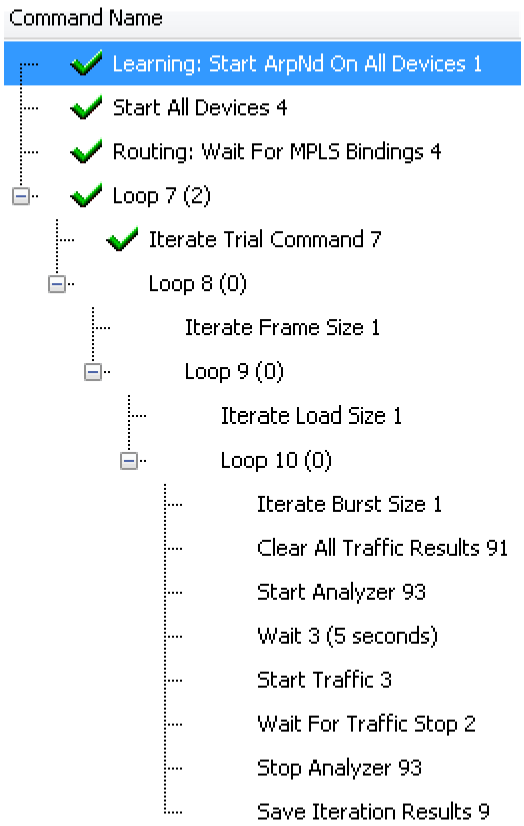


Figure 5.3: Buffer size estimation test steps

In general, the test scenario consists of two main loops. The first (internal) loop is used to iterate the burst size (Figure 5.4) – which is the number of packets sent at maximum speed.

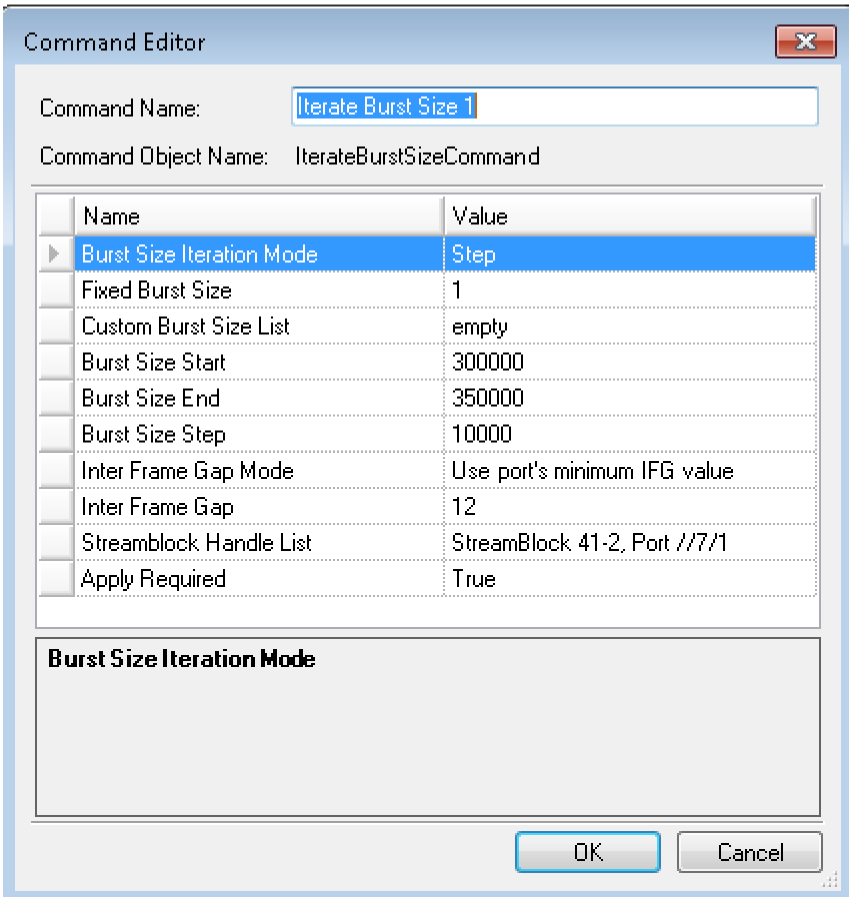


Figure 5.4: Burst size iteration loop

The second, outer, loop is used to increase the mean traffic load (speed). Additionally, the test may be repeated for a given number of frame sizes in order to determine whether the number of small packets has some influence on the buffering performance. It is crucial not to send frames of a specific size that could artificially improve the performance results. In this case, the Internet MIX [CAIDA] pattern can be used instead of frame size iteration.

Next, the measurement results are saved (for example to a database) for each iteration. The number of lost frames is important in this case, as the test is looking for the burst size value which does not lead to packet/frame drops.

6 Example Performance Test: the LSR Use Case

This section contains example test results for the measurements described earlier. In the testbed, an Edgecore AS5912-54X-O-AC-F white box and a Dell EMC S4248FBL-ON white box were tested under the OcNOS operating system. The results presented in this section by way of example were collected for the Edgecore AS5912-54X-O-AC-F switch.

Note:

The tests were performed with the Spirent TestCenter N11U platform, but similar functionality should also be available on other advanced network tester platforms.

6.1 Control Plane

Looking at the following examples of control plane tests for an LSR router use case, the first step is the configuration of the surrounding infrastructure to the DUT (see Figure 5.1). In this case, a set of two IS-IS routes were enabled on tester interfaces connected to the DUT (Figure 6.1).

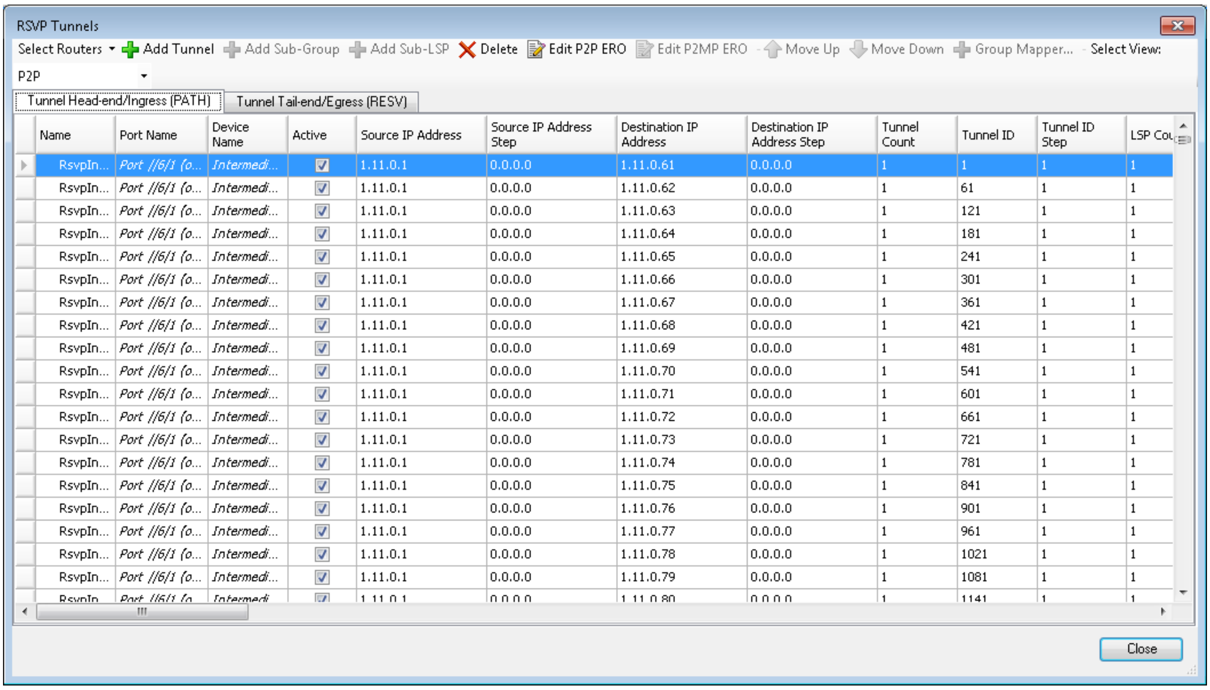
›4 | DS-Lite | BFD | RSVP | ISIS

Device Name	Tags	Device Count	›isable IP	IP Version	Level	Network Type	Router Priority	System ID	Host Name
Intermediate Router 1	Router	1	☐	IPv4	L2	Broadcast	0	00:10:94:00:00:09	Spirent-1
Intermediate Router 2	Router	1	☐	IPv4	L2	Broadcast	0	00:10:94:00:00:0A	Spirent-1

Figure 6.1: Emulated IS-IS router configuration example

For the LSR use case, the number of generated routes depends on the emulated network topology size (as there are no BGP transit routes on a pure P router). In order to check how the DUT operates in a mid-size MPLS core network, a network consisting of 11 neighbouring routers was defined using interfaces on the network tester. One of the routers was a DUT neighbour intermediate router and 10 were last-hop routers (destination routers). For the presented case, this gives 22 emulated routers.

