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Evaluation of the Tellabs 1150 GPON Multiservice Access Platform

Joseph P. Brenkosh, Glen B. Roybal, Brian L. Amberg, David G. Heckart, Janice M. Vaughan

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ABSTRACT

Over the last two years, Sandia National Laboratories made a significant investment in its network infrastructure with the Network Revitalization Project. There were two main components to this project: a Multiprotocol Label Switching (MPLS) enabled backbone network and a Gigabit Passive Optical Network (GPON) access layer.

The GPON equipment used in the Network Revitalization Project is from Tellabs. This equipment includes the Tellabs 1150 Multiservice Access Platform (MSAP) Optical Line Terminal (OLT), the Tellabs ONT709 Optical Network Terminal (ONT), and the Panorama Integrated Network Manager (INM). In order to fully utilize this equipment to its greatest capacity, it needed to be thoroughly tested. This report documents that testing.

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GLOSSSARY

ACL	access control list
ARP	Address Resolution Protocol
bps	bits per second
CLI	command line interface
CoS	Class of Service
DHCP	Dynamic Host Configuration Protocol
DSCP	Differentiated Services Code Point
FEC	Forward Error Correction
fps	frames per second
Gbps	gigabits per second
GEM	GPON Encapsulation Method
GPON	Gigabit Passive Optical Network
GUI	Graphical User Interface
IP	Internet Protocol
IPTM	Internet Protocol Telephone Manager
INM	Integrated Network Manager
ITU-T	International Telecommunication Union Telecom. Standardization Sector
LAN	Local Area Network
MAC	Media Access Control
Mbps	megabits per second
µs	microseconds
MOS	Mean Opinion Score
MPEG	Motion Picture Experts Group
MPLS	Multiprotocol Label Switching
MSAP	Multiservice Access Platform
NA	Not Applicable
NASA	National Aeronautics and Space Administration
OLT	Optical Line Terminal
ONT	Optical Network Terminal
PCoIP	PC over IP
PLOAM	Physical Layer Operations, Administration, and Maintenance
PON	Passive Optical Network
QoS	Quality of Service
RDP	Remote Desktop Protocol
RDT	Remote Distribution Terminal
RFC	Request for Comments
s	seconds
SCP	Secure Copy
SNL	Sandia National Laboratories
SRN	Sandia Restricted Network
VDI	Virtual Desktop Infrastructure
VLAN	Virtual Local Area Network
VoIP	Voice over Internet Protocol

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1. INTRODUCTION

Over the last two years, Sandia National Laboratories has made a significant investment in its network infrastructure with the Network Revitalization Project. There were two main components to this project: a Multiprotocol Label Switching (MPLS) enabled backbone network and a Gigabit Passive Optical Network (GPON) access layer.

The GPON equipment used in the Network Revitalization Project is from Tellabs. This equipment includes the Tellabs 1150 Multiservice Access Platform (MSAP) Optical Line Terminal (OLT), the Tellabs ONT709 Optical Network Terminal (ONT), and the Tellabs Panorama Integrated Network Manager (INM). In order to fully utilize this equipment, it needed to be thoroughly tested. This report documents that testing. The MPLS equipment used in this project (Juniper MX480 routers) was not tested in this report.

This report begins with an introduction to the Tellabs 1150 MSAP. It then presents results of throughput tests using the Spirent TestCenter. Because Sandia National Laboratories plans to deploy Voice over IP (VoIP) using this equipment, VoIP testing was also performed and the results documented in the next section. The Tellabs 1150 MSAP will also be heavily used for video. Streaming video was tested, and the results of those tests are then presented. Zero Clients offer the potential for huge cost savings and were also tested and the results documented in the next section. Because GPON is designed to be an access layer network technology, the end user field testing results of various applications are then documented. No network equipment is very useful if it cannot be operated securely. For that reason, security tests were performed and the results are presented in the next section. Next, the operations and management of Tellabs 1150 MSAP and the Tellabs ONT709 using the Panorama INM are discussed. Finally, the report ends with a recommendation about using this platform at Sandia National Laboratories (SNL).

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2. INTRODUCTION TO THE TELLABS 1150 MSAP

2.1 Tellabs GPON Equipment

It is assumed that the reader has a basic knowledge of GPON technology. For those who do not, please refer to SAND2009-4741 [1] which provides introductory information on GPON technology.

Tellabs offers a full line of GPON equipment depending upon the capacity required. The equipment tested was the following:

Tellabs 1150 MSAP - This is the OLT. It consists of the 1150 chassis and various modules which are inserted into the chassis. The 1150 MSAP supports up to 16 GPON QOIU7 modules. Each module has 4 GPON ports. Therefore, the 1150 MSAP can support 64 GPON ports. Each GPON port can support up to 32 ONTs. This allows the 1150 MSAP to support up to 2048 ONTs. The 1150 MSAP can have up to a 400 Gbps switching fabric capacity. Also, it can have 4 uplinks which operate at 10 Gbps and 8 uplinks which operate at 1 Gbps depending upon the configuration.

Tellabs ONT709 - This ONT has four Ethernet ports providing 10/100/1000 Base-T connectivity. The ONT709 is compliant to ITU-T G.984 recommendations.

Tellabs Panorama INM - This is the software that is used to manage the Tellabs OLTs and ONTs. It is supported on Windows and Solaris platforms. It operates in a client/server fashion which allows concurrent access to the Panorama server from multiple Panorama clients.

The Tellabs 1150 MSAP hardware and software used is presented in Table 1.

Table 1. Tellabs 1150 MSAP Hardware and Software

Hardware and Software	Model or Version
Chassis	1150 MSAP
Modules	
Controller and Uplink	ESU2A
GPON Module	2x QOIU7A
ONT	8x ONT709
Software	
Software Release	FP25.5.1_013274
Network Manager	Panorama INM 9.3.2.0.5

2.2 Other Equipment

There are several other networking components that are needed for the Tellabs 1150 MSAP to function. They can be categorized as PON equipment and other network equipment.

2.2.1 PON Equipment

This equipment is not specific to GPON and can be used with other Passive Optical Network (PON) technologies such as EPON or XG-PON.

Splitter - Each GPON port connects to a single strand of single-mode fiber. This fiber connects to an optical splitter. Optical splitters come in various sizes or number of splits. Typical sizes are 1x2, 1x4, 1x16, and 1x32. All testing performed in this report used 1x16 splitters. Actual production deployments will most likely use 1x32 splitters. The splitter outputs connect to the ONT709s.

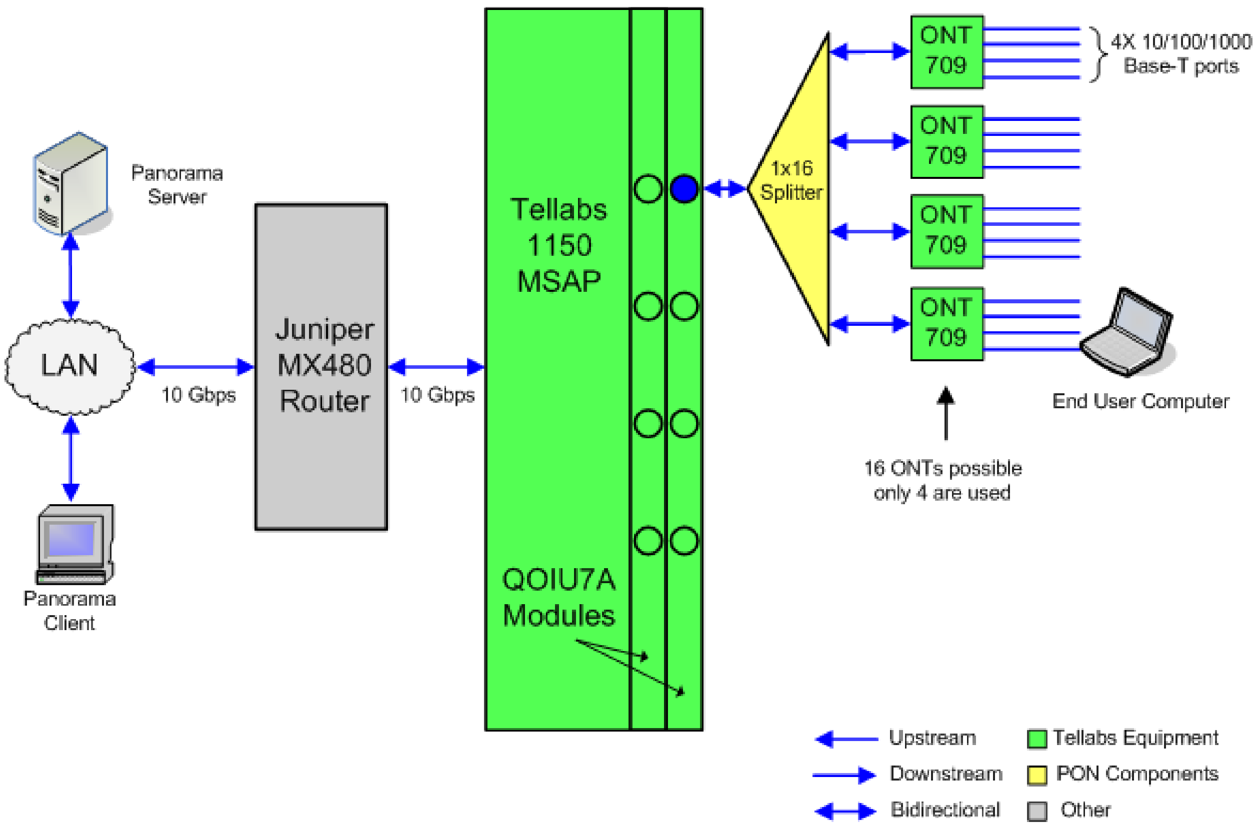
2.2.2 Other Network Equipment

Router - The uplink(s) from the Tellabs 1150 MSAP need to connect to a router. The router performs several important functions. It allows the GPON users to connect to the rest of the network. It provides routing functions for GPON users who are on different Virtual Local Area Networks (VLANs) on the same Tellabs 1150 MSAP to communicate. Users on the same VLAN who are on the same Tellabs 1150 MSAP will not need a router to communicate if they are using the “Full Bridging” mode of operation on the Tellabs 1150 MSAP. The router used for this testing is the Juniper Networks MX480.

Other LAN Equipment - This is other network gear such as switches and other routers which are not directly connected to the Tellabs 1150 MSAP. They provide connectivity to the Panorama server and other gear such as the Dynamic Host Configuration Protocol (DHCP) server.

Figure 1 illustrates a typical Tellabs 1150 MSAP GPON test configuration. The router is used to connect the GPON network to the rest of the network. The Tellabs 1150 MSAP is used to distribute an optical signal to the user network devices which are ONT709s. The Panorama INM server is used to manage the Tellabs 1150 MSAP and the ONT709s.

Figure 1. Tellabs 1150 MSAP GPON Test Configuration



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3. SPIRENT TESTCENTER PERFORMANCE TESTING

3.1 Spirent TestCenter Test Configuration

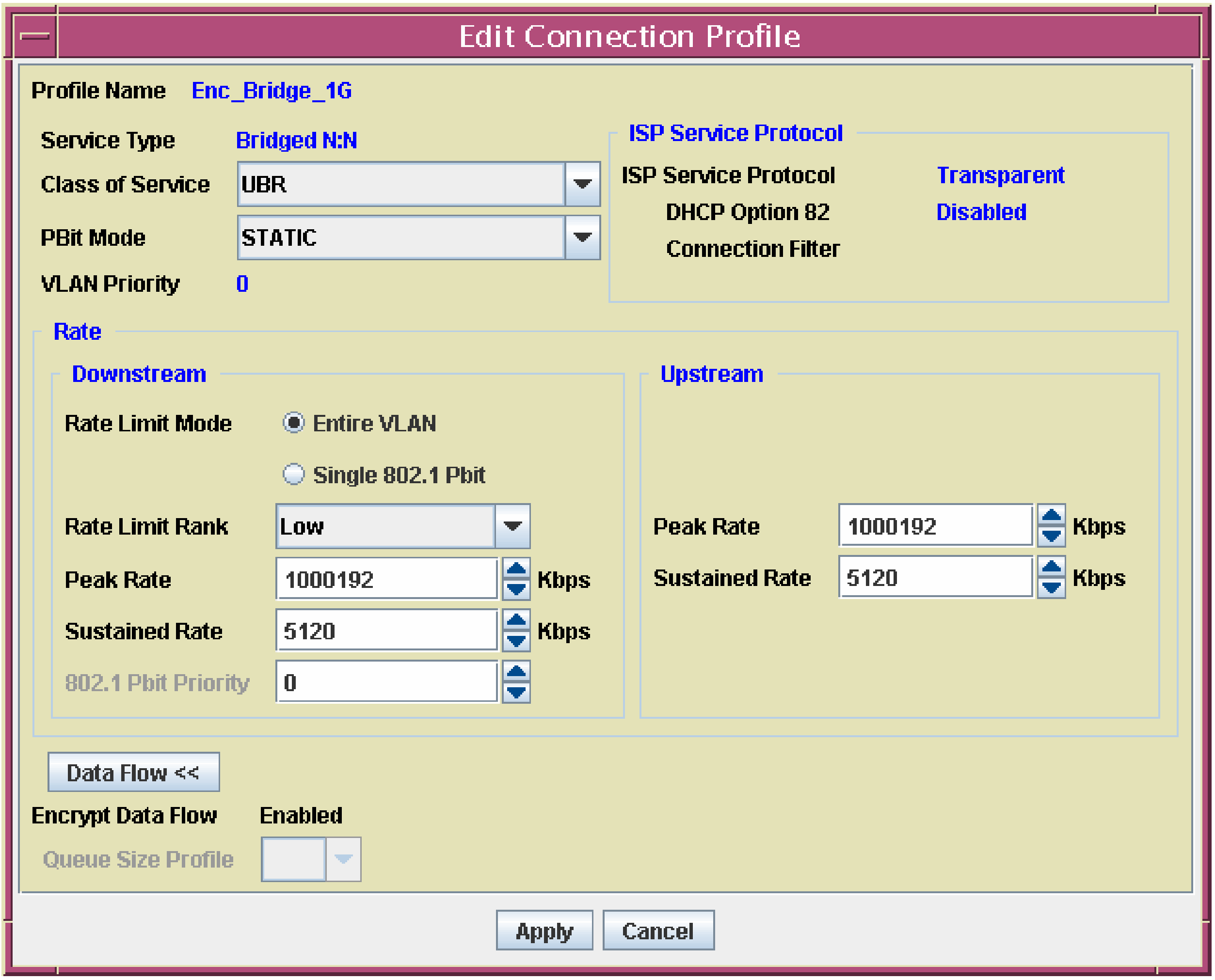
The first set of tests performed used the Spirent TestCenter. The Spirent TestCenter is a testing platform from Spirent Communications. The Spirent TestCenter consists of a chassis and various test modules such as multi-port 1 Gigabit Ethernet (used) and 10 Gigabit Ethernet modules (not used) and testing software. The Spirent TestCenter hardware and software used in these tests are listed in Table 2.

Table 2. Spirent TestCenter Hardware and Software

Hardware and Software	Model or Version
Chassis	SPT-2000A-HS
Modules	2x HyperMetrics CM-1G-D4 (4 Port Gigabit Ethernet)
Software	
Firmware Version	TestCenter 3.71
Test Suite	RFC 2544
Test Duration	60 seconds
Test Protocol Packets	IP Experimental (Protocol = 253)

For all testing performed, unless otherwise noted, the following traffic profile shown in Figure 2 was set on each ONT709 port that was connected to each Spirent TestCenter port. Note that Encrypt Data Flow (downstream encryption) was enabled. Also, unless otherwise noted, Forward Error Correction (FEC) was enabled on all GPON ports being tested.