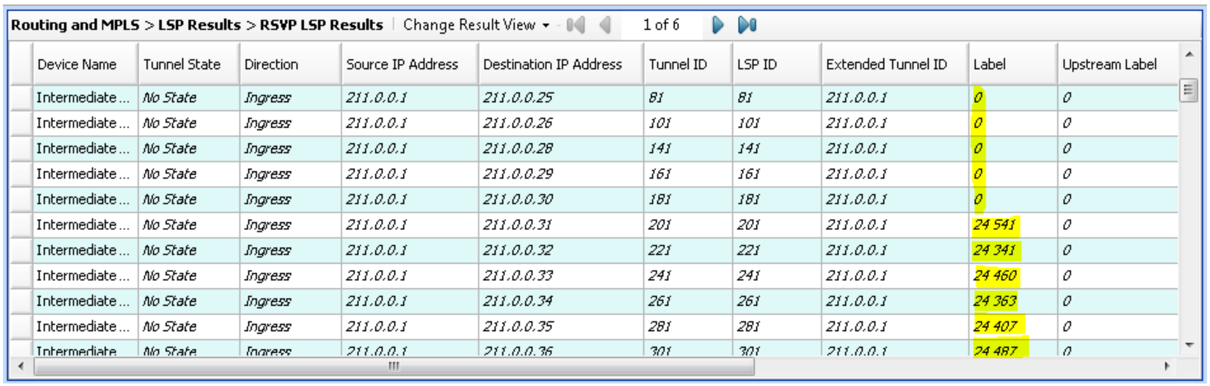
Next, the RSVP protocol was configured. RSVP is used to signal a number of transit LSPs (2x900 LSPs) passing through the DUT (Figure 6.2). It is recommended to estimate the number of expected LSPs in the production network and use similar values in the testbed.



Name	Port Name	Device Name	Active	Source IP Address	Source IP Address Step	Destination IP Address	Destination IP Address Step	Tunnel Count	Tunnel ID	Tunnel ID Step	LSP Cou
RsvpIn...	Port //6/1 (o...	Intermedi...	☑	1.11.0.1	0.0.0.0	1.11.0.61	0.0.0.0	1	1	1	1
RsvpIn...	Port //6/1 (o...	Intermedi...	☑	1.11.0.1	0.0.0.0	1.11.0.62	0.0.0.0	1	61	1	1
RsvpIn...	Port //6/1 (o...	Intermedi...	☑	1.11.0.1	0.0.0.0	1.11.0.63	0.0.0.0	1	121	1	1
RsvpIn...	Port //6/1 (o...	Intermedi...	☑	1.11.0.1	0.0.0.0	1.11.0.64	0.0.0.0	1	181	1	1
RsvpIn...	Port //6/1 (o...	Intermedi...	☑	1.11.0.1	0.0.0.0	1.11.0.65	0.0.0.0	1	241	1	1
RsvpIn...	Port //6/1 (o...	Intermedi...	☑	1.11.0.1	0.0.0.0	1.11.0.66	0.0.0.0	1	301	1	1
RsvpIn...	Port //6/1 (o...	Intermedi...	☑	1.11.0.1	0.0.0.0	1.11.0.67	0.0.0.0	1	361	1	1
RsvpIn...	Port //6/1 (o...	Intermedi...	☑	1.11.0.1	0.0.0.0	1.11.0.68	0.0.0.0	1	421	1	1
RsvpIn...	Port //6/1 (o...	Intermedi...	☑	1.11.0.1	0.0.0.0	1.11.0.69	0.0.0.0	1	481	1	1
RsvpIn...	Port //6/1 (o...	Intermedi...	☑	1.11.0.1	0.0.0.0	1.11.0.70	0.0.0.0	1	541	1	1
RsvpIn...	Port //6/1 (o...	Intermedi...	☑	1.11.0.1	0.0.0.0	1.11.0.71	0.0.0.0	1	601	1	1
RsvpIn...	Port //6/1 (o...	Intermedi...	☑	1.11.0.1	0.0.0.0	1.11.0.72	0.0.0.0	1	661	1	1
RsvpIn...	Port //6/1 (o...	Intermedi...	☑	1.11.0.1	0.0.0.0	1.11.0.73	0.0.0.0	1	721	1	1
RsvpIn...	Port //6/1 (o...	Intermedi...	☑	1.11.0.1	0.0.0.0	1.11.0.74	0.0.0.0	1	781	1	1
RsvpIn...	Port //6/1 (o...	Intermedi...	☑	1.11.0.1	0.0.0.0	1.11.0.75	0.0.0.0	1	841	1	1
RsvpIn...	Port //6/1 (o...	Intermedi...	☑	1.11.0.1	0.0.0.0	1.11.0.76	0.0.0.0	1	901	1	1
RsvpIn...	Port //6/1 (o...	Intermedi...	☑	1.11.0.1	0.0.0.0	1.11.0.77	0.0.0.0	1	961	1	1
RsvpIn...	Port //6/1 (o...	Intermedi...	☑	1.11.0.1	0.0.0.0	1.11.0.78	0.0.0.0	1	1021	1	1
RsvpIn...	Port //6/1 (o...	Intermedi...	☑	1.11.0.1	0.0.0.0	1.11.0.79	0.0.0.0	1	1081	1	1
RsvpIn...	Port //6/1 (o...	Intermedi...	☑	1.11.0.1	0.0.0.0	1.11.0.80	0.0.0.0	1	1141	1	1

Figure 6.2: Examples of emulated RSVP LSPs

After the LSPs have been configured on the network tester the LSP status can be verified on the DUT and on the network tester itself (Figure 6.5 and Figure 6.4). As shown in Figure 6.4, 2x900 LSP were implemented for the test. This gives a complete overview of the full signalling process.



Device Name	Tunnel State	Direction	Source IP Address	Destination IP Address	Tunnel ID	LSP ID	Extended Tunnel ID	Label	Upstream Label
Intermediate ...	No State	Ingress	211.0.0.1	211.0.0.25	81	81	211.0.0.1	0	0
Intermediate ...	No State	Ingress	211.0.0.1	211.0.0.26	101	101	211.0.0.1	0	0
Intermediate ...	No State	Ingress	211.0.0.1	211.0.0.28	141	141	211.0.0.1	0	0
Intermediate ...	No State	Ingress	211.0.0.1	211.0.0.29	161	161	211.0.0.1	0	0
Intermediate ...	No State	Ingress	211.0.0.1	211.0.0.30	181	181	211.0.0.1	0	0
Intermediate ...	No State	Ingress	211.0.0.1	211.0.0.31	201	201	211.0.0.1	24 541	0
Intermediate ...	No State	Ingress	211.0.0.1	211.0.0.32	221	221	211.0.0.1	24 341	0
Intermediate ...	No State	Ingress	211.0.0.1	211.0.0.33	241	241	211.0.0.1	24 460	0
Intermediate ...	No State	Ingress	211.0.0.1	211.0.0.34	261	261	211.0.0.1	24 363	0
Intermediate ...	No State	Ingress	211.0.0.1	211.0.0.35	281	281	211.0.0.1	24 407	0
Intermediate	No State	Ingress	211.0.0.1	211.0.0.36	301	301	211.0.0.1	24 487	0

Figure 6.3: Examples of emulated RSVP LSP status

Port Name	Device Name	Router State	LSP Up	LSP Down	LSP Connecting	Egress LSP Up	Tx Hello	Rx Hello	Tx PATH	Rx PATH	Tx RESV	Rx RESV
Port //6/1	Intermediate Router 1	RSVP_STATE_UP	900	0	0	900	0	0	4 574	3 600	1 800	1 800
Port //6/2	Intermediate Router 2	RSVP_STATE_UP	900	0	0	900	0	0	4 940	3 600	1 800	1 800

Figure 6.4: Example of RSVP protocol summary results

Once all the signalling protocols are operating properly, traffic can be mapped to emulated LSPs and the accuracy of the forwarding mechanism can be additionally verified. In the example shown in Figure 6.5, a traffic stream block was defined that emulates data exchange over LSP tunnels.