Figure 2. ONT709 Traffic Profile with Encryption Enabled

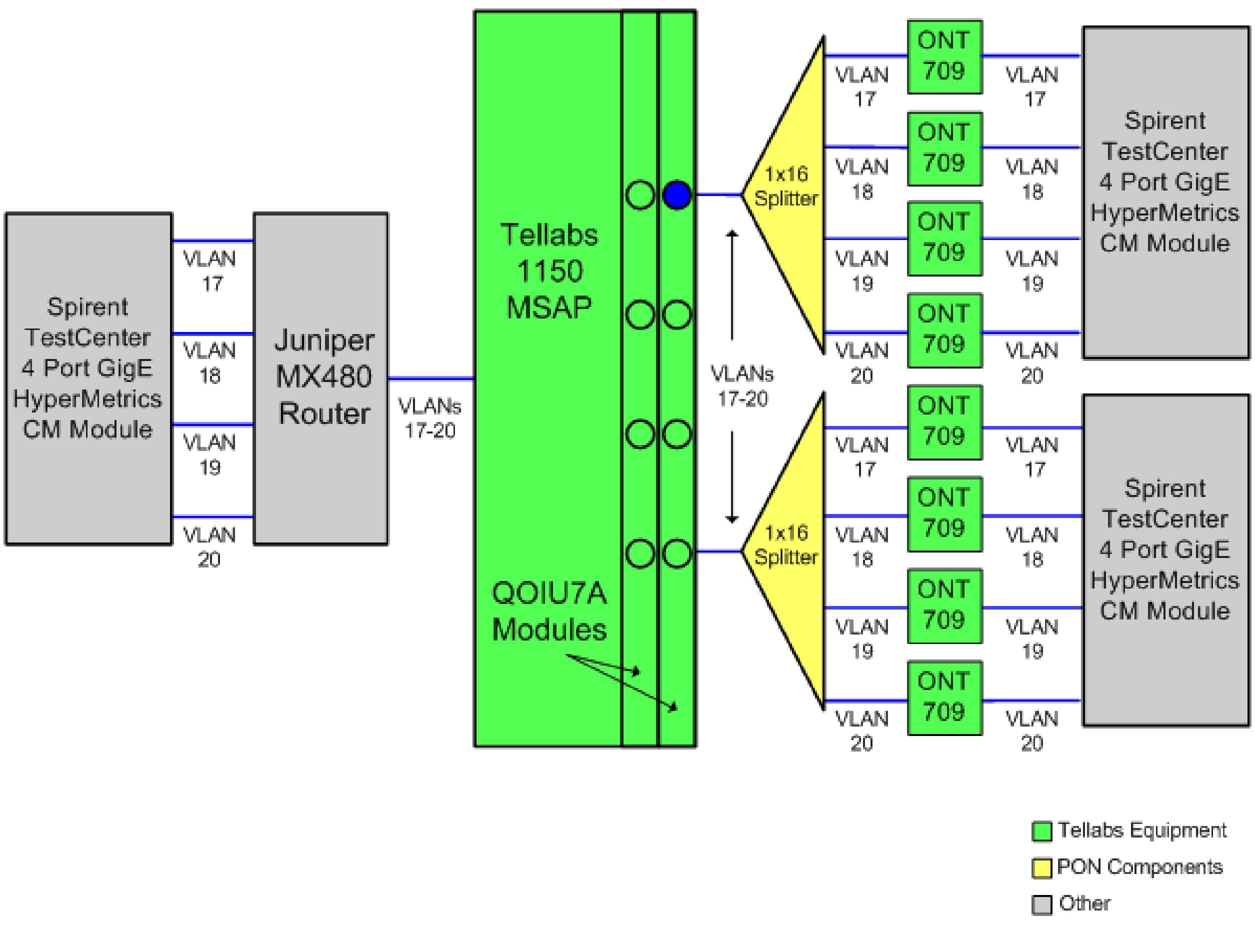


3.2 Spirent TestCenter Test Strategy

As illustrated in Figure 3, the four 10/100/1000 Base-T ports on one Spirent TestCenter CM-1G-D4 module were connected to a port on each of four ONT709s. The four ports from the other CM-1G-D4 module were connected to ports on the Juniper MX480. Each port on the Spirent TestCenter CM-1G-D4 modules was in a separate VLAN. The ONT709 port that was connected to the Spirent TestCenter CM-1G-D4 module was also in the same VLAN as the port on the CM-1G-D4 module. The 10 Gbps uplink from the Tellabs 1150 MSAP carried all 4 test VLANs into the Juniper MX480. There was no routing performed by the Juniper MX480. Note that only 4 ports on the 16 port splitters are being used. Also note that there are only two CM-1G-D4 modules being used for testing, but depending upon the test, the modules can be used in three different locations.

Once properly connected, the RFC 2544 test suite was run on the Spirent TestCenter for 1, 2, 3, and 4 streams. For the purpose of these tests, a stream can be defined as a separate data flow from a Spirent TestCenter CM-1G-D4 port through the ONT709 and Tellabs 1150 MSAP through the Juniper router to a port in the same VLAN on the other Spirent CM-1G-D4. Unless otherwise noted, there is only 1 stream per ONT709. For each stream, the Ethernet frame size was varied to include 64, 128, 256, 512, 1024, 1500, and 1518 byte Ethernet frames. Each frame size iteration ran for 60 seconds or until a frame drop. If there was a frame drop, the load was decreased; if there was no drop, the load was increased. Each test was run 5 times and the mean computed from those values. The following graphs present a summary of the results. Detailed results for these tests are presented in Appendices A through K.

Figure 3. VLAN Configuration for all Spirent TestCenter Testing



3.3 Upstream, Downstream, and Bidirectional Testing

Tests were performed for upstream, downstream, and bidirectional traffic. The purpose of these tests is to determine what forwarding rate the Tellabs 1150 MSAP can support on a single GPON port.

Upstream performance testing was performed first. The configuration for upstream testing is illustrated in Figure 4. Data flows from right to left as is denoted by the arrows.

Figure 4. Configuration for Upstream Performance Testing

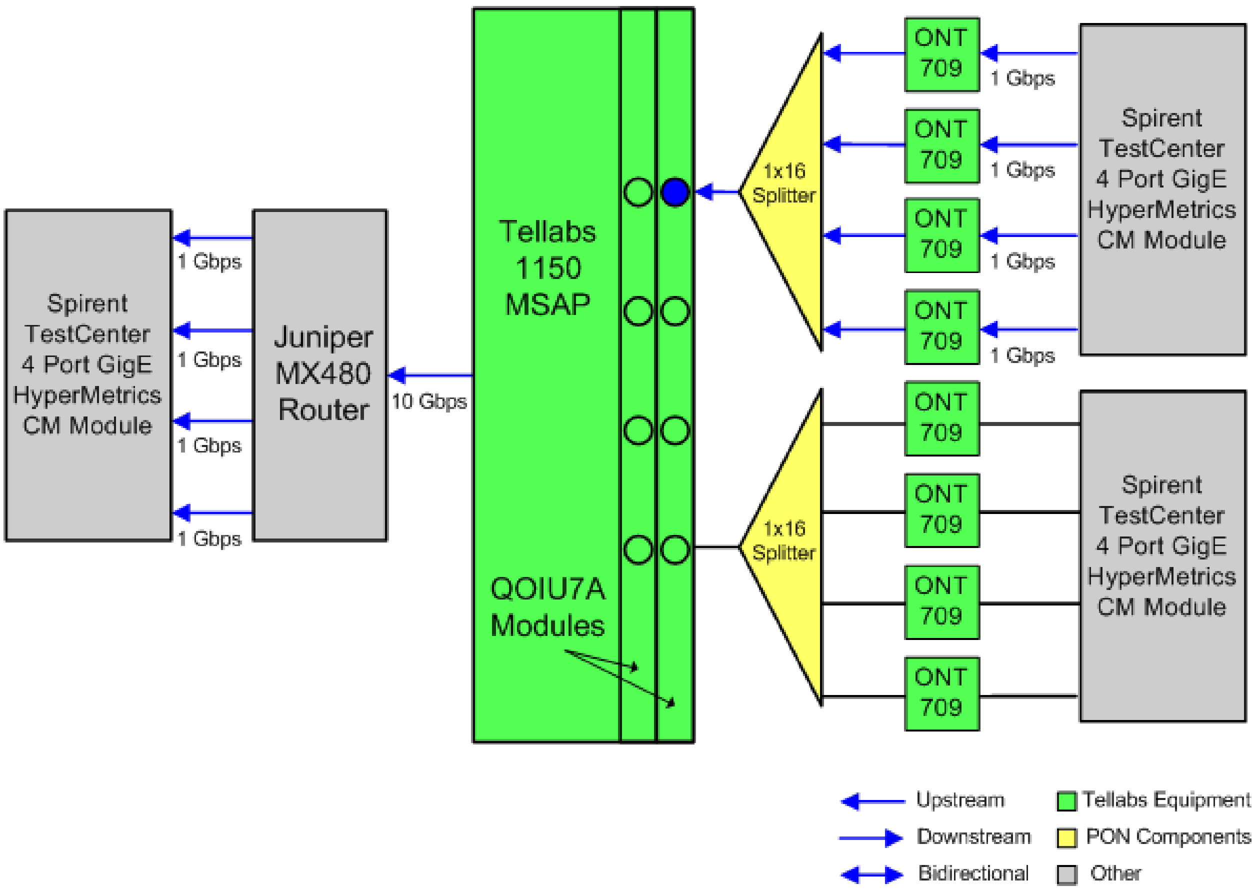
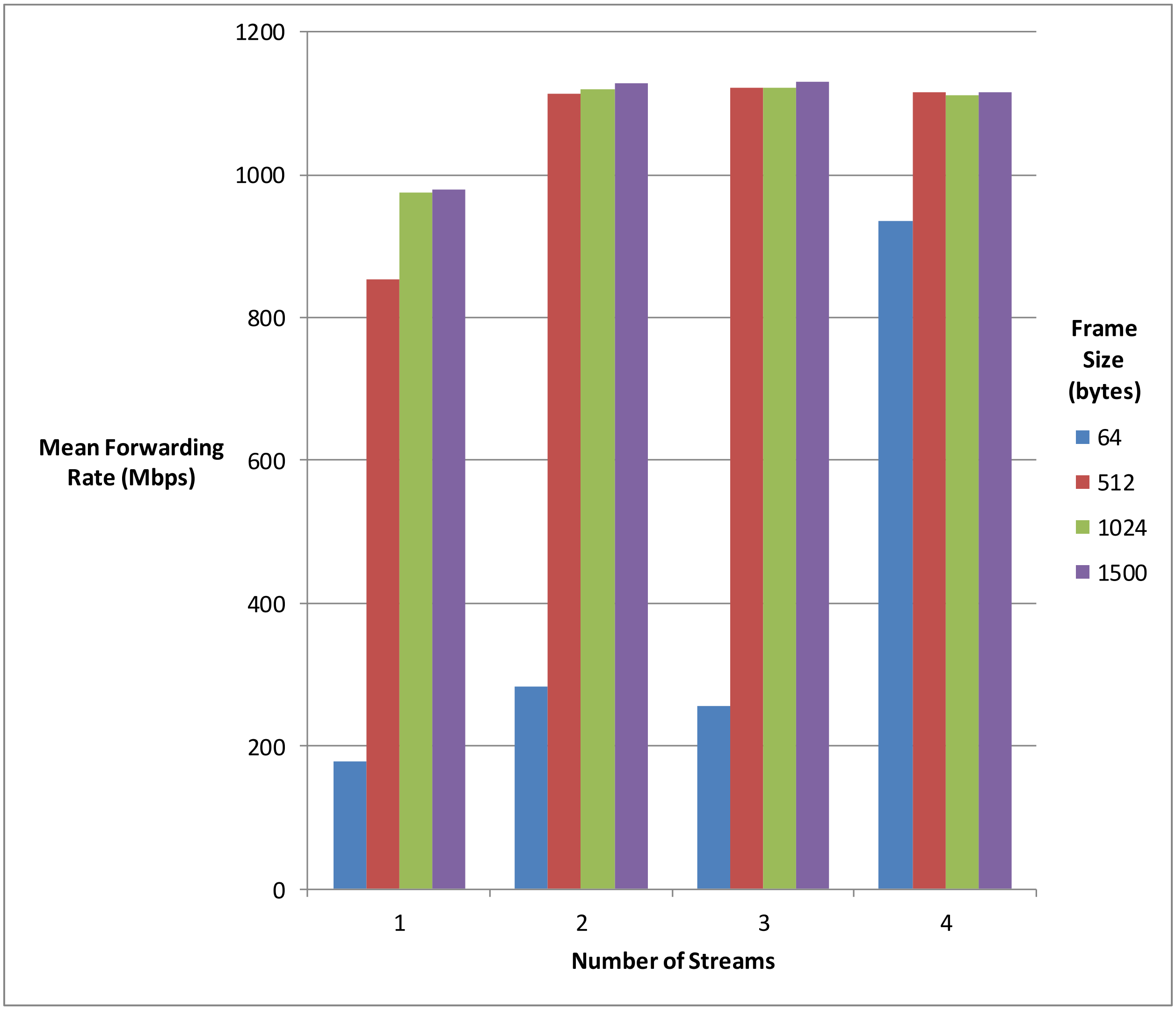


Figure 5 presents the mean upstream forwarding rate performance results for 5 trials with 1, 2, 3, and 4 streams. Ethernet frame sizes are 64, 512, 1024, and 1500 bytes. As is illustrated, a GPON port on the Tellabs 1150 MSAP can support upstream forwarding rates of over 1100 Mbps when more than one ONT709 is used. Detailed results are presented in Appendix A.

Figure 5. Mean Upstream Forwarding Rate Performance Results



Downstream performance testing was performed next. The configuration for downstream performance testing is illustrated in Figure 6. Data flows from left to right as is denoted by the arrows.

Figure 6. Configuration for Downstream Performance Testing

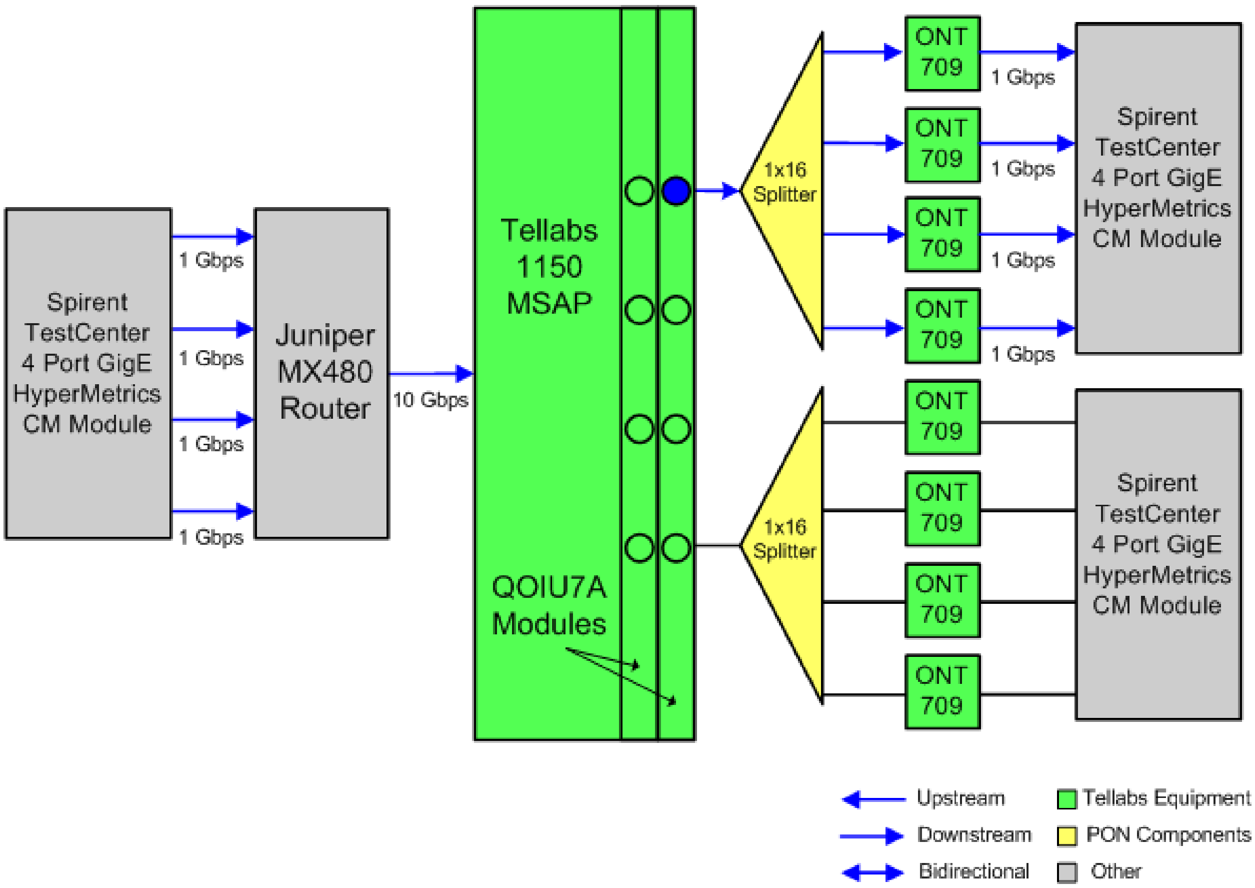
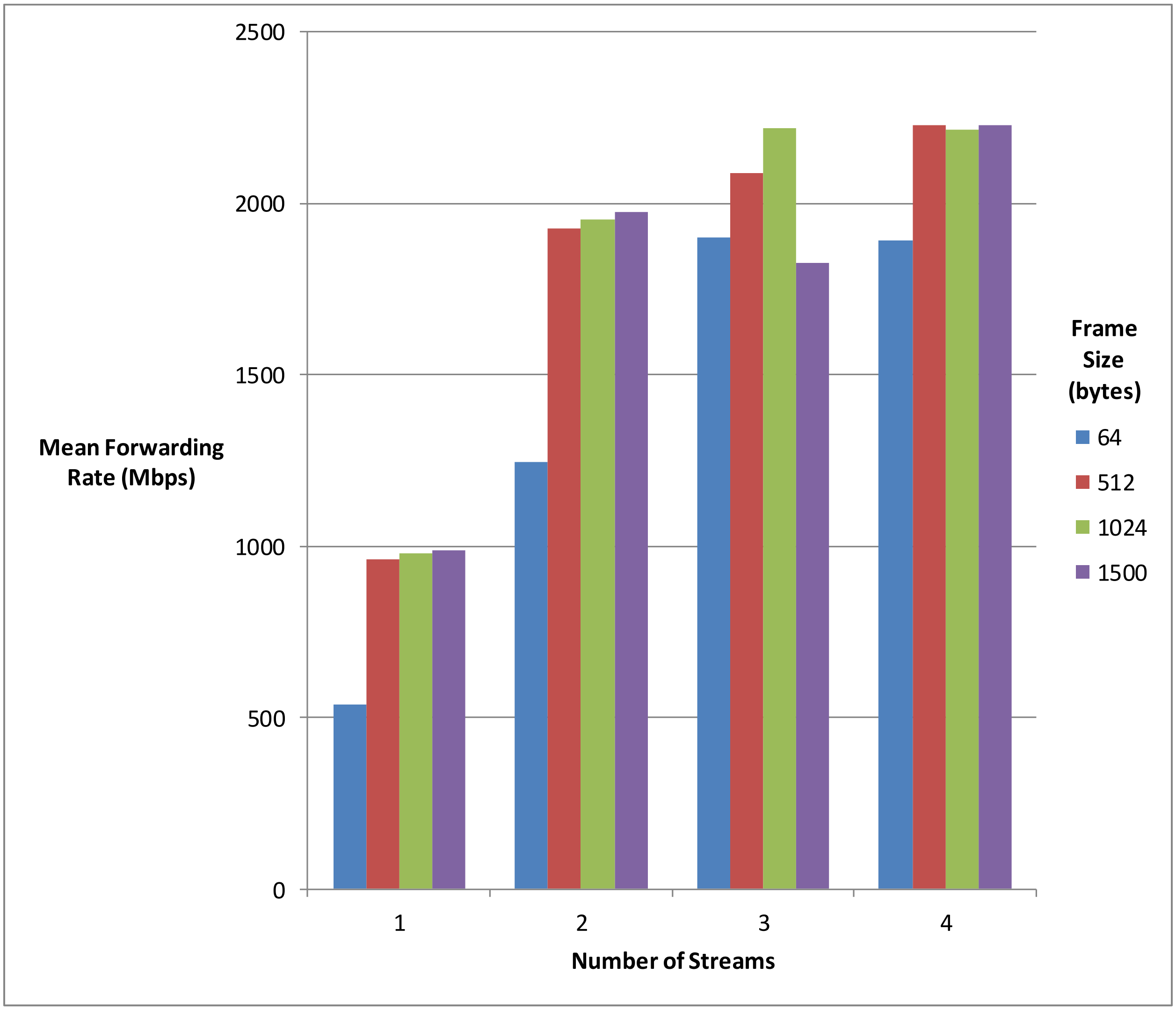


Figure 7 presents the mean downstream forwarding rate performance results for 5 trials with 1, 2, 3, and 4 streams. Ethernet frame sizes are 64, 512, 1024, and 1500 bytes. As is illustrated, a GPON port on the Tellabs 1150 MSAP can support downstream forwarding rates of over 2200 Mbps when more than two ONT709s are used. Detailed results are presented in Appendix B.

Figure 7. Mean Downstream Forwarding Rate Performance Results



Bidirectional performance testing was performed next. The configuration for bidirectional performance testing is illustrated in Figure 8. Data flows upstream and downstream simultaneously as is denoted by the arrows.

Figure 8. Configuration for Bidirectional Performance Testing

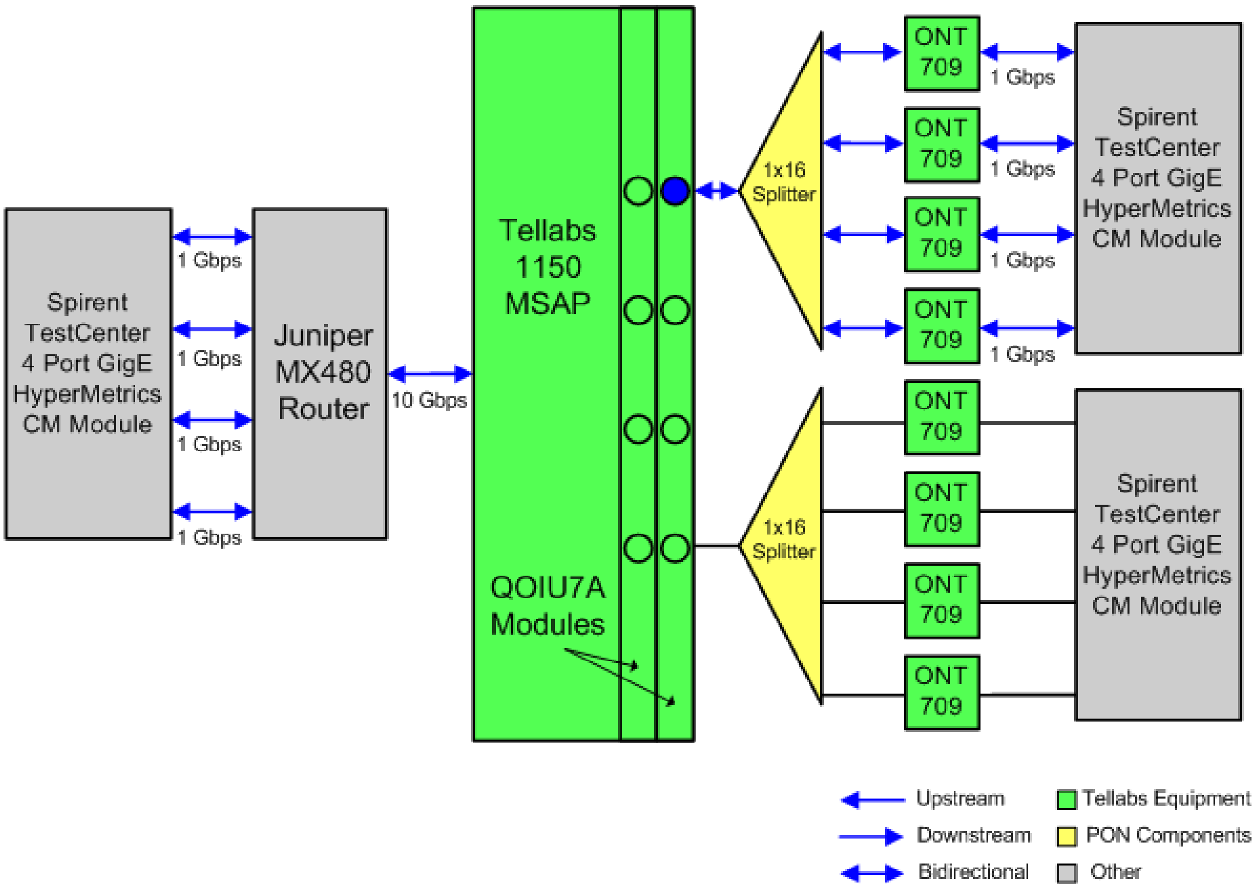
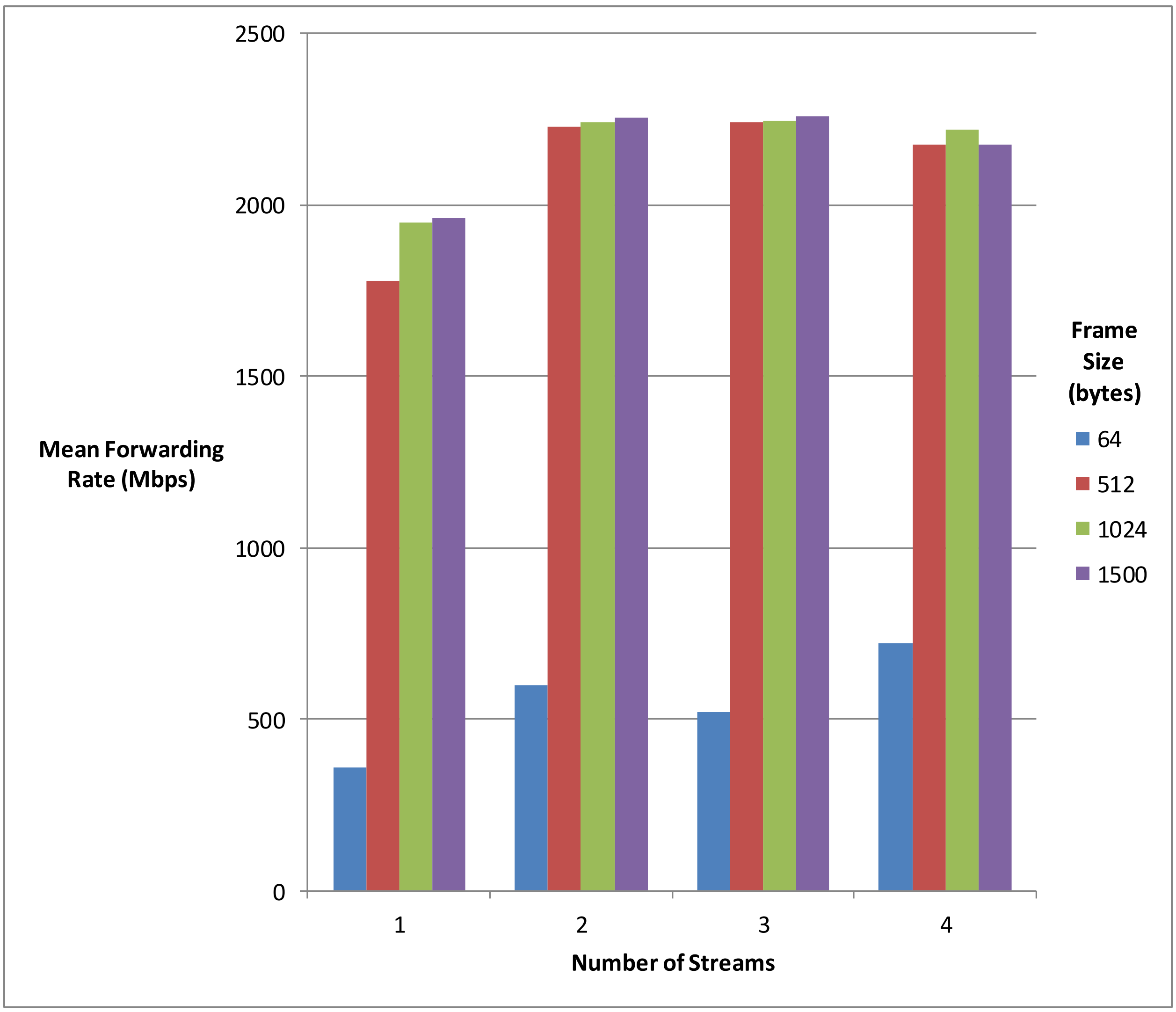


Figure 9 presents the mean aggregate bidirectional forwarding rate performance results for 5 trials with 1, 2, 3, and 4 streams. Ethernet frame sizes are 64, 512, 1024, and 1500 bytes. As is illustrated, a GPON port on the Tellabs 1150 MSAP can support bidirectional forwarding rates of over 2200 Mbps when more than one ONT709 is used. Note that the forwarding rate aggregate is the sum of the forwarding rates in each direction, as it would not be possible for a GPON port to support upstream forwarding rates at 2000 Mbps. Also, these are the results of RFC 2544 tests which do not fully test the asymmetric GPON forwarding rates of 1.244 Gbps upstream and 2.488 Gbps downstream independently in each direction [4]. Manual testing has shown that a GPON port on the Tellabs 1150 MSAP can support aggregate bidirectional forwarding rates of over 3000 Mbps. Detailed results are presented in Appendix C.

Figure 9. Mean Aggregate Bidirectional Forwarding Rate Performance Results



3.4 GPON Port to GPON Port Testing Using Different GPON Modules

The purpose of these tests is to determine what forwarding rate the Tellabs 1150 MSAP can support between GPON ports that are located on different GPON modules. These tests were performed for unidirectional and bidirectional traffic. For unidirectional tests, traffic will be flowing upstream on the source GPON port and downstream on the destination GPON port. The configuration for this test is shown in Figure 10.