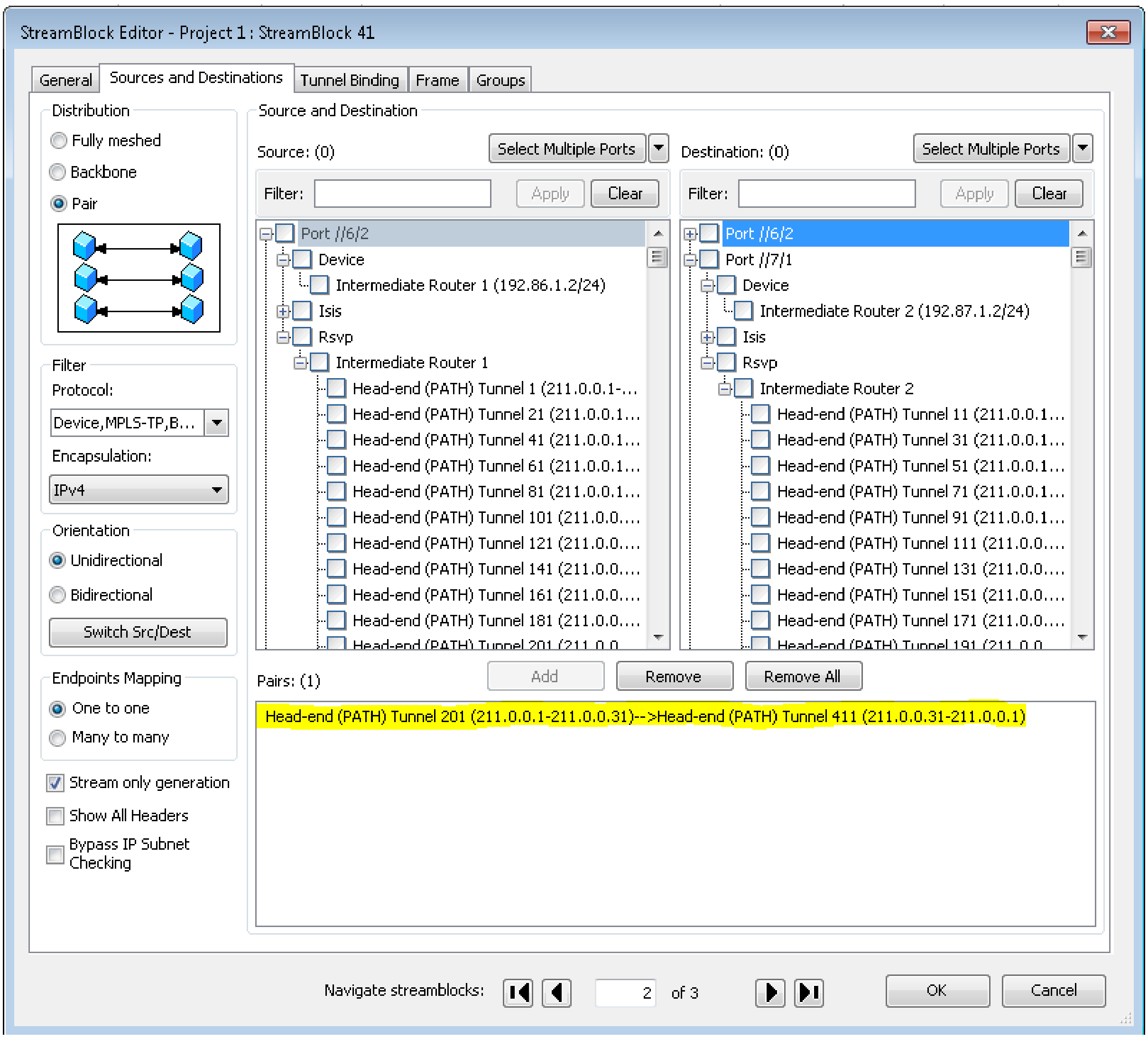


Figure 6.5: Examples of traffic stream definition on network tester

6.2 Data Plane

6.2.1 Switching Performance

Switching performance testing must be done for a specific use case, using the exact configuration of networking devices. The approach used in section 6.1 can be reused here. The packets sent to the DUT to validate the control plane performance do not need to reach a high throughput but the same type of packet can be reused. This is what is called a data stream in the traffic injector used. The network tester produces a large amount of data as a result of measurement. In order to analyse it efficiently, a level of hierarchical overview of the collected data is provided by regrouping data streams into larger blocks called stream blocks. In Figure 6.6, the measurements for two stream blocks are presented (LSP-3 and LSP-4). Within the LSP-3 stream block, the traffic was sent from port 6/1 of the tester and expected to be received at port 6/2. The LSP-4 stream block transferred the data in the opposite direction. Next, the total number of sent and received frames for each stream block is presented. As shown in Figure 6.6, there is a significant difference between the number of sent and received frames, which will be examined further.

Tx Port	Rx Port	Stream Block	Tx Count (Frames)	Rx Count (Frames)
Port //6/1	Port //6/2	LSP-3	21 511 013 851	5 006 260 099
Port //6/2	Port //6/1	LSP-4	21 510 453 759	5 006 590 467

Figure 6.6: Stream block basic results example

For a more precise analysis, detailed data are presented in Figure 6.7. It can be noted that the LSP-3 stream block consists of a number of individual streams. Each stream represents the traffic sent by an individual LSP established with the RSVP protocol. Again, the number of sent and received frames for each stream is shown. This is useful to identify the faulty LSP. In the presented example, a significant difference can be seen between the number of sent and received frames for each stream.

Tx Port	Rx Port	Stream Block	Stream Id	Stream Index	Tx Count (Frames)	Rx Count (Frames)	Expected Rx Count (Frames)	Tx-Rx (Frames)	Tx-Rx (%)
Port //6/1	Port //6/2	LSP-3	65 536	0	11 949 802	2 781 241	11 949 802	9 168 561	76,726
Port //6/1	Port //6/2	LSP-3	65 537	1	11 949 802	2 781 241	11 949 802	9 168 561	76,726
Port //6/1	Port //6/2	LSP-3	65 538	2	11 949 802	2 781 241	11 949 802	9 168 561	76,726
Port //6/1	Port //6/2	LSP-3	65 539	3	11 949 802	2 781 241	11 949 802	9 168 561	76,726
Port //6/1	Port //6/2	LSP-3	65 540	4	11 949 802	2 781 241	11 949 802	9 168 561	76,726
Port //6/1	Port //6/2	LSP-3	65 541	5	11 949 802	2 781 241	11 949 802	9 168 561	76,726
Port //6/1	Port //6/2	LSP-3	65 542	6	11 949 802	2 781 241	11 949 802	9 168 561	76,726
Port //6/1	Port //6/2	LSP-3	65 543	7	11 949 803	2 781 241	11 949 803	9 168 562	76,726
Port //6/1	Port //6/2	LSP-3	65 544	8	11 949 803	2 781 241	11 949 803	9 168 562	76,726
Port //6/1	Port //6/2	LSP-3	65 545	9	11 949 803	2 781 241	11 949 803	9 168 562	76,726
Port //6/1	Port //6/2	LSP-3	65 546	10	11 949 803	2 781 241	11 949 803	9 168 562	76,726
Port //6/1	Port //6/2	LSP-3	65 547	11	11 949 803	2 781 241	11 949 803	9 168 562	76,726

Figure 6.7: Individual stream measurements example

The above examples imply some common problems for all test traffic. Further analysis indicated an MTU misconfiguration problem between the network tester and the DUT. MTU handling is one of the common differences between hardware and software platforms. This fact needs to be taken into account when preparing a test configuration.

A successful example of another measurement is presented in Figure 6.8.

Tx Port	Rx Port	Stream Block	Stream Id	Stream Index	Tx Count (Frames)	Rx Count (Frames)	Expected Rx Count (Frames)	Tx-Rx (Frames)	Tx-Rx (%)
Port //6/2	Port //7/2	StreamBlock 41-2	65 536	0	82 200 000	82 200 000	82 200 000	0	0
Port //7/1	Port //7/2	StreamBlock 43-2	131 072	0	81 900 001	81 900 001	81 900 001	0	0

Figure 6.8: Individual stream block measurement example (without lost frames)

6.2.2 Burst Size

In order to estimate the burst size for the DUT, three interfaces were used, including two ingress interfaces and one egress interface. The goal of the test was to send more traffic than the total egress interface capacity for a short period of time and to check how many packets are buffered before being dropped by the DUT.