Figure 10. Configuration for Unidirectional Performance Testing Using Different GPON Modules

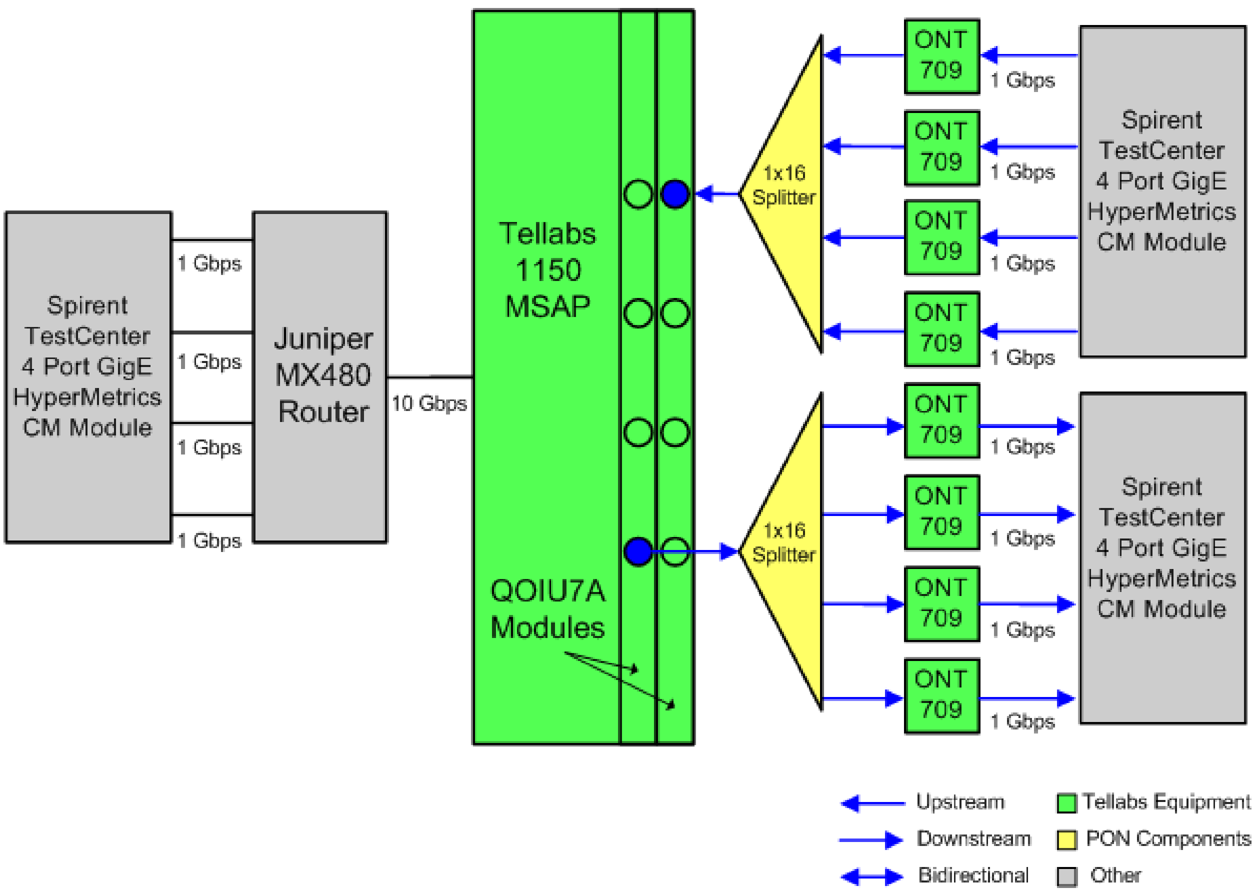
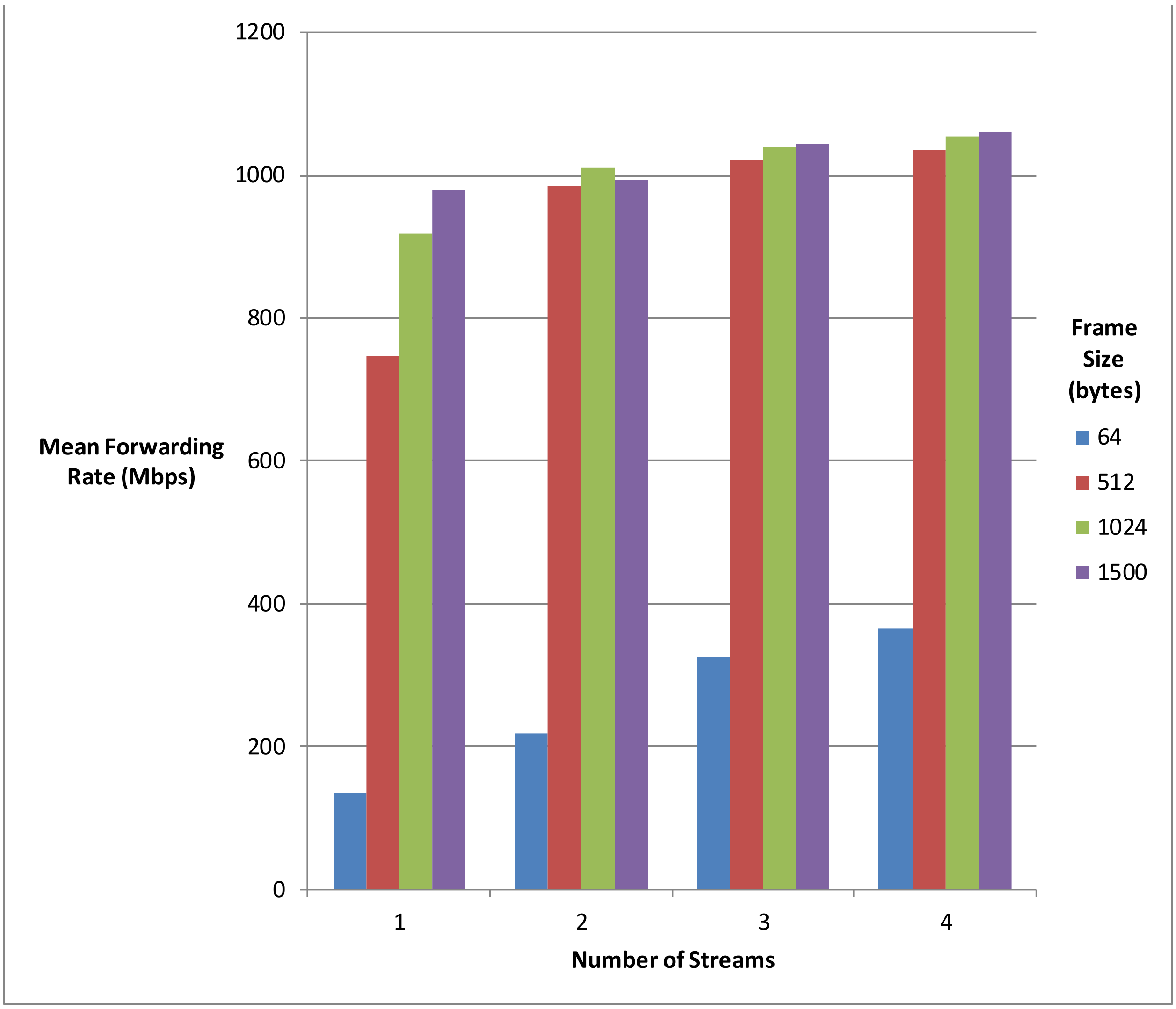


Figure 11 presents the mean unidirectional forwarding rate performance results using different GPON modules for 5 trials with 1, 2, 3, and 4 streams. Ethernet frame sizes are 64, 512, 1024, and 1500 bytes. As is illustrated, a GPON port on the Tellabs 1150 MSAP can support forwarding rates of over 1000 Mbps when more than two ONT709s are used and the destination ONT709s are located on a GPON port on a different GPON module. Detailed results are presented in Appendix D.

Figure 11. Mean Unidirectional Forwarding Rate Performance Results Using Different GPON Modules



Bidirectional performance testing between ONT709s located on ports on different GPON modules was also performed. For these tests, data was flowing upstream and downstream simultaneously on each GPON port as illustrated in Figure 12.

Figure 12. Configuration for Bidirectional Performance Testing Using Different GPON Modules

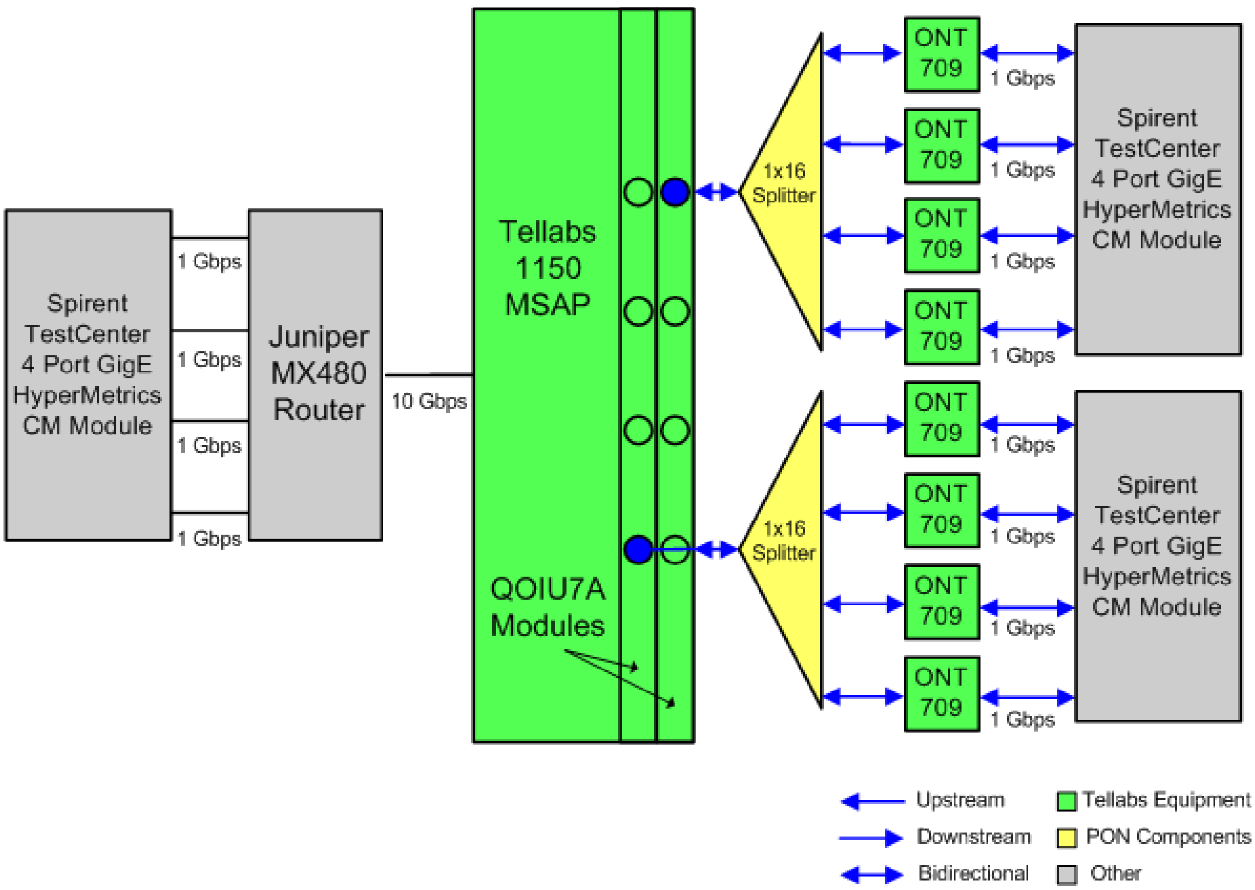
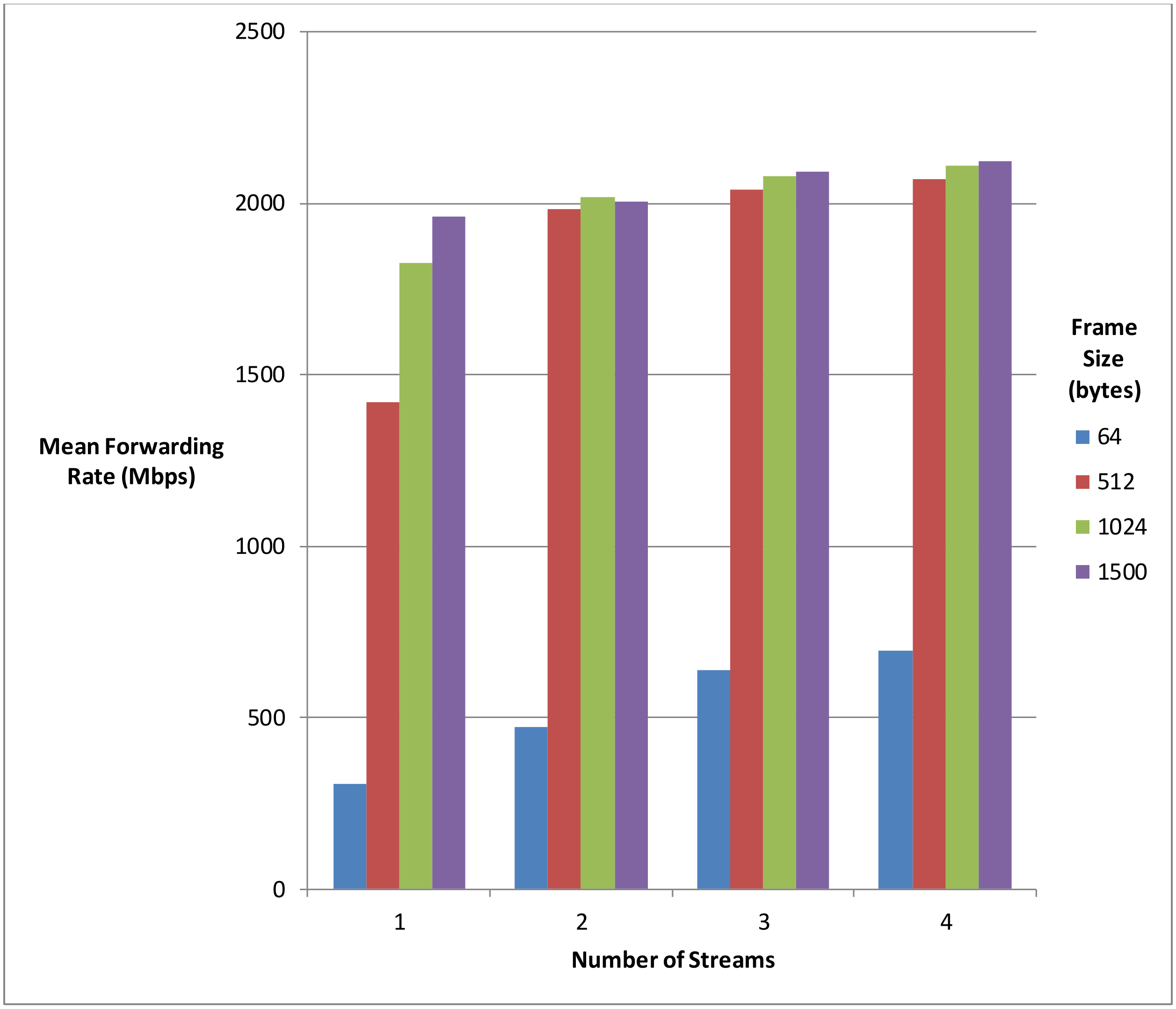


Figure 13 presents the mean aggregate bidirectional forwarding rate performance results using different GPON modules for 5 trials with 1, 2, 3, and 4 streams. Ethernet frame sizes are 64, 512, 1024, and 1500 bytes. As is illustrated, a GPON port on the Tellabs 1150 MSAP can support forwarding rates of over 2000 Mbps when more than two ONT709s are used and the destination ONT709s are located on a GPON port on a different GPON module. Detailed results are presented in Appendix D.

Figure 13. Mean Aggregate Bidirectional Forwarding Rate Performance Results Using Different GPON Modules



3.5 GPON Port to GPON Port Testing Using the Same GPON Module

The purpose of these tests is to determine what forwarding rate the Tellabs 1150 MSAP can support between ONT709s when the GPON ports are located on the same GPON module. These tests were performed for unidirectional and bidirectional traffic. For unidirectional tests, traffic will be flowing upstream on the source GPON port and downstream on the destination GPON port. The configuration for this test is shown in Figure 14.

Figure 14. Configuration for Unidirectional Performance Testing Using the Same GPON Module

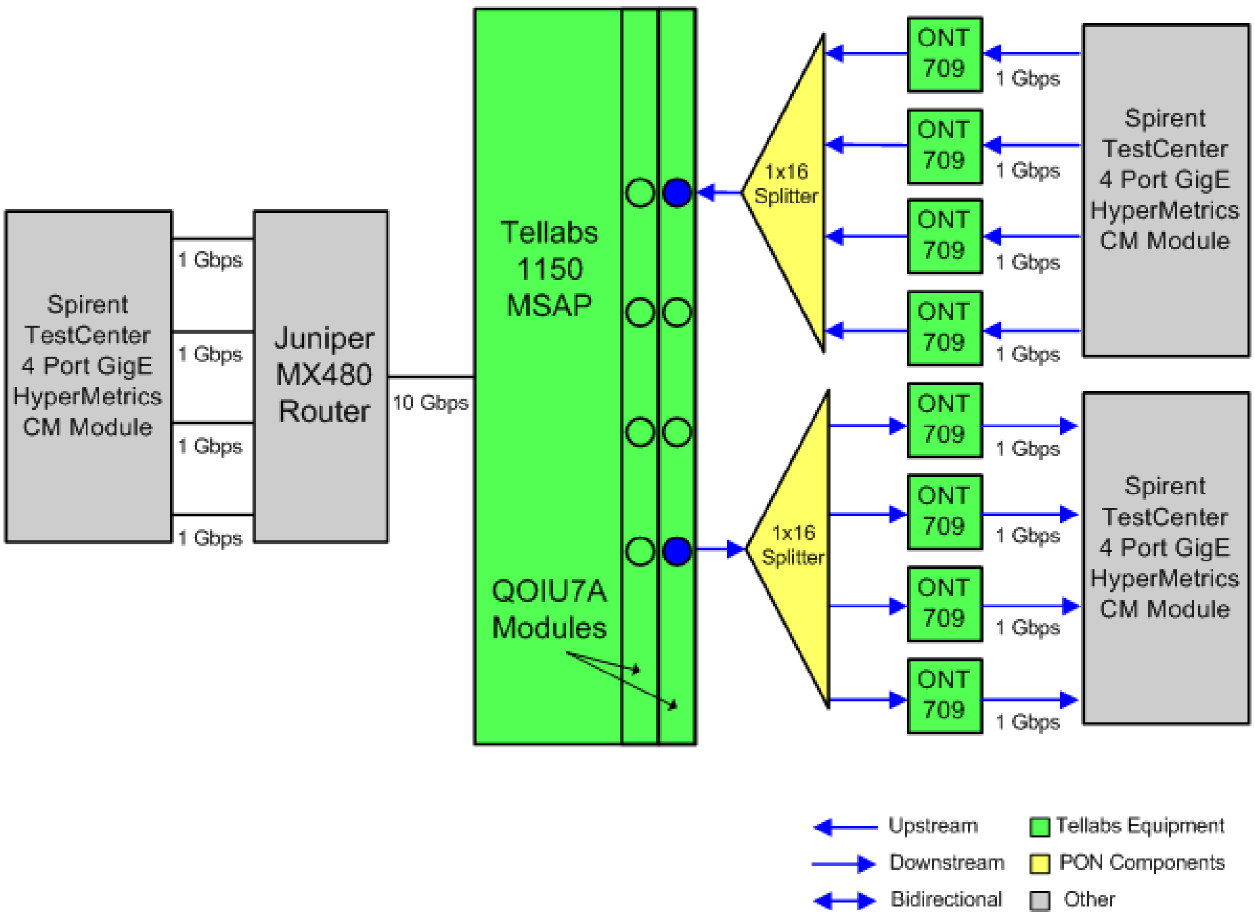
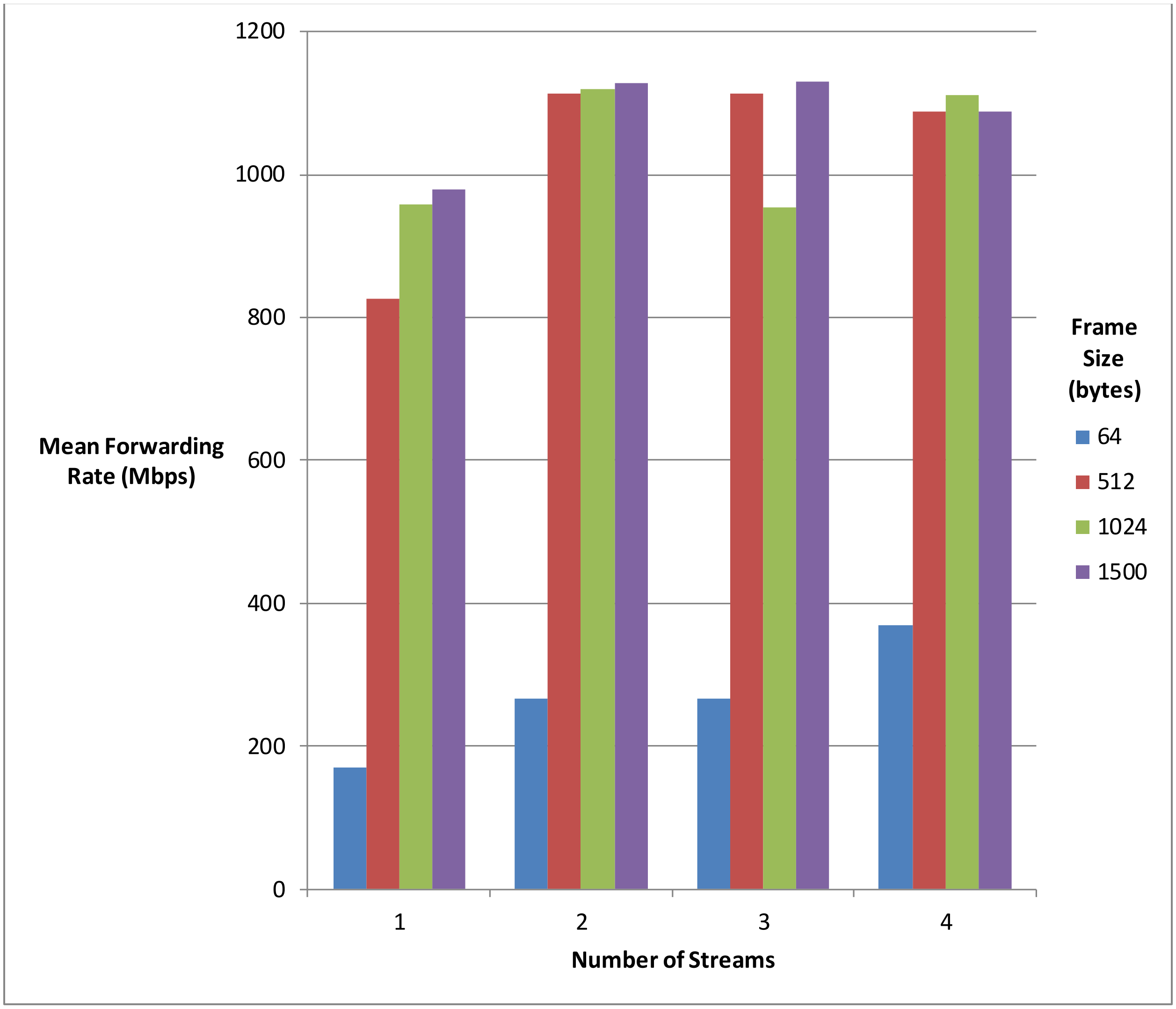


Figure 15 presents the mean unidirectional forwarding rate performance results using the same GPON module for 5 trials with 1, 2, 3, and 4 streams. Ethernet frame sizes are 64, 512, 1024, and 1500 bytes. As is illustrated, a GPON port on the Tellabs 1150 MSAP can support forwarding rates of over 1100 Mbps when two or more ONT709s are used and the destination ONT709s are located on a different GPON port on the same GPON module. Detailed results are presented in Appendix E.

Figure 15. Mean Unidirectional Forwarding Rate Performance Results Using the Same GPON Module



Bidirectional performance testing between ONT709s located on ports on the same GPON module was performed next. For these tests, data was flowing upstream and downstream simultaneously on each GPON port as illustrated in Figure 16.

Figure 16. Configuration for Bidirectional Performance Testing Using the Same GPON Module

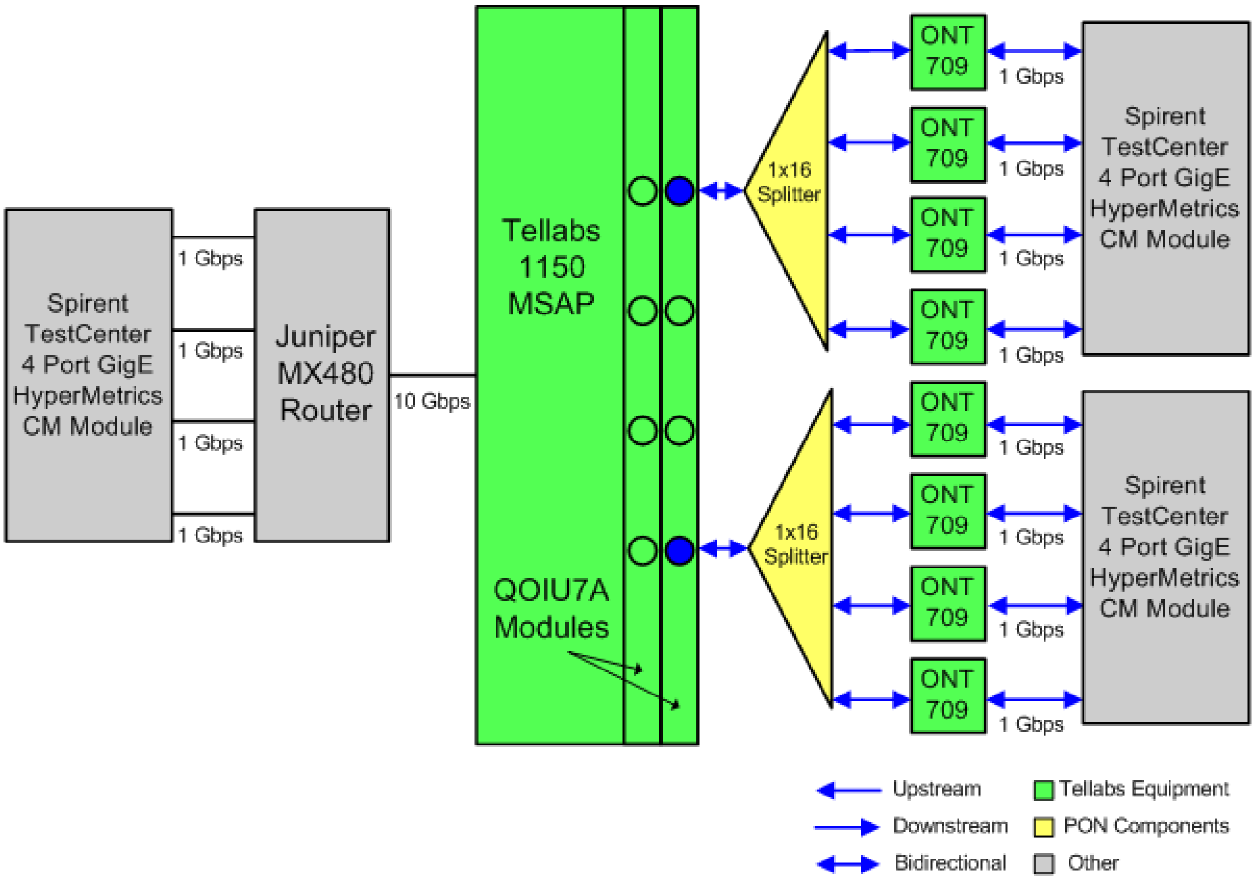
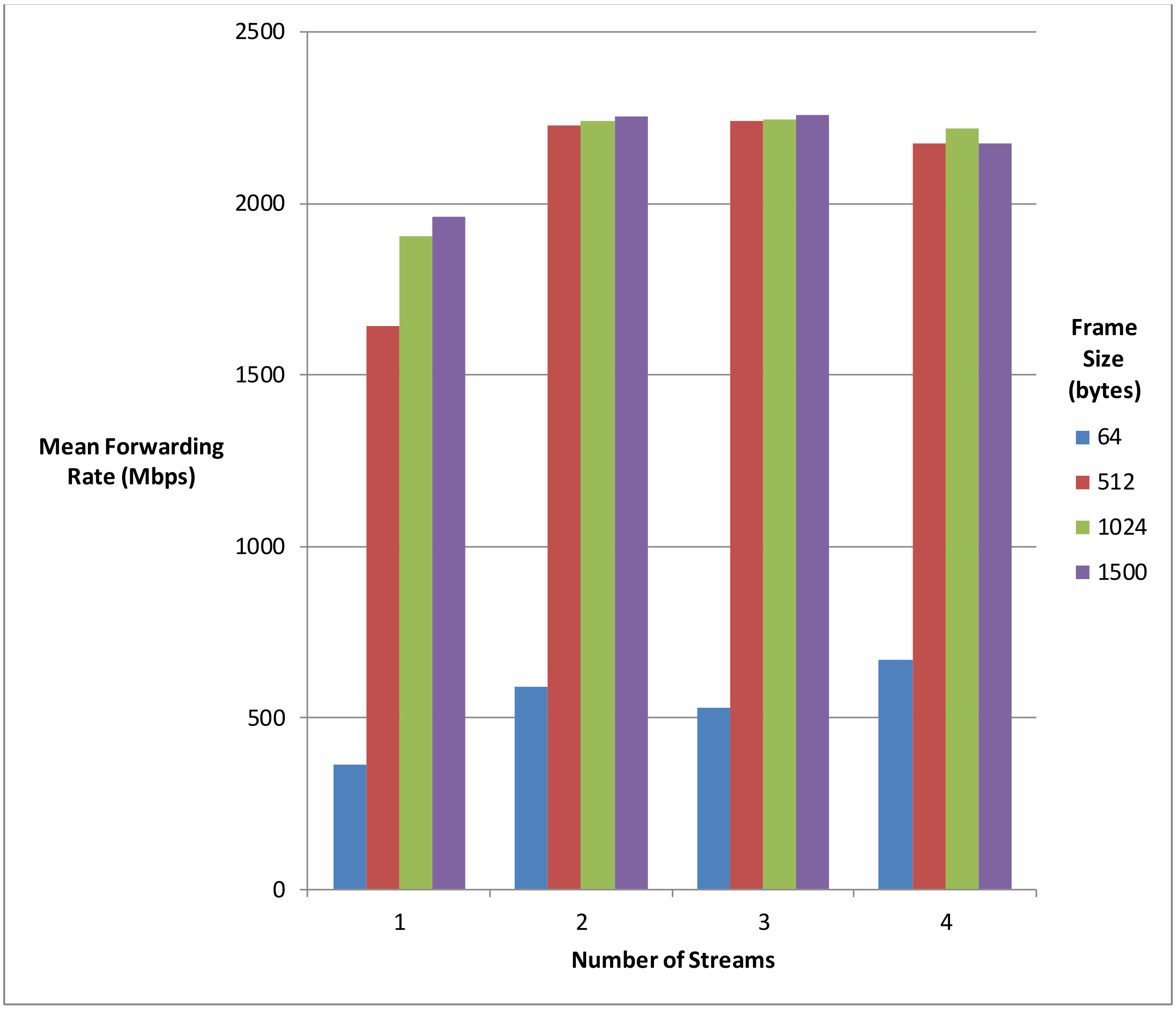


Figure 17 presents the mean aggregate bidirectional performance results using the same GPON module for 5 trials with 1, 2, 3, and 4 streams. Ethernet frame sizes are 64, 512, 1024, and 1500 bytes. As is illustrated, a GPON port on the Tellabs 1150 MSAP can support forwarding rates of over 2000 Mbps when two or more ONT709s are used and the destination ONTs are located on a GPON port on the same GPON module. Detailed results are presented in Appendix E.

Figure 17. Mean Aggregate Bidirectional Performance Results Using the Same GPON Module



3.6 Single ONT709 Testing

The purpose of these tests is to determine what forwarding rate a single Tellabs ONT709 can support. These tests were performed for upstream, downstream, and bidirectional traffic. The tests were conducted for 1, 2, 3, and 4 ports through a single ONT709. Upstream performance testing was performed first. The configuration for this test is shown in Figure 18.