The burst size test consists of several iterations. In each step the number of packets sent with maximum speed (line-rate) was increased. Table 6.1 presents the load and burst size for each test interface, and the total number of frames sent and received during each test step iteration.

iMIX	Duration (seconds)	Load (%)	Burst size (packets)	Tx Frames	Rx Frames	Frame Loss
Default	10	25	300000	164094616	164094615	1
Default	10	25	310000	164101282	164101280	2
Default	10	25	320000	164101642	164101642	0
Default	10	25	330000	164101095	164101094	1
Default	10	25	340000	164198274	164198274	0
Default	10	25	350000	164199178	164199178	0
Default	10	25	360000	164100548	164100548	0
Default	10	25	370000	164150470	164121767	28703
Default	10	25	380000	164199155	164119437	79718
Default	10	25	390000	164250366	164119897	130469
Default	10	25	400000	164195943	164015144	180799
Default	10	25	410000	164293138	164063449	229689
Default	10	25	420000	163807802	163528782	279020
Default	10	25	430000	164395878	164065643	330235
Default	10	25	440000	164395361	164015909	379452
Default	10	25	450000	164250220	163819443	430777
Default	10	25	460000	164000206	163520188	480018
Default	10	25	470000	164050194	163521677	528517
Default	10	25	480000	164397161	163817198	579963
Default	10	25	490000	164350174	163721072	629102
Default	10	30	300000	196826355	196826354	1
Default	10	30	310000	196844832	196844830	2
Default	10	30	320000	196850130	196850130	0
Default	10	30	330000	196850607	196850606	1
Default	10	30	340000	196852433	196852433	0
Default	10	30	350000	196750788	196750788	0

iMIX	Duration (seconds)	Load (%)	Burst size (packets)	Tx Frames	Rx Frames	Frame Loss
Default	10	30	360000	196853728	196853728	0
Default	10	30	370000	196913870	196885239	28631
Default	10	30	380000	196850056	196770373	79683
Default	10	30	390000	196659583	196529807	129776
Default	10	30	400000	196724653	196544351	180302
Default	10	30	410000	196790256	196560304	229952
Default	10	30	420000	196849630	196570672	278958
Default	10	30	430000	196950304	196619101	331203
Default	10	30	440000	196700282	196319904	380378
Default	10	30	450000	197047464	196618784	428680
Default	10	30	460000	196850088	196369507	480581
Default	10	30	470000	196593068	196061762	531306
Default	10	30	480000	197100220	196521978	578242
Default	10	30	490000	196650208	196021660	628548

Table 6.1: Example of the burst size test results

As can be noted, for burst sizes lower than or equal to 360,000 packets, there is no major frame loss. However, for burst size greater than 360,000 packets, high frame loss is observed independently from the load size. This allows an estimate that the DUT can handle about 1.2Mpps in the buffer (for the iMIX packet size distribution pattern). This value should then be taken into account when a hardware platform is selected for a given use case.

7 Conclusions

A NOS is often evaluated by a network operator (or an institution network engineer) from the point of view of functionality, to verify whether it contains the features needed to build a solution for a given use case, and can interoperate with other components in the overall solution.

However, it is also important to consider the performance of the solution. While data plane and control plane tests can be conducted separately in a testbed, to obtain the most accurate performance figures for a white box testbed, it is recommended that combined data plane and control plane tests be performed. Several use cases can be validated for a specific hardware. Being able to handle several use cases could be seen as an advantage depending on the hardware deployment strategy adopted.

The overall solution performance will always depend on the combination of the hardware platform and the NOS used (see Appendix A), which is precisely why it is important to understand how to both define and run the most appropriate tests to conduct performance evaluations for a given combination, including both control and data plane tests.

Depending on the test goals, the user may try to establish maximum performance values for a given set of enabled features and level of traffic or may verify the device operation under given network conditions. In the first case, the combined (data plane and control plane) test of the performance limit can be evaluated for the targeted use case. Using the second approach, the user can verify if the DUT has sufficient capacity for the targeted use case.

The goal of the example test conducted in the lab and described in this document was to assess the data plane performance for a specific use case (LSP router). This type of test allows users to evaluate hardware performance and system stability in a real production environment, in real use case conditions (for example the number of routes or LSPs, BGP sessions, etc.). These tests should last long enough to correctly validate the DUT.

Based on the experiences of the WP6 team, it is recommended to perform a 24-hour test with generated traffic and a 7-day test verifying control plane stability. In this context a test scenario should include automatic generation of topology change events. Taking into account the scale of work needed for the validation process, specific network testing equipment was used. The network tester provided testing scenarios related to the RFC benchmarks [RFC2889, RFC3918], and BGP or IS-IS topologies. In addition, the WP6 test team adjusted the RFC 2889 test scenario for the NREN MPLS backbone use case.

During the tests conducted in the lab no hardware limitation related to features offered by the NOS was found. This suggests that the tested NOS (OcNOS) properly maps (bounds) its functionality to the hardware resources of the white box platform and that the features offered by the NOS can be implemented using the chosen white box hardware.

The example test results provided in Appendix A, which were obtained using a network tester device, show that buffer size differs between hardware platforms. This result confirms the importance of hardware platform selection when a white box-based solution is planned for deployment in the network.

Appendix A Burst Test Results

A.1 Arista 7280SR

iMIX Distribution	Duration (Seconds)	Load (%)	Burst size (packets)	Tx Frames	Rx Frames	Rx Expected Frames	Frame Loss
AristaMPLS	10	25	300000	164173178	164173178	164173178	0
AristaMPLS	10	25	310000	164153284	164153284	164153284	0
AristaMPLS	10	25	320000	164146748	164146748	164146748	0
AristaMPLS	10	25	330000	164243074	164243074	164243074	0
AristaMPLS	10	25	340000	164200822	164200822	164200822	0
AristaMPLS	10	25	350000	164250658	164250658	164250658	0
AristaMPLS	10	25	360000	164100548	164100548	164100548	0
AristaMPLS	10	25	370000	164150470	164150470	164150470	0
AristaMPLS	10	25	380000	164342883	164342883	164342883	0
AristaMPLS	10	25	390000	164250366	164250366	164250366	0
AristaMPLS	10	25	400000	164341337	164341337	164341337	0
AristaMPLS	10	25	410000	164441483	164441483	164441483	0
AristaMPLS	10	25	420000	163949976	163949976	163949976	0
AristaMPLS	10	25	430000	164450254	164450254	164450254	0
AristaMPLS	10	25	440000	164500236	164488864	164500236	11372
AristaMPLS	10	25	450000	164250220	164204166	164250220	46054
AristaMPLS	10	25	460000	164000206	163919802	164000206	80404
AristaMPLS	10	25	470000	164050194	163935817	164050194	114377
AristaMPLS	10	25	480000	164540250	164391318	164540250	148932
AristaMPLS	10	25	490000	164350174	164167212	164350174	182962
AristaMPLS	10	30	300000	196942040	196942040	196942040	0
AristaMPLS	10	30	310000	196953444	196953444	196953444	0
AristaMPLS	10	30	320000	196901970	196901970	196901970	0
AristaMPLS	10	30	330000	196951314	196951314	196951314	0
AristaMPLS	10	30	340000	197000986	197000986	197000986	0
AristaMPLS	10	30	350000	196894947	196894947	196894947	0
AristaMPLS	10	30	360000	197024993	197024993	197024993	0
AristaMPLS	10	30	370000	197050564	197050564	197050564	0
AristaMPLS	10	30	380000	197027130	197027130	197027130	0
AristaMPLS	10	30	390000	196829703	196829703	196829703	0
AristaMPLS	10	30	400000	196895148	196881629	196895148	13519
AristaMPLS	10	30	410000	196956261	196894950	196956261	61311
AristaMPLS	10	30	420000	197024514	196915406	197024514	109108
AristaMPLS	10	30	430000	196950304	196793450	196950304	156854
AristaMPLS	10	30	440000	196700282	196495716	196700282	204566
AristaMPLS	10	30	450000	197215834	197169795	197215834	46039
AristaMPLS	10	30	460000	197023954	196943635	197023954	80319
AristaMPLS	10	30	470000	196764029	196649696	196764029	114333
AristaMPLS	10	30	480000	197100220	196951135	197100220	149085
AristaMPLS	10	30	490000	196650208	196467410	196650208	182798
AristaMPLS	10	35	300000	229675207	229675207	229675207	0
AristaMPLS	10	35	310000	229664626	229664626	229664626	0
AristaMPLS	10	35	320000	229702298	229702298	229702298	0
AristaMPLS	10	35	330000	229651532	229651532	229651532	0
AristaMPLS	10	35	340000	229706011	229706011	229706011	0
AristaMPLS	10	35	350000	229742652	222704096	229742652	7038556
AristaMPLS	10	35	360000	229623484	229623484	229623484	0