Figure 18. Configuration for Upstream Performance Testing Using a Single ONT709

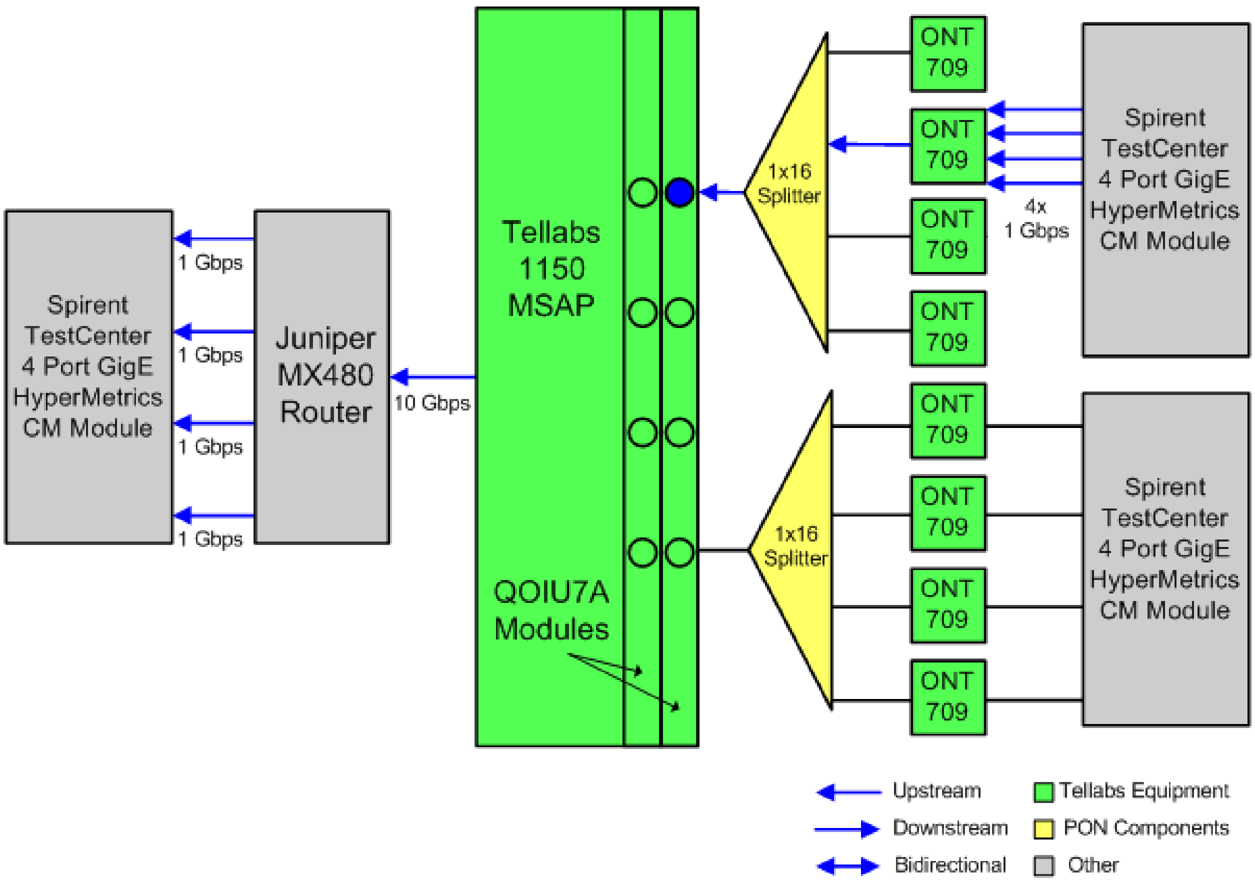
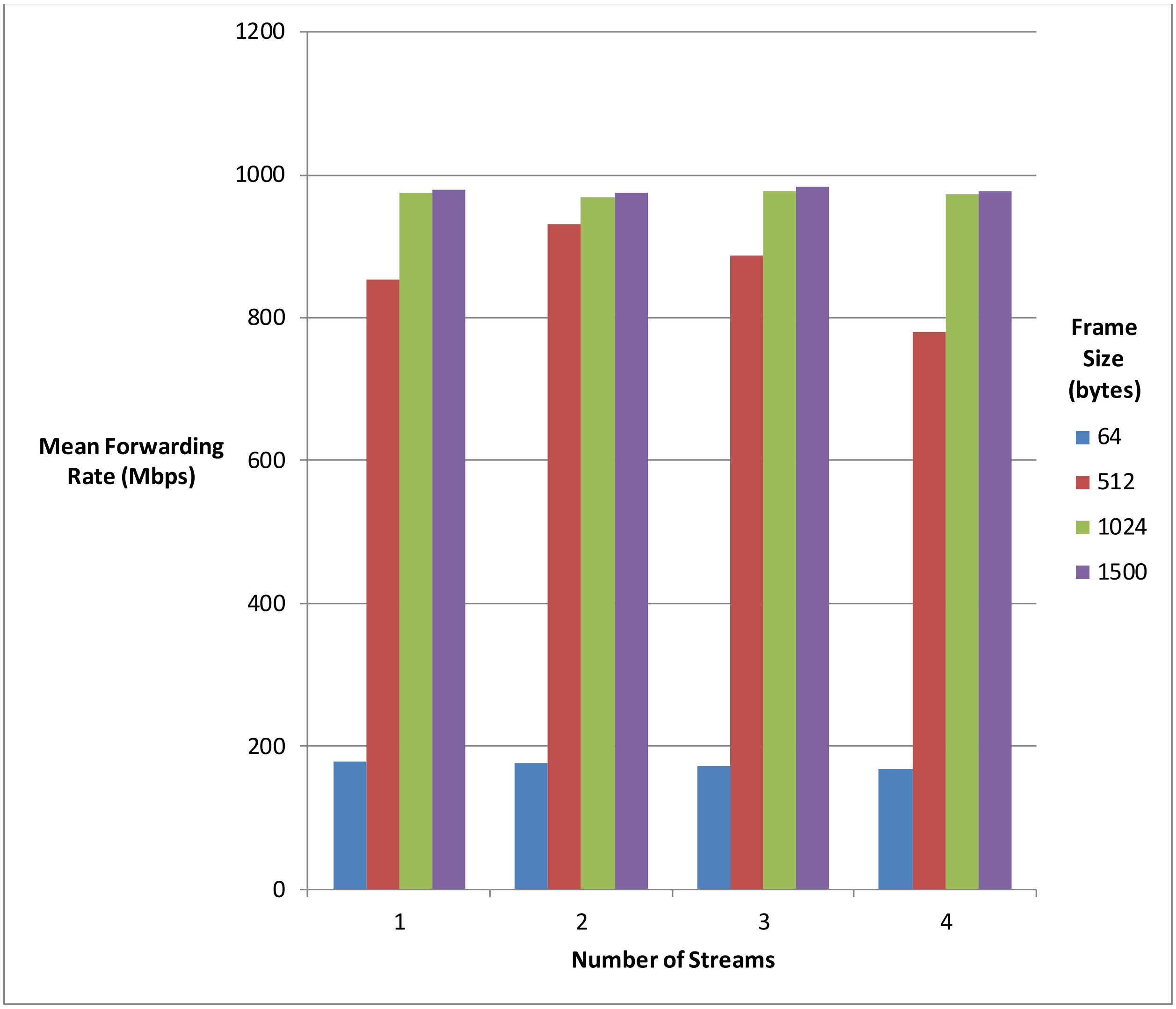


Figure 19 presents the mean upstream forwarding rate performance results using a single ONT709 for 5 trials with 1, 2, 3, and 4 streams. Ethernet frame sizes are 64, 512, 1024, and 1500 bytes. As is illustrated, a single Tellabs ONT709 can support upstream forwarding rates of nearly 1000 Mbps for 1, 2, 3, and 4 streams. Detailed results for 1 stream are presented in Table 27 in Appendix A. Detailed results for 2, 3, and 4 streams are presented in Appendix F.

Figure 19. Mean Upstream Forwarding Rate Performance Results Using a Single ONT709



Downstream performance testing using a single ONT709 was also performed. The configuration for downstream performance testing is illustrated in Figure 20.

Figure 20. Configuration for Downstream Performance Testing Using a Single ONT709

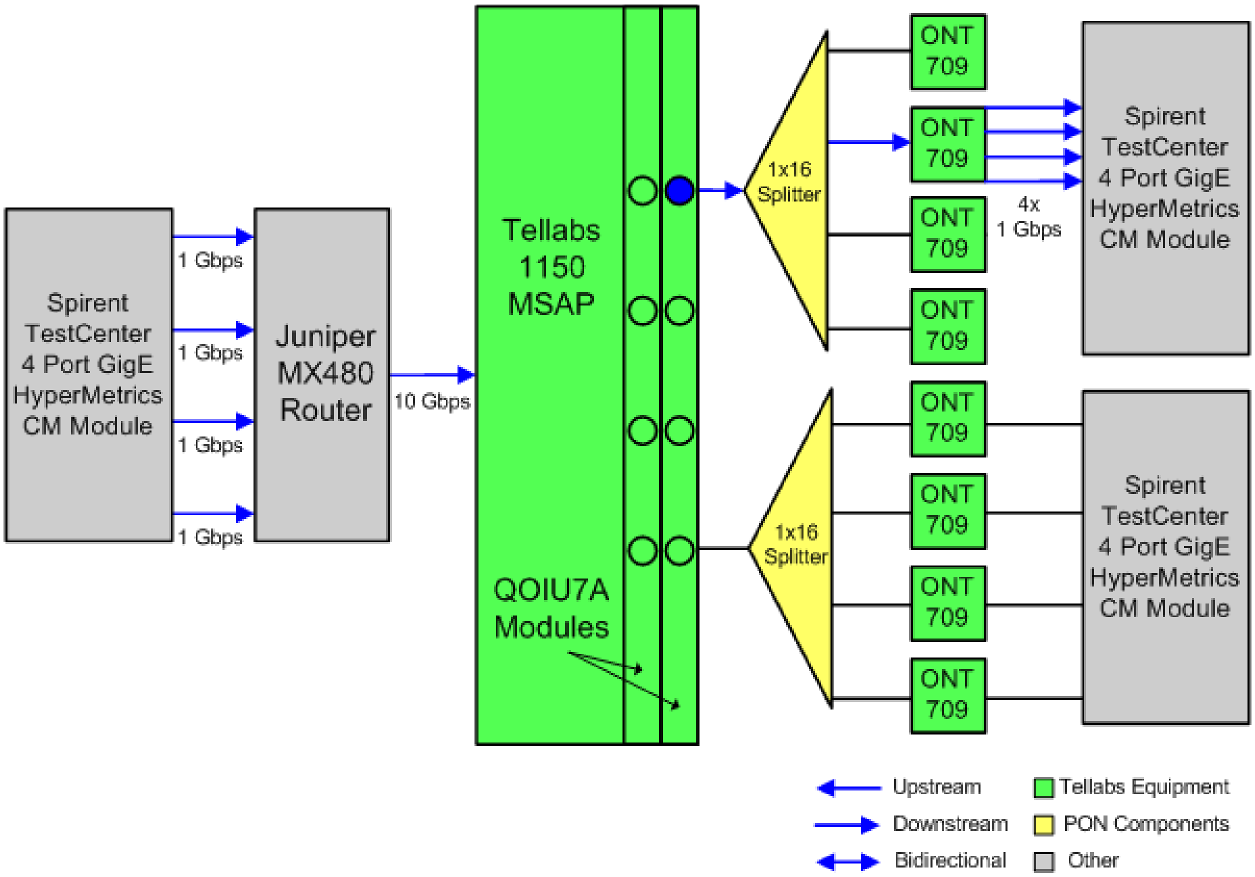
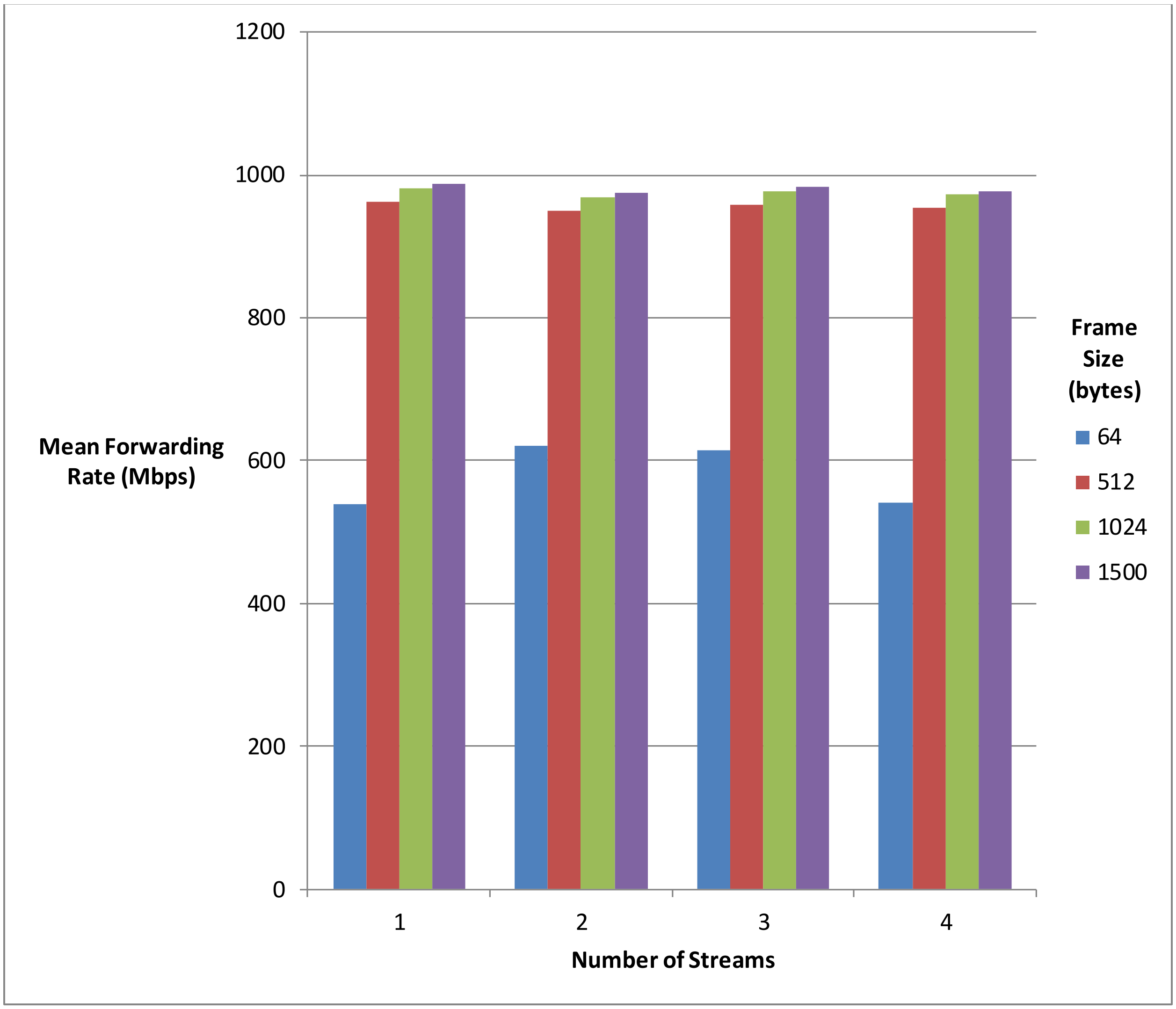


Figure 21 presents the mean downstream forwarding rate performance results using a single ONT709 for 5 trials with 1, 2, 3, and 4 streams. Ethernet frame sizes are 64, 512, 1024, and 1500 bytes. As is illustrated, a single Tellabs ONT709 can support downstream forwarding rates of nearly 1000 Mbps for 1, 2, 3, and 4 streams. Detailed results for 1 stream can be found in Table 31 in Appendix B. Detailed results for 2, 3, and 4 streams are presented in Appendix G.

Figure 21. Mean Downstream Forwarding Rate Performance Results Using a Single ONT709



Bidirectional performance testing for a single ONT709 was also performed. For these tests, data was flowing upstream and downstream simultaneously on each ONT709 port as illustrated in Figure 22.