iMIX Distribution	Duration (Seconds)	Load (%)	Burst size (packets)	Tx Frames	Rx Frames	Rx Expected Frames	Frame Loss
AristaMPLS	10	35	370000	229701361	229701361	229701361	0
AristaMPLS	10	35	380000	229704645	229704645	229704645	0
AristaMPLS	10	35	390000	229748330	229748330	229748330	0
AristaMPLS	10	35	400000	229539633	222039618	229539633	7500015
AristaMPLS	10	35	410000	229581453	229581453	229581453	0
AristaMPLS	10	35	420000	229800384	229800384	229800384	0
AristaMPLS	10	35	430000	229497710	229497710	229497710	0
AristaMPLS	10	35	440000	229704113	229692755	229704113	11358
AristaMPLS	10	35	450000	229745525	229699525	229745525	46000
AristaMPLS	10	35	460000	229600288	229519967	229600288	80321
AristaMPLS	10	35	470000	229743072	229628563	229743072	114509
AristaMPLS	10	35	480000	229500256	229351368	229500256	148888
AristaMPLS	10	35	490000	229581539	229398682	229581539	182857
AristaMPLS	10	40	300000	262376244	262376244	262376244	0
AristaMPLS	10	40	310000	262388558	262388558	262388558	0
AristaMPLS	10	40	320000	262389013	262389013	262389013	0
AristaMPLS	10	40	330000	262365519	262365519	262365519	0
AristaMPLS	10	40	340000	262389274	262389274	262389274	0
AristaMPLS	10	40	350000	262365670	262365670	262365670	0
AristaMPLS	10	40	360000	262430617	262430617	262430617	0
AristaMPLS	10	40	370000	262365769	262365769	262365769	0
AristaMPLS	10	40	380000	262389467	262389467	262389467	0
AristaMPLS	10	40	390000	262350584	262350584	262350584	0
AristaMPLS	10	40	400000	262481788	262481788	262481788	0
AristaMPLS	10	40	410000	262350478	262350478	262350478	0
AristaMPLS	10	40	420000	262291319	262291319	262291319	0
AristaMPLS	10	40	430000	262340202	253890189	262340202	8450013
AristaMPLS	10	40	440000	262500376	262488968	262500376	11408
AristaMPLS	10	40	450000	262365832	262319788	262365832	46044
AristaMPLS	10	40	460000	262389535	262309403	262389535	80132
AristaMPLS	10	40	470000	262528313	262413985	262528313	114328
AristaMPLS	10	40	480000	262291364	262142377	262291364	148987
AristaMPLS	10	40	490000	262430491	262247429	262430491	183062
AristaMPLS	10	45	300000	295078777	295078777	295078777	0
AristaMPLS	10	45	310000	295055902	286055722	295055902	9000180
AristaMPLS	10	45	320000	295086374	295086374	295086374	0
AristaMPLS	10	45	330000	295070685	295070685	295070685	0
AristaMPLS	10	45	340000	295070683	295070683	295070683	0
AristaMPLS	10	45	350000	295090022	286075764	295090022	9014258
AristaMPLS	10	45	360000	295070756	295070756	295070756	0
AristaMPLS	10	45	370000	295050844	295050844	295050844	0
AristaMPLS	10	45	380000	295070791	295070791	295070791	0
AristaMPLS	10	45	390000	295070800	295070800	295070800	0
AristaMPLS	10	45	400000	295086228	292806906	295086228	2279322
AristaMPLS	10	45	410000	295107892	295107892	295107892	0
AristaMPLS	10	45	420000	295070839	295070839	295070839	0
AristaMPLS	10	45	430000	295081589	285331574	295081589	9750015
AristaMPLS	10	45	440000	295049749	295038310	295049749	11439
AristaMPLS	10	45	450000	295038370	294992382	295038370	45988
AristaMPLS	10	45	460000	295145604	295065388	295145604	80216
AristaMPLS	10	45	470000	295006941	294892465	295006941	114476
AristaMPLS	10	45	480000	295070843	294921981	295070843	148862
AristaMPLS	10	45	490000	295139984	286406979	295139984	8733005
AristaMPLS	10	50	300000	327711355	317269451	327711355	10441904
AristaMPLS	10	50	310000	327744640	327002258	327744640	742382
AristaMPLS	10	50	320000	327751336	327006598	327751336	744738
AristaMPLS	10	50	330000	327742032	326996379	327742032	745653
AristaMPLS	10	50	340000	327741229	326994843	327741229	746386
AristaMPLS	10	50	350000	327740831	326992139	327740831	748692
AristaMPLS	10	50	360000	327744588	327001538	327744588	743050
AristaMPLS	10	50	370000	327747422	327006452	327747422	740970
AristaMPLS	10	50	380000	327752418	327010930	327752418	741488
AristaMPLS	10	50	390000	327743133	310470499	327743133	17272634
AristaMPLS	10	50	400000	327752412	327011851	327752412	740561
AristaMPLS	10	50	410000	327751330	327008471	327751330	742859

iMIX Distribution	Duration (Seconds)	Load (%)	Burst size (packets)	Tx Frames	Rx Frames	Rx Expected Frames	Frame Loss
AristaMPLS	10	50	420000	327743529	327002658	327743529	740871
AristaMPLS	10	50	430000	327742110	326998254	327742110	743856
AristaMPLS	10	50	440000	327739836	326989340	327739836	750496
AristaMPLS	10	50	450000	327745821	326970595	327745821	775226
AristaMPLS	10	50	460000	327752373	326934701	327752373	817672
AristaMPLS	10	50	470000	327752313	326902824	327752313	849489
AristaMPLS	10	50	480000	327744157	326863719	327744157	880438
AristaMPLS	10	50	490000	327743665	326829332	327743665	914333
AristaMPLS	10	55	300000	360385392	323476102	360385392	36909290
AristaMPLS	10	55	310000	360357208	317692537	360357208	42664671
AristaMPLS	10	55	320000	360395698	326175841	360395698	34219857
AristaMPLS	10	55	330000	360380010	326184238	360380010	34195772
AristaMPLS	10	55	340000	360395520	326172362	360395520	34223158
AristaMPLS	10	55	350000	360404630	326188890	360404630	34215740
AristaMPLS	10	55	360000	360414209	326237172	360414209	34177037
AristaMPLS	10	55	370000	360404592	326186659	360404592	34217933
AristaMPLS	10	55	380000	360383850	318018714	360383850	42365136
AristaMPLS	10	55	390000	360350713	321787867	360350713	38562846
AristaMPLS	10	55	400000	360354506	326907320	360354506	33447186
AristaMPLS	10	55	410000	360433371	326911999	360433371	33521372
AristaMPLS	10	55	420000	360352196	326901263	360352196	33450933
AristaMPLS	10	55	430000	360364491	326701619	360364491	33662872
AristaMPLS	10	55	440000	360334789	317637799	360334789	42696990
AristaMPLS	10	55	450000	360351685	309165615	360351685	51186070
AristaMPLS	10	55	460000	360348303	326170300	360348303	34178003
AristaMPLS	10	55	470000	360395455	326196857	360395455	34198598
AristaMPLS	10	55	480000	360352150	326196274	360352150	34155876
AristaMPLS	10	55	490000	360451886	326359825	360451886	34092061

A.2 Juniper PTX

iMIX Distribution	Duration (Seconds)	Load (%)	Rx Frame Rate(fps)	Tx Frames	Rx Frames	Rx Expected Frames	Frame Loss
Default	10	25	300000	164107671	164107670	164107671	1
Default	10	25	310000	164101233	164101233	164101233	0
Default	10	25	320000	164101642	164101642	164101642	0
Default	10	25	330000	164102566	164102566	164102566	0
Default	10	25	340000	164199438	164199438	164199438	0
Default	10	25	350000	164199650	164199650	164199650	0
Default	10	25	360000	164100548	164100548	164100548	0
Default	10	25	370000	164150470	164150470	164150470	0
Default	10	25	380000	164197239	164197239	164197239	0
Default	10	25	390000	164250366	164250366	164250366	0
Default	10	25	400000	164198706	164198706	164198706	0
Default	10	25	410000	164293418	164293418	164293418	0
Default	10	25	420000	163807788	163807788	163807788	0
Default	10	25	430000	164396778	164396778	164396778	0
Default	10	25	440000	164398001	164398001	164398001	0
Default	10	25	450000	164250220	164250220	164250220	0
Default	10	25	460000	164000206	164000206	164000206	0
Default	10	25	470000	164050194	164050194	164050194	0
Default	10	25	480000	164397540	164397540	164397540	0
Default	10	25	490000	164350174	164350174	164350174	0
Default	10	30	300000	196833871	196833871	196833871	0
Default	10	30	310000	196850820	196850820	196850820	0
Default	10	30	320000	196849310	196849310	196849310	0
Default	10	30	330000	196853984	196853984	196853984	0
Default	10	30	340000	196850396	196850396	196850396	0
Default	10	30	350000	196750788	196750788	196750788	0
Default	10	30	360000	196848977	196848977	196848977	0
Default	10	30	370000	196916931	196916930	196916931	1
Default	10	30	380000	196853818	196853818	196853818	0
Default	10	30	390000	196659556	196659556	196659556	0
Default	10	30	400000	196724627	196724627	196724627	0
Default	10	30	410000	196790226	196790224	196790226	2
Default	10	30	420000	196852085	196852084	196852085	1
Default	10	30	430000	196950304	196950304	196950304	0
Default	10	30	440000	196700282	196700281	196700282	1
Default	10	30	450000	197048056	197048056	197048056	0
Default	10	30	460000	196851332	196851332	196851332	0
Default	10	30	470000	196593028	196593027	196593028	1
Default	10	30	480000	197100220	197100218	197100220	2
Default	10	30	490000	196650208	196650208	196650208	0
Default	10	35	300000	229528275	229528275	229528275	0
Default	10	35	310000	229547419	229547419	229547419	0
Default	10	35	320000	229507636	229507635	229507636	1
Default	10	35	330000	229542214	229542214	229542214	0
Default	10	35	340000	229508092	229508092	229508092	0
Default	10	35	350000	229546196	229546195	229546196	1
Default	10	35	360000	229500766	229500766	229500766	0
Default	10	35	370000	229508287	229508287	229508287	0
Default	10	35	380000	229508314	229508314	229508314	0
Default	10	35	390000	229545745	229545745	229545745	0
Default	10	35	400000	229500460	229500459	229500460	1
Default	10	35	410000	229382647	229382646	229382647	1
Default	10	35	420000	229672595	229672594	229672595	1
Default	10	35	430000	229450354	229450354	229450354	0

iMIX Distribution	Duration (Seconds)	Load (%)	Rx Frame Rate(fps)	Tx Frames	Rx Frames	Rx Expected Frames	Frame Loss
Default	10	35	440000	229508448	229508448	229508448	0
Default	10	35	450000	229549191	229549191	229549191	0
Default	10	35	460000	229600288	229600288	229600288	0
Default	10	35	470000	229542937	229542936	229542937	1
Default	10	35	480000	229500256	229500255	229500256	1
Default	10	35	490000	229382699	229382699	229382699	0
Default	10	40	300000	262209021	262209021	262209021	0
Default	10	40	310000	262208318	262208318	262208318	0
Default	10	40	320000	262202623	262202622	262202623	1
Default	10	40	330000	262205354	262205353	262205354	1
Default	10	40	340000	262201312	262201312	262201312	0
Default	10	40	350000	262251050	262251050	262251050	0
Default	10	40	360000	262201624	262201624	262201624	0
Default	10	40	370000	262150750	262150749	262150750	1
Default	10	40	380000	262161228	262161227	262161228	1
Default	10	40	390000	262277287	262277287	262277287	0
Default	10	40	400000	262250653	262250653	262250653	0
Default	10	40	410000	262299626	262299626	262299626	0
Default	10	40	420000	262200438	262200438	262200438	0
Default	10	40	430000	262112866	262112865	262112866	1
Default	10	40	440000	262302930	262302930	262302930	0
Default	10	40	450000	262136750	262136750	262136750	0
Default	10	40	460000	262161332	262161332	262161332	0
Default	10	40	470000	262301301	262301299	262301301	2
Default	10	40	480000	262064126	262064126	262064126	0
Default	10	40	490000	262204784	262204783	262204784	1
Default	10	45	300000	294855043	294855042	294855043	1
Default	10	45	310000	294850083	294850083	294850083	0
Default	10	45	320000	294851727	294851726	294851727	1
Default	10	45	330000	294846751	294846750	294846751	1
Default	10	45	340000	294853239	294853239	294853239	0
Default	10	45	350000	294835469	294835469	294835469	0
Default	10	45	360000	294872521	294872521	294872521	0
Default	10	45	370000	294862777	294862777	294862777	0
Default	10	45	380000	294814147	294814146	294814147	1
Default	10	45	390000	294814164	294814163	294814164	1
Default	10	45	400000	294835584	294835584	294835584	0
Default	10	45	410000	294852534	294852534	294852534	0
Default	10	45	420000	294814209	294814209	294814209	0
Default	10	45	430000	294824664	294824663	294824664	1
Default	10	45	440000	294793195	294793195	294793195	0
Default	10	45	450000	294782821	294782821	294782821	0
Default	10	45	460000	294894096	294894094	294894096	2
Default	10	45	470000	294920883	294920880	294920883	3
Default	10	45	480000	294814231	294814230	294814231	1
Default	10	45	490000	294883616	294883616	294883616	0
Default	10	50	300000	327468926	327468926	327468926	0
Default	10	50	310000	327465218	327465217	327465218	1
Default	10	50	320000	327464433	327464432	327464433	1
Default	10	50	330000	327466115	327466115	327466115	0
Default	10	50	340000	327466075	327466074	327466075	1
Default	10	50	350000	327465224	327465222	327465224	2
Default	10	50	360000	327466095	327466094	327466095	1
Default	10	50	370000	327466104	327466103	327466104	1
Default	10	50	380000	327459129	327459129	327459129	0
Default	10	50	390000	327466099	327466099	327466099	0
Default	10	50	400000	327456936	327456936	327456936	0

iMIX Distribution	Duration (Seconds)	Load (%)	Rx Frame Rate(fps)	Tx Frames	Rx Frames	Rx Expected Frames	Frame Loss
Default	10	50	410000	327466449	327466448	327466449	1
Default	10	50	420000	327466091	327466089	327466091	2
Default	10	50	430000	327466102	327466102	327466102	0
Default	10	50	440000	327466090	327466090	327466090	0
Default	10	50	450000	327459238	327459237	327459238	1
Default	10	50	460000	327467125	327467125	327467125	0
Default	10	50	470000	327467527	327467527	327467527	0
Default	10	50	480000	327466115	327466114	327466115	1
Default	10	50	490000	327459684	327459684	327459684	0
Default	10	55	300000	360044681	329993362	360044681	30051319
Default	10	55	310000	360039376	329771367	360039376	30268009
Default	10	55	320000	360038105	329729613	360038105	30308492
Default	10	55	330000	360038261	329728107	360038261	30310154
Default	10	55	340000	360035043	329630497	360035043	30404546
Default	10	55	350000	360041795	329656372	360041795	30385423
Default	10	55	360000	360035409	329625248	360035409	30410161
Default	10	55	370000	360019307	329592412	360019307	30426895
Default	10	55	380000	360034318	329592158	360034318	30442160
Default	10	55	390000	360034951	329576226	360034951	30458725
Default	10	55	400000	360037716	329555190	360037716	30482526
Default	10	55	410000	360011920	329545315	360011920	30466605
Default	10	55	420000	360033443	329514723	360033443	30518720
Default	10	55	430000	360054391	329516134	360054391	30538257
Default	10	55	440000	360021576	329469014	360021576	30552562
Default	10	55	450000	360034262	329451197	360034262	30583065
Default	10	55	460000	360041830	329427069	360041830	30614761
Default	10	55	470000	360083121	329512866	360083121	30570255
Default	10	55	480000	360035862	329383145	360035862	30652717
Default	10	55	490000	360041698	329416213	360041698	30625485

A.3 Dell

A.3.1 Dell EMC S4248FBL-ON with OcNOS

iMIX Distribution	Duration (Seconds)	Load (%)	Rx Frame Rate(fps)	Tx Frames	Rx Frames	Rx Expected Frames	Frame Loss
Default	10	25	300000	164094616	164094615	164094616	1
Default	10	25	310000	164101282	164101280	164101282	2
Default	10	25	320000	164101642	164101642	164101642	0
Default	10	25	330000	164101095	164101094	164101095	1
Default	10	25	340000	164198274	164198274	164198274	0
Default	10	25	350000	164199178	164199178	164199178	0
Default	10	25	360000	164100548	164100548	164100548	0
Default	10	25	370000	164150470	164121767	164150470	28703
Default	10	25	380000	164199155	164119437	164199155	79718
Default	10	25	390000	164250366	164119897	164250366	130469
Default	10	25	400000	164195943	164015144	164195943	180799
Default	10	25	410000	164293138	164063449	164293138	229689
Default	10	25	420000	163807802	163528782	163807802	279020
Default	10	25	430000	164395878	164065643	164395878	330235
Default	10	25	440000	164395361	164015909	164395361	379452
Default	10	25	450000	164250220	163819443	164250220	430777
Default	10	25	460000	164000206	163520188	164000206	480018
Default	10	25	470000	164050194	163521677	164050194	528517
Default	10	25	480000	164397161	163817198	164397161	579963
Default	10	25	490000	164350174	163721072	164350174	629102
Default	10	30	300000	196826355	196826354	196826355	1
Default	10	30	310000	196844832	196844830	196844832	2
Default	10	30	320000	196850130	196850130	196850130	0
Default	10	30	330000	196850607	196850606	196850607	1
Default	10	30	340000	196852433	196852433	196852433	0
Default	10	30	350000	196750788	196750788	196750788	0
Default	10	30	360000	196853728	196853728	196853728	0
Default	10	30	370000	196913870	196885239	196913870	28631
Default	10	30	380000	196850056	196770373	196850056	79683
Default	10	30	390000	196659583	196529807	196659583	129776
Default	10	30	400000	196724653	196544351	196724653	180302
Default	10	30	410000	196790256	196560304	196790256	229952
Default	10	30	420000	196849630	196570672	196849630	278958
Default	10	30	430000	196950304	196619101	196950304	331203
Default	10	30	440000	196700282	196319904	196700282	380378
Default	10	30	450000	197047464	196618784	197047464	428680
Default	10	30	460000	196850088	196369507	196850088	480581
Default	10	30	470000	196593068	196061762	196593068	531306
Default	10	30	480000	197100220	196521978	197100220	578242
Default	10	30	490000	196650208	196021660	196650208	628548
Default	10	35	300000	229537387	229537387	229537387	0
Default	10	35	310000	229541874	229541874	229541874	0
Default	10	35	320000	229507674	229507674	229507674	0
Default	10	35	330000	229541911	229541911	229541911	0
Default	10	35	340000	229508123	229508123	229508123	0
Default	10	35	350000	229541873	229541873	229541873	0
Default	10	35	360000	229500766	229500766	229500766	0
Default	10	35	370000	229508314	229479414	229508314	28900
Default	10	35	380000	229508364	229428058	229508364	80306
Default	10	35	390000	229541842	229411626	229541842	130216
Default	10	35	400000	229500460	229321540	229500460	178920