Figure 22. Configuration for Bidirectional Performance Testing Using a Single ONT709

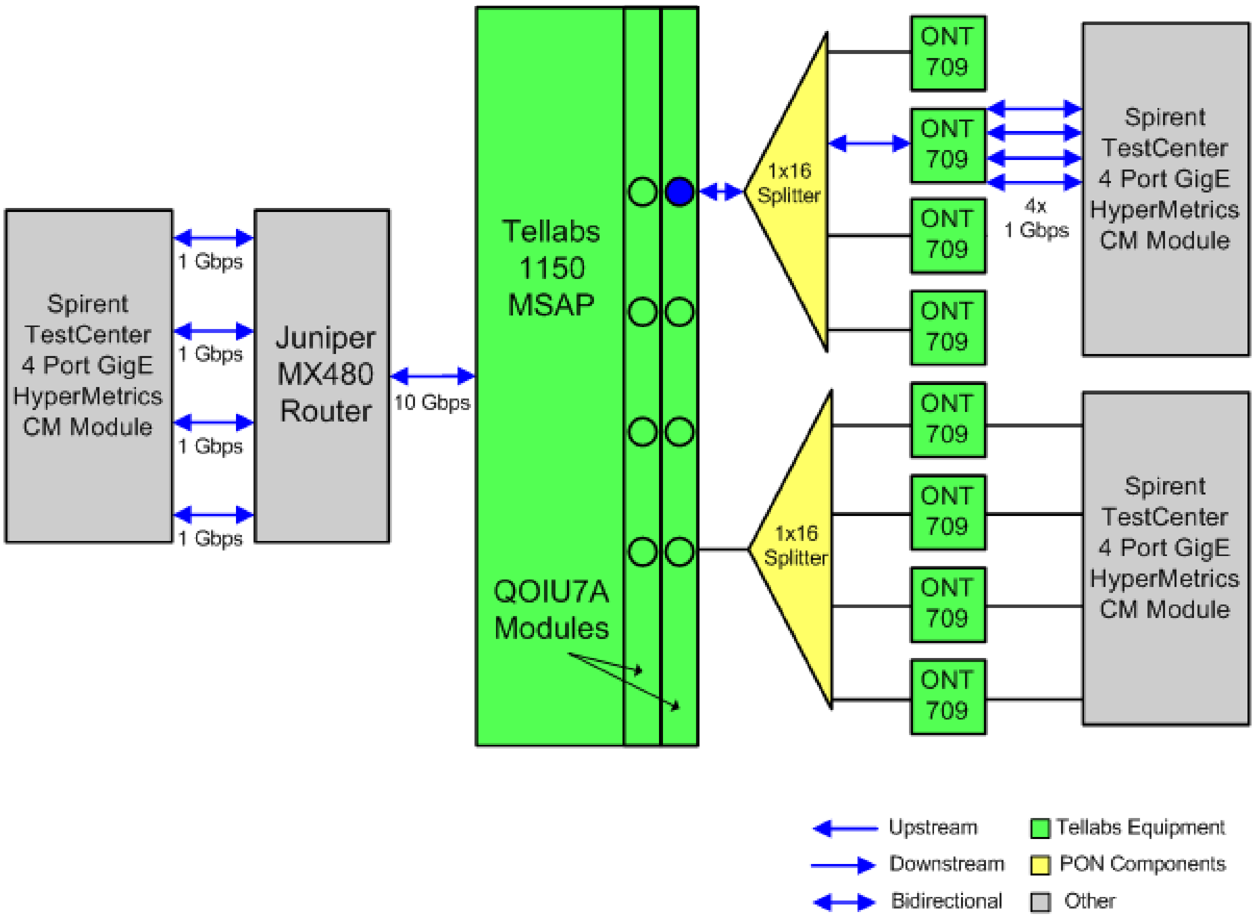
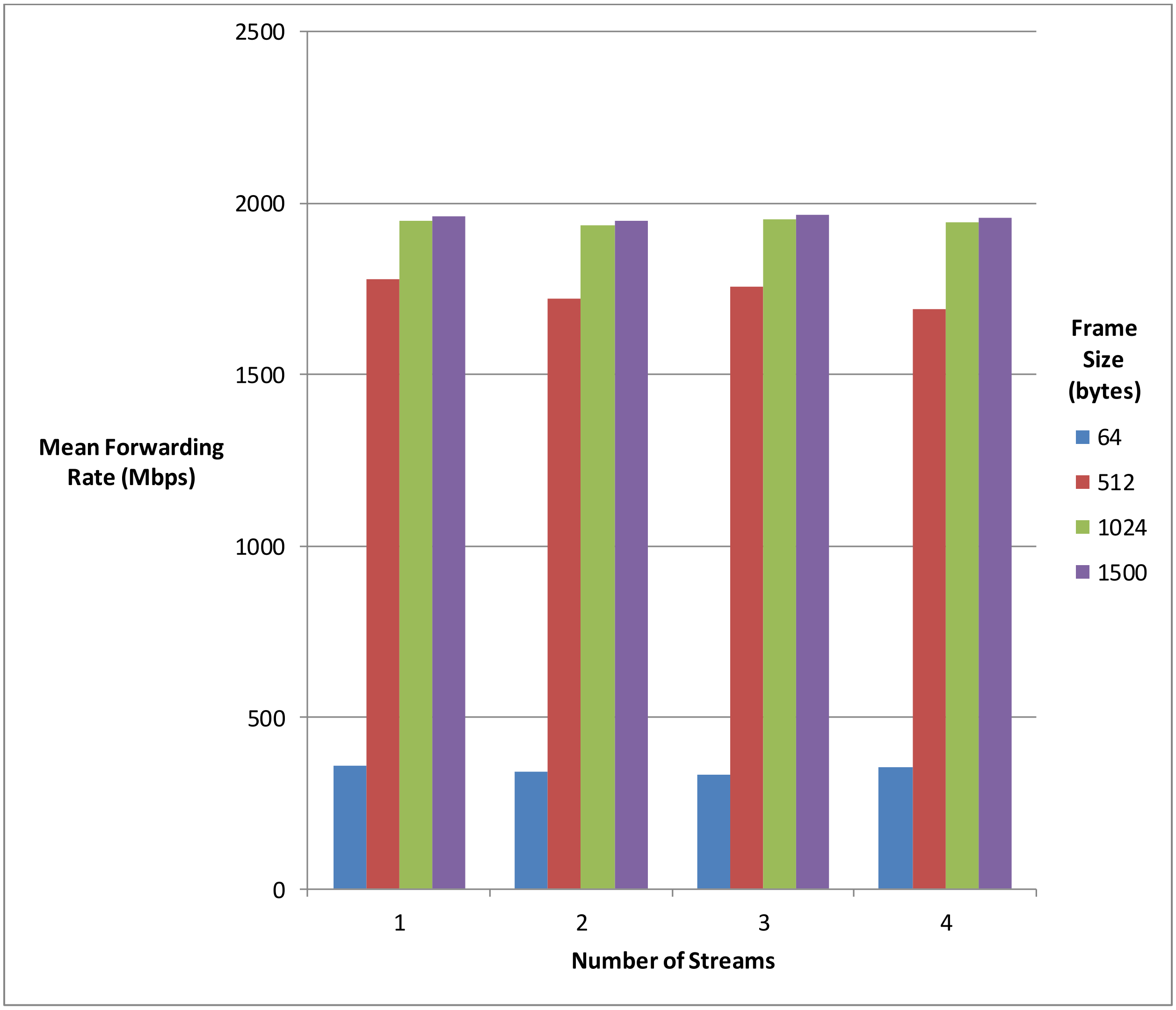


Figure 23 presents the mean aggregate bidirectional forwarding rate results using a single ONT709 for 5 trials with 1, 2, 3, and 4 streams. Ethernet frame sizes are 64, 512, 1024, and 1500 bytes. As is illustrated, a single Tellabs ONT709 can support aggregate bidirectional forwarding rates of almost 2000 Mbps for 1, 2, 3, and 4 streams. Detailed results for 1 stream can be found in Table 35 in Appendix C. Detailed results for 2, 3, and 4 streams are presented in Appendix H.

Figure 23. Mean Aggregate Bidirectional Forwarding Rate Performance Results Using a Single ONT709



3.7 GPON Parameter Testing

GPON as defined in ITU-T G.984 recommendations supports several parameters that were tested. One parameter is encryption which is performed in the downstream direction only. This parameter can be enabled or disabled in the Connection Profile which is used for every connection provisioned on an ONT709 port. The profile is illustrated in Figure 2.

Forward Error Correction (FEC) is another parameter which can be enabled or disabled for an individual GPON port on the Tellabs 1150 MSAP. When FEC is enabled, a checksum is transmitted in GPON Encapsulation Method (GEM) frames sent between the Tellabs 1150 MSAP and the ONT709s. The purpose of enabling FEC is to allow an ONT709, which has received GEM frames containing errors, to correct those errors [2].

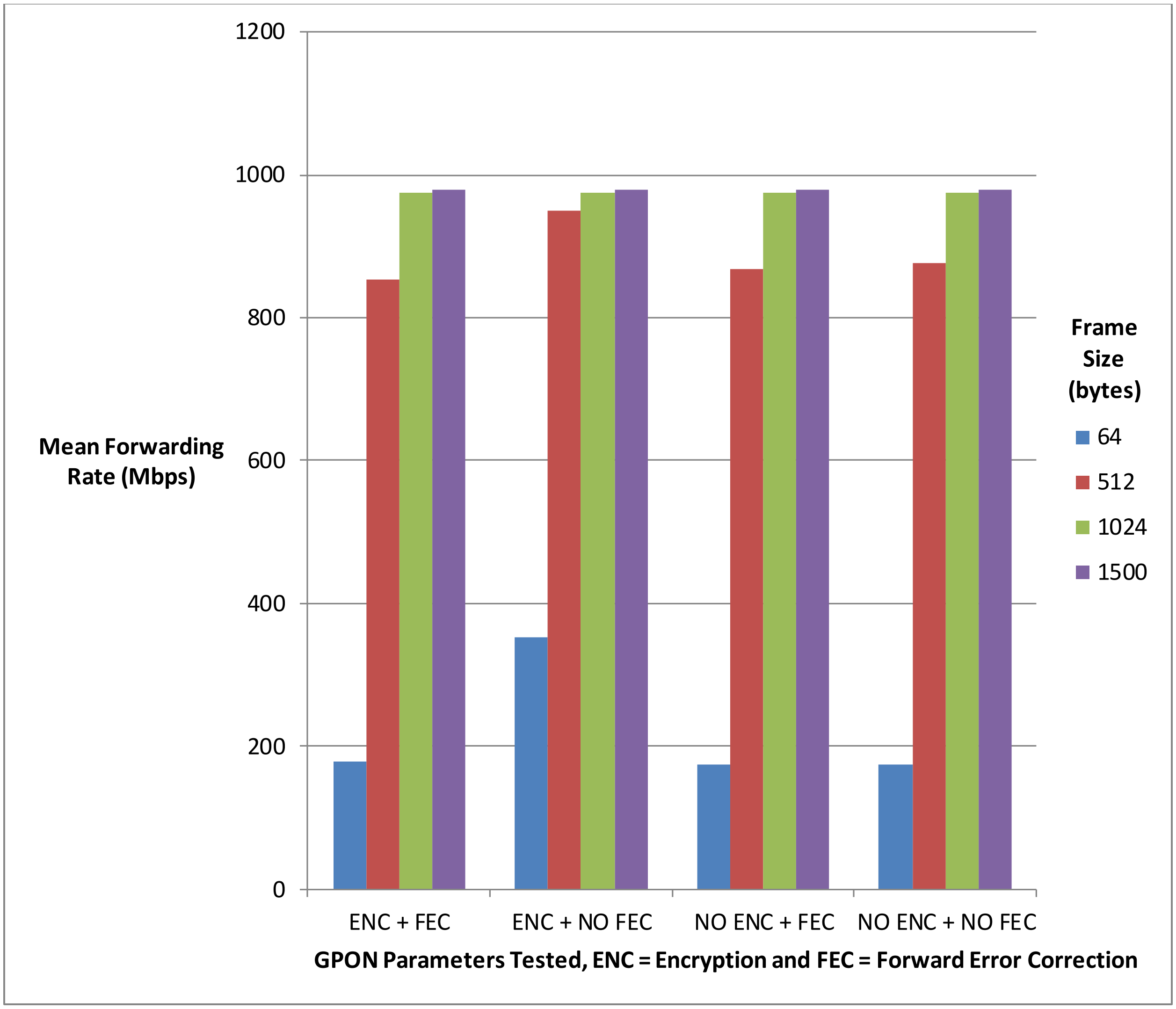
Although encryption and FEC are performed in the downstream direction only, tests were performed for upstream, downstream, and bidirectional for completeness. Upstream testing was performed first. The configuration for this test is illustrated in Figure 4.

The captions are as follows:
ENC - Encryption is enabled.
NO ENC - Encryption is disabled.
FEC - Forward Error Correction is Enabled.
NO FEC - Forward Error Correction is Disabled.

These 4 parameters are tested in all possible combinations as is noted in the X axis values in Figures 24–26.

Figure 24 presents the mean upstream forwarding rate performance results with GPON parameters varied for a single stream from an ONT709 for 5 trials. Ethernet frame sizes are 64, 512, 1024, and 1500 bytes. As is illustrated, upstream forwarding rates are unaffected regardless of whether encryption or FEC is enabled. It is not fully understood at this time why the forwarding rate for 64 byte Ethernet frames was unusually high when encryption was enabled and FEC was disabled. More testing needs to be performed. Detailed results for ENC + FEC can be found in Table 27 in Appendix A. Detailed results for the other GPON parameters are presented in Appendices I, J, and K.

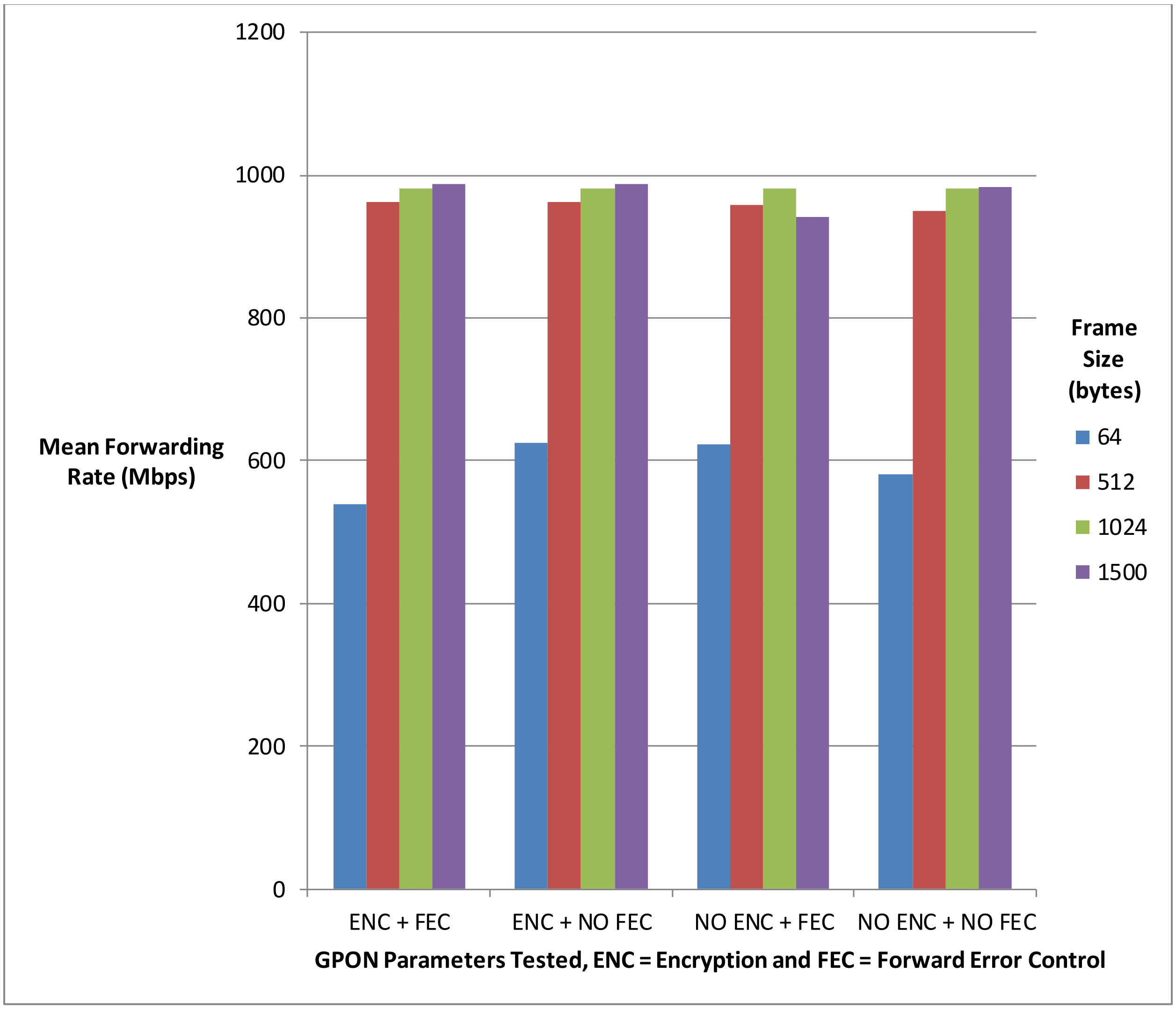
Figure 24. Mean Upstream Forwarding Rate Performance Results with GPON Parameters Varied



The same test was then performed for encryption and FEC in the downstream direction for a single stream. The configuration for that test is illustrated in Figure 6.