iMIX Distribution	Duration (Seconds)	Load (%)	Rx Frame Rate(fps)	Tx Frames	Rx Frames	Rx Expected Frames	Frame Loss
Default	10	35	410000	229382666	229152253	229382666	230413
Default	10	35	420000	229672479	229392392	229672479	280087
Default	10	35	430000	229450354	229120895	229450354	329459
Default	10	35	440000	229508473	229127276	229508473	381197
Default	10	35	450000	229540729	229110605	229540729	430124
Default	10	35	460000	229600288	229120516	229600288	479772
Default	10	35	470000	229544991	229014526	229544991	530465
Default	10	35	480000	229500256	228920970	229500256	579286
Default	10	35	490000	229382733	228751490	229382733	631243
Default	10	40	300000	262200870	262200870	262200870	0
Default	10	40	310000	262205245	262205243	262205245	2
Default	10	40	320000	262204792	262204791	262204792	1
Default	10	40	330000	262202794	262202792	262202794	2
Default	10	40	340000	262201312	262201311	262201312	1
Default	10	40	350000	262251050	262251050	262251050	0
Default	10	40	360000	262203065	262203064	262203065	1
Default	10	40	370000	262150750	262120208	262150750	30542
Default	10	40	380000	262161277	262080364	262161277	80913
Default	10	40	390000	262276561	262148236	262276561	128325
Default	10	40	400000	262253336	262073699	262253336	179637
Default	10	40	410000	262297394	262067808	262297394	229586
Default	10	40	420000	262200438	261920427	262200438	280011
Default	10	40	430000	262112910	261783525	262112910	329385
Default	10	40	440000	262301504	261921538	262301504	379966
Default	10	40	450000	262136777	261706398	262136777	430379
Default	10	40	460000	262161367	261680988	262161367	480379
Default	10	40	470000	262298138	261769146	262298138	528992
Default	10	40	480000	262064187	261484721	262064187	579466
Default	10	40	490000	262201468	261570323	262201468	631145
Default	10	45	300000	294850989	294850989	294850989	0
Default	10	45	310000	294847770	294847768	294847770	2
Default	10	45	320000	294845421	294845421	294845421	0
Default	10	45	330000	294846785	294846785	294846785	0
Default	10	45	340000	294846124	294846124	294846124	0
Default	10	45	350000	294835517	294835517	294835517	0
Default	10	45	360000	294868459	294868458	294868459	1
Default	10	45	370000	294858479	294828190	294858479	30289
Default	10	45	380000	294814184	294733826	294814184	80358
Default	10	45	390000	294814211	294684781	294814211	129430
Default	10	45	400000	294835607	294655186	294835607	180421
Default	10	45	410000	294848427	294619399	294848427	229028
Default	10	45	420000	294814268	294534480	294814268	279788
Default	10	45	430000	294824683	294495776	294824683	328907
Default	10	45	440000	294793246	294413482	294793246	379764
Default	10	45	450000	294782865	294352975	294782865	429890
Default	10	45	460000	294890318	294410256	294890318	480062
Default	10	45	470000	294920773	294389955	294920773	530818
Default	10	45	480000	294814254	294234974	294814254	579280
Default	10	45	490000	294880433	294251611	294880433	628822
Default	10	50	300000	327472683	326296937	327472683	1175746
Default	10	50	310000	327464282	326309281	327464282	1155001
Default	10	50	320000	327456625	326301337	327456625	1155288
Default	10	50	330000	327466145	326309283	327466145	1156862
Default	10	50	340000	327466111	326307060	327466111	1159051
Default	10	50	350000	327465257	326303428	327465257	1161829
Default	10	50	360000	327466140	326309850	327466140	1156290
Default	10	50	370000	327466119	326287324	327466119	1178795

iMIX Distribution	Duration (Seconds)	Load (%)	Rx Frame Rate(fps)	Tx Frames	Rx Frames	Rx Expected Frames	Frame Loss
Default	10	50	380000	327460447	326233668	327460447	1226779
Default	10	50	390000	327466149	326183848	327466149	1282301
Default	10	50	400000	327457525	326128956	327457525	1328569
Default	10	50	410000	327466458	326083748	327466458	1382710
Default	10	50	420000	327466124	326028650	327466124	1437474
Default	10	50	430000	327466129	325986823	327466129	1479306
Default	10	50	440000	327466145	325933126	327466145	1533019
Default	10	50	450000	327452960	325874576	327452960	1578384
Default	10	50	460000	327467151	325830890	327467151	1636261
Default	10	50	470000	327467591	325781704	327467591	1685887
Default	10	50	480000	327466135	325735418	327466135	1730717
Default	10	50	490000	327449556	325672461	327449556	1777095
Default	10	55	300000	360061379	325561068	360061379	34500311
Default	10	55	310000	360037207	326315198	360037207	33722009
Default	10	55	320000	360035701	326310238	360035701	33725463
Default	10	55	330000	360037939	326310309	360037939	33727630
Default	10	55	340000	360033145	326305058	360033145	33728087
Default	10	55	350000	360033290	326308279	360033290	33725011
Default	10	55	360000	360031927	326293522	360031927	33738405
Default	10	55	370000	360015819	326294474	360015819	33721345
Default	10	55	380000	360036178	326293246	360036178	33742932
Default	10	55	390000	360035062	326257060	360035062	33778002
Default	10	55	400000	360034992	326214844	360034992	33820148
Default	10	55	410000	360006221	326168331	360006221	33837890
Default	10	55	420000	360034632	326129360	360034632	33905272
Default	10	55	430000	360054455	326091092	360054455	33963363
Default	10	55	440000	360014557	326056976	360014557	33957581
Default	10	55	450000	360036286	326013663	360036286	34022623
Default	10	55	460000	360037511	325968727	360037511	34068784
Default	10	55	470000	360083155	325937454	360083155	34145701
Default	10	55	480000	360031012	325886209	360031012	34144803
Default	10	55	490000	360038554	325862051	360038554	34176503

A.3.2 Dell EMC S4248FBL-ON with OcNOS and QoS Enabled

iMIX Distribution	Duration (Seconds)	Load (%)	Rx Frame Rate(fps)	Tx Frames	Rx Frames	Rx Expected Frames	Frame Loss
Default	10	25	300000	164094763	164094763	164094763	0
Default	10	25	310000	164101284	164101282	164101284	2
Default	10	25	320000	164101642	164101642	164101642	0
Default	10	25	330000	164101095	164101095	164101095	0
Default	10	25	340000	164194574	164194574	164194574	0
Default	10	25	350000	164199226	164199226	164199226	0
Default	10	25	360000	164100548	164100548	164100548	0
Default	10	25	370000	164150470	164121797	164150470	28673
Default	10	25	380000	164197859	164118405	164197859	79454
Default	10	25	390000	164250366	164120671	164250366	129695
Default	10	25	400000	164197781	164018450	164197781	179331
Default	10	25	410000	164297409	164067208	164297409	230201
Default	10	25	420000	163807802	163528203	163807802	279599
Default	10	25	430000	164393769	164063796	164393769	329973
Default	10	25	440000	164395515	164015271	164395515	380244
Default	10	25	450000	164250220	163821664	164250220	428556
Default	10	25	460000	164000206	163520961	164000206	479245
Default	10	25	470000	164050194	163520014	164050194	530180
Default	10	25	480000	164393705	163814362	164393705	579343
Default	10	25	490000	164350174	163720273	164350174	629901
Default	10	30	300000	196826171	196826170	196826171	1
Default	10	30	310000	196847607	196847606	196847607	1
Default	10	30	320000	196852531	196852531	196852531	0
Default	10	30	330000	196847365	196847365	196847365	0
Default	10	30	340000	196849261	196849257	196849261	4
Default	10	30	350000	196750788	196750785	196750788	3
Default	10	30	360000	196848899	196848895	196848899	4
Default	10	30	370000	196916919	196886462	196916919	30457
Default	10	30	380000	196853898	196775009	196853898	78889
Default	10	30	390000	196659576	196529938	196659576	129638
Default	10	30	400000	196724660	196544952	196724660	179708
Default	10	30	410000	196790249	196560840	196790249	229409
Default	10	30	420000	196849279	196568578	196849279	280701
Default	10	30	430000	196950304	196620354	196950304	329950
Default	10	30	440000	196700282	196320177	196700282	380105
Default	10	30	450000	197046352	196616980	197046352	429372
Default	10	30	460000	196850744	196371469	196850744	479275
Default	10	30	470000	196593043	196064785	196593043	528258
Default	10	30	480000	197100220	196520305	197100220	579915
Default	10	30	490000	196650208	196020024	196650208	630184
Default	10	35	300000	229535482	229535482	229535482	0
Default	10	35	310000	229542036	229542035	229542036	1
Default	10	35	320000	229507675	229507675	229507675	0
Default	10	35	330000	229541392	229541392	229541392	0
Default	10	35	340000	229508119	229508119	229508119	0
Default	10	35	350000	229544417	229544416	229544417	1
Default	10	35	360000	229500766	229500766	229500766	0
Default	10	35	370000	229508309	229479039	229508309	29270
Default	10	35	380000	229508365	229428982	229508365	79383
Default	10	35	390000	229544388	229414758	229544388	129630
Default	10	35	400000	229500460	229320064	229500460	180396
Default	10	35	410000	229382672	229152920	229382672	229752
Default	10	35	420000	229672946	229393763	229672946	279183
Default	10	35	430000	229450354	229120932	229450354	329422
Default	10	35	440000	229508471	229128388	229508471	380083

iMIX Distribution	Duration (Seconds)	Load (%)	Rx Frame Rate(fps)	Tx Frames	Rx Frames	Rx Expected Frames	Frame Loss
Default	10	35	450000	229542900	229113712	229542900	429188
Default	10	35	460000	229600288	229120692	229600288	479596
Default	10	35	470000	229545360	229015336	229545360	530024
Default	10	35	480000	229500256	228920140	229500256	580116
Default	10	35	490000	229382733	228751871	229382733	630862
Default	10	40	300000	262200459	262200459	262200459	0
Default	10	40	310000	262205245	262205245	262205245	0
Default	10	40	320000	262207193	262207192	262207193	1
Default	10	40	330000	262201749	262201748	262201749	1
Default	10	40	340000	262201312	262201311	262201312	1
Default	10	40	350000	262249197	262249197	262249197	0
Default	10	40	360000	262202874	262202874	262202874	0
Default	10	40	370000	262150750	262122147	262150750	28603
Default	10	40	380000	262161269	262081489	262161269	79780
Default	10	40	390000	262276325	262145863	262276325	130462
Default	10	40	400000	262250139	262070714	262250139	179425
Default	10	40	410000	262298701	262069356	262298701	229345
Default	10	40	420000	262200438	261921855	262200438	278583
Default	10	40	430000	262112910	261781924	262112910	330986
Default	10	40	440000	262302400	261923067	262302400	379333
Default	10	40	450000	262136777	261707849	262136777	428928
Default	10	40	460000	262161368	261680541	262161368	480827
Default	10	40	470000	262301267	261771378	262301267	529889
Default	10	40	480000	262064174	261483997	262064174	580177
Default	10	40	490000	262201968	261571734	262201968	630234
Default	10	45	300000	294852803	294852798	294852803	5
Default	10	45	310000	294848816	294848809	294848816	7
Default	10	45	320000	294851229	294851227	294851229	2
Default	10	45	330000	294846784	294846781	294846784	3
Default	10	45	340000	294847614	294847611	294847614	3
Default	10	45	350000	294835517	294835514	294835517	3
Default	10	45	360000	294869280	294869277	294869280	3
Default	10	45	370000	294863241	294834610	294863241	28631
Default	10	45	380000	294814188	294734285	294814188	79903
Default	10	45	390000	294814211	294683748	294814211	130463
Default	10	45	400000	294835607	294655113	294835607	180494
Default	10	45	410000	294847385	294616439	294847385	230946
Default	10	45	420000	294814253	294534643	294814253	279610
Default	10	45	430000	294824684	294496194	294824684	328490
Default	10	45	440000	294793262	294413458	294793262	379804
Default	10	45	450000	294782857	294352975	294782857	429882
Default	10	45	460000	294892893	294413103	294892893	479790
Default	10	45	470000	294924038	294393419	294924038	530619
Default	10	45	480000	294814254	294235889	294814254	578365
Default	10	45	490000	294882990	294252006	294882990	630984
Default	10	50	300000	327473926	326302063	327473926	1171863
Default	10	50	310000	327465251	326312852	327465251	1152399
Default	10	50	320000	327456081	326300801	327456081	1155280
Default	10	50	330000	327464472	326302498	327464472	1161974
Default	10	50	340000	327466124	326311763	327466124	1154361
Default	10	50	350000	327465258	326308913	327465258	1156345
Default	10	50	360000	327466142	326304960	327466142	1161182
Default	10	50	370000	327466121	326278879	327466121	1187242
Default	10	50	380000	327456033	326225715	327456033	1230318
Default	10	50	390000	327466139	326179828	327466139	1286311
Default	10	50	400000	327452872	326120131	327452872	1332741
Default	10	50	410000	327466458	326082305	327466458	1384153

iMIX Distribution	Duration (Seconds)	Load (%)	Rx Frame Rate(fps)	Tx Frames	Rx Frames	Rx Expected Frames	Frame Loss
Default	10	50	420000	327466127	326035861	327466127	1430266
Default	10	50	430000	327466129	325987356	327466129	1478773
Default	10	50	440000	327466126	325931482	327466126	1534644
Default	10	50	450000	327454745	325874738	327454745	1580007
Default	10	50	460000	327467141	325830915	327467141	1636226
Default	10	50	470000	327467589	325785284	327467589	1682305
Default	10	50	480000	327466129	325733415	327466129	1732714
Default	10	50	490000	327452310	325676188	327452310	1776122
Default	10	55	300000	360065928	325601581	360065928	34464347
Default	10	55	310000	360033089	326313982	360033089	33719107
Default	10	55	320000	360037992	326305963	360037992	33732029
Default	10	55	330000	360033488	326308584	360033488	33724904
Default	10	55	340000	360031449	326302092	360031449	33729357
Default	10	55	350000	360036104	326293274	360036104	33742830
Default	10	55	360000	360032973	326294340	360032973	33738633
Default	10	55	370000	360015567	326292605	360015567	33722962
Default	10	55	380000	360033383	326289406	360033383	33743977
Default	10	55	390000	360032305	326250740	360032305	33781565
Default	10	55	400000	360035080	326215002	360035080	33820078
Default	10	55	410000	360003839	326174096	360003839	33829743
Default	10	55	420000	360033039	326127534	360033039	33905505
Default	10	55	430000	360054450	326113679	360054450	33940771
Default	10	55	440000	360012375	326046657	360012375	33965718
Default	10	55	450000	360034183	325999968	360034183	34034215
Default	10	55	460000	360035776	325975734	360035776	34060042
Default	10	55	470000	360083155	325937217	360083155	34145938
Default	10	55	480000	360035178	325889775	360035178	34145403
Default	10	55	490000	360037824	325859378	360037824	34178446

References

[RFC2889] *Benchmarking Methodology for LAN Switching Devices*, R. Mandeville and J.Perser, IETF RFC 2889, August 2000.

[RFC2544] *Benchmarking Methodology for Network Interconnect Devices*, S. Bradner, J. McQuaid, IETF RFC 2544, March 1999.

[RFC3918] *Methodology for IP Multicast Benchmarking*, D. Stopp, B. Hickman, IETF RFC 3918, October 2004.

[GNS3] *GNS3 Network emulator* https://gns3.com/

[STC] *Spirent Test Center* https://spirent.com/

[CAIDA] *Trends in Wide Area IP Traffic Patterns*, Sean McCreary and KC Claffy, CAIDA, San Diego Supercomputer Center, University of California, San Diego.

[ABSTRACT_MODEL] P4 Language Specification, Version 1.0.5, November 26, 2018,

Glossary

BFD	Bidirectional Forwarding Detection
BGP	Border Gateway Protocol
CPU	Central Processing Unit
FID	Forwarding Information Database
HOLB	Head-of-Line Blocking
IGP	Interior Gateway Protocol
IMIX	Internet Mix or IMIX (typical Internet traffic passing through network equipment)
IS-IS	Intermediate System-to-Intermediate System
LSP	Label-Switched Path
LSR	Label Switch Router
MPLS	Multiprotocol Label Switching
MTU	Maximum Transmission Unit
NOS	Network Operating System
PISA	Protocol Independent Switch Architecture
Pps	Packets per second
QoS	Quality of Service
RSVP	Resource Reservation Protocol
SDK	Software Development Kit
SRAM	Static Random Access Memory
TCAM	Ternary content addressable memory
White box	Regardless of the actual chassis color, a network device used for packet/frame switching allowing to run an independent NOS as a control plane