Figure 25 presents the mean downstream forwarding rate performance results with GPON parameters varied for a single stream from an ONT709 for 5 trials. Ethernet frame sizes are 64, 512, 1024, and 1500 bytes. As is illustrated, downstream forwarding rates are unaffected regardless of whether encryption or FEC is enabled. Note that these tests were performed in a laboratory environment and even though FEC was enabled, it was not needed because of the short distance from GPON port to ONT709. Detailed results for ENC + FEC can be found in Table 31 in Appendix B. Detailed results for the other GPON parameters are presented in Appendices I, J, and K.

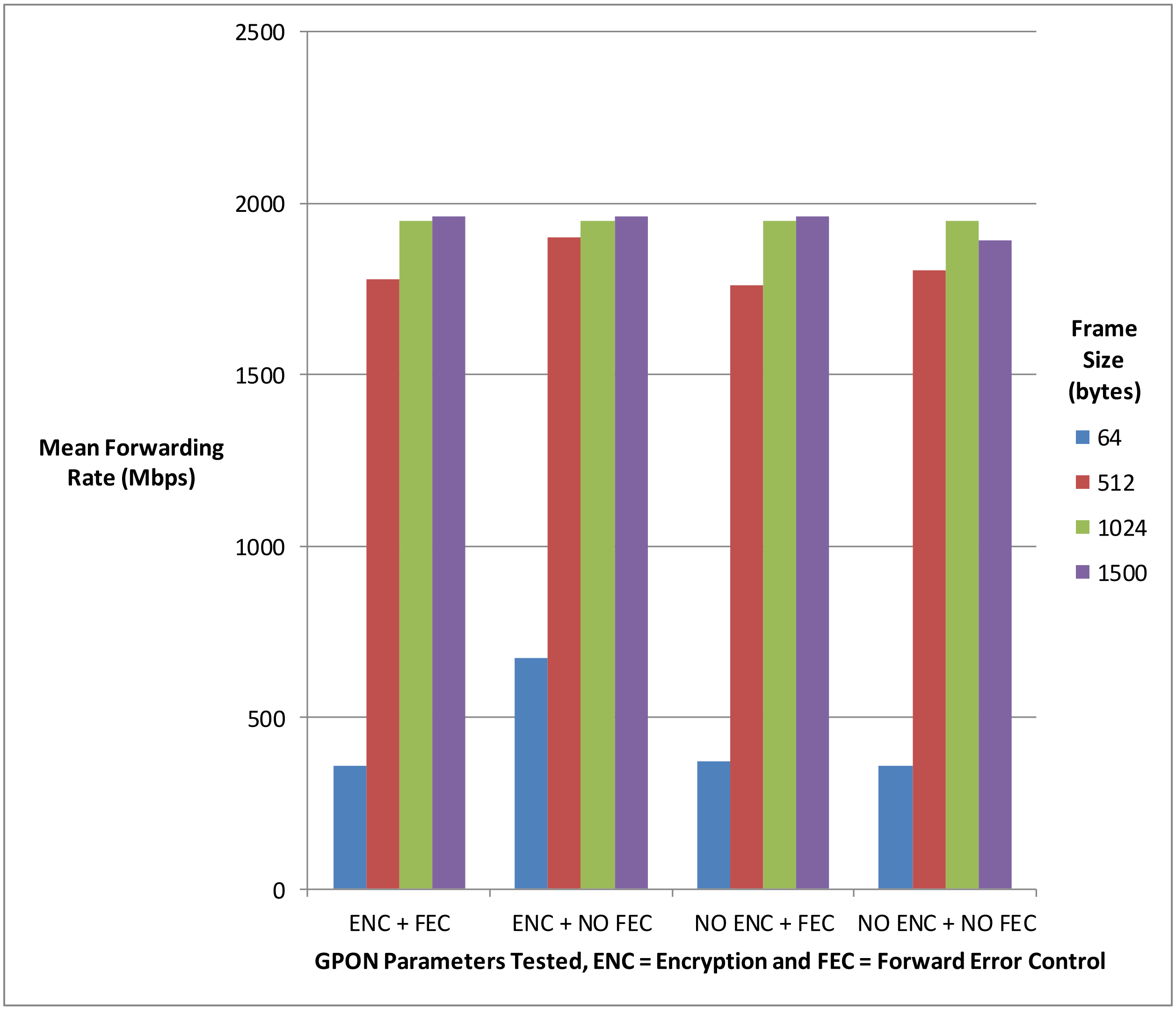
Figure 25. Mean Downstream Forwarding Rate Performance Results with GPON Parameters Varied



The same test was also performed for encryption and FEC for bidirectional traffic for a single stream. The configuration for that test is illustrated in Figure 8.

Figure 26 presents the mean aggregate bidirectional forwarding rate performance results with GPON parameters varied for a single stream from an ONT709 for 5 trials. Ethernet frame sizes are 64, 512, 1024, and 1500 bytes. As is illustrated, bidirectional forwarding rates are unaffected regardless of whether encryption or FEC is enabled. As was the case for upstream traffic, the forwarding rate for 64 byte Ethernet frames was unusually high when encryption was enabled and FEC was disabled. Detailed results for ENC + FEC can be found in Table 35 in Appendix C. Detailed results for the other GPON parameters are presented in Appendices I, J, and K.

Figure 26. Mean Aggregate Bidirectional Forwarding Rate Performance Results with GPON Parameters Varied

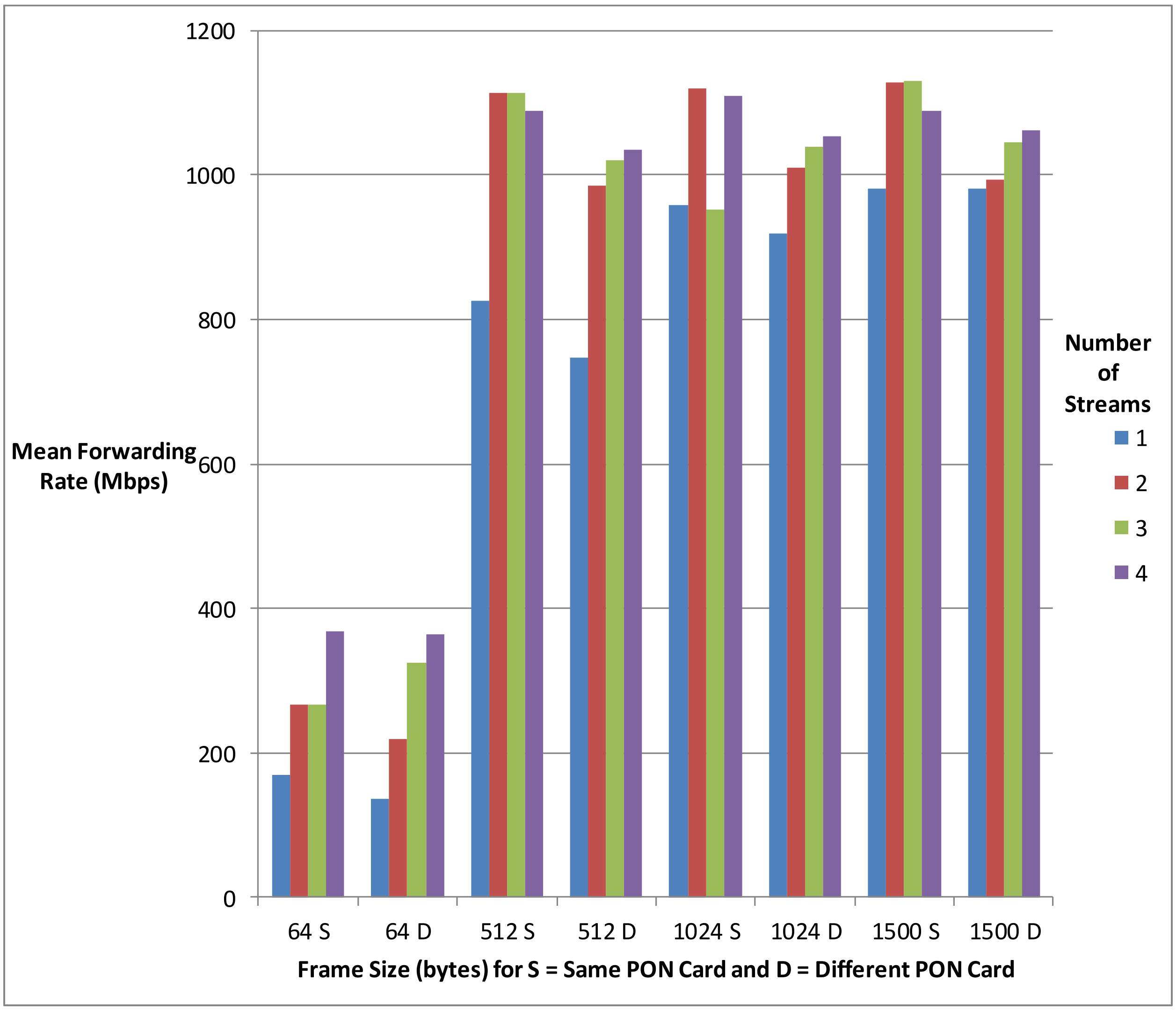


3.8 GPON Port to GPON Port Comparison Testing

From the tests performed in Sections 3.4 and 3.5, it was possible to combine the results and determine if the unidirectional forwarding rates for ONT709s on a GPON port were affected if the destination ONT709s were on a GPON port located on the same GPON module or a different GPON module. The configurations tested are illustrated in Figures 10 and 14.

Figure 27 presents the mean unidirectional GPON port to GPON port forwarding rate performance results for 1, 2, 3, and 4 streams from ONT709s on a GPON port located on the same GPON module and also for ONT709s on a GPON port located on a different GPON module. These tests were conducted for 5 trials. Ethernet frame sizes are 64, 512, 1024, and 1500 bytes. As is illustrated, there is a slight performance advantage when the destination ONT709s are on a GPON port located on the same GPON module.

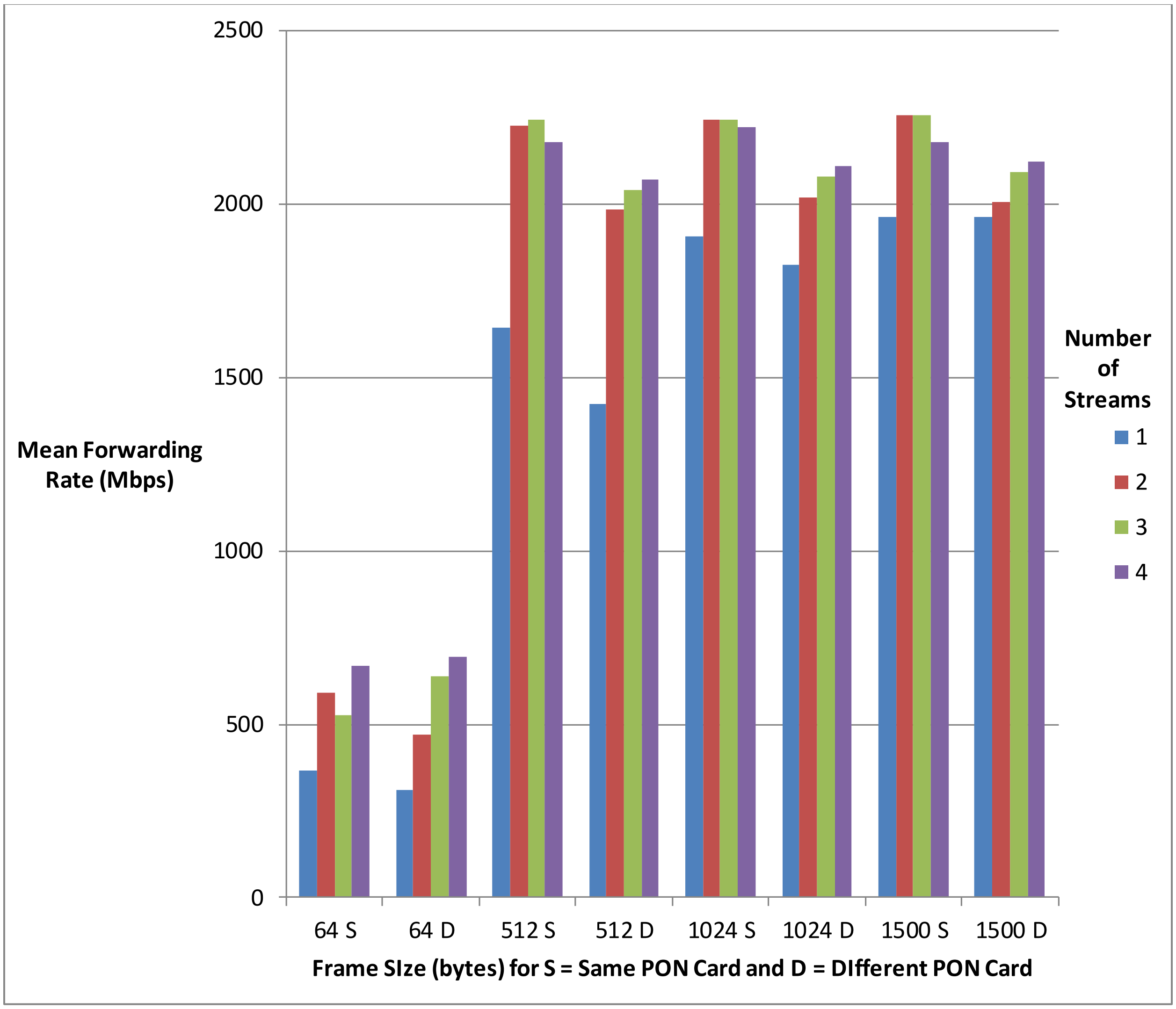
Figure 27. Mean Unidirectional GPON Port to GPON Port Forwarding Rate Performance Results



From the tests performed in Sections 3.4 and 3.5, it was also possible to combine the results and determine if the bidirectional forwarding rates for ONT709s on a GPON port were affected if the destination ONT709s were on a GPON port located on the same GPON module or a different GPON module. The configurations tested are illustrated in Figures 12 and 16.

Figure 28 presents the mean aggregate bidirectional GPON port to GPON port forwarding rate performance results for 1, 2, 3, and 4 streams from ONT709s on a GPON port located on the same GPON module and also for ONT709s on a GPON port located on a different GPON module. These tests were conducted for 5 trials. Ethernet frame sizes are 64, 512, 1024, and 1500 bytes. As is illustrated, there is a slight performance advantage when the destination ONT709s are on a GPON port located on the same GPON module.

Figure 28. Mean Aggregate Bidirectional GPON Port to GPON Port Forwarding Rate Performance Results



3.9 Spirent TestCenter Performance Testing Summary

Based on the results presented in this section, the following conclusions can be reached:

- A Tellabs 1150 MSAP GPON port can support upstream forwarding rates of over 1100 Mbps.
- A Tellabs 1150 MSAP GPON port can support downstream forwarding rates of over 2200 Mbps.
- A Tellabs 1150 MSAP GPON port can support aggregate bidirectional forwarding rates of over 2200 Mbps using RFC 2544 testing.
- A Tellabs 1150 MSAP GPON port can support aggregate bidirectional forwarding rates of over 3000 Mbps using manual Spirent TestCenter testing.
- A single Tellabs ONT709 can support upstream forwarding rates of nearly 1000 Mbps.
- A single Tellabs ONT709 can support downstream forwarding rates of nearly 1000 Mbps.
- A single Tellabs ONT709 can support aggregate bidirectional forwarding rates of nearly 2000 Mbps.
- Enabling downstream encryption does not affect performance for a Tellabs ONT709.
- Enabling FEC on a Tellabs 1150 GPON port does not affect performance in a laboratory environment.
- There is a slight performance advantage when ONT709s are sending/receiving data from a GPON port on the same GPON module as compared to ONT709s sending/receiving data from a GPON port located on a different GPON module.

4. VOIP TESTING

4.1 VoIP at Sandia National Laboratories

Sandia National Laboratories is in the process of piloting VoIP. Although there is a small deployment at an offsite location, the larger deployment will be using GPON with the Tellabs 1150 MSAP. For that reason, VoIP over GPON needed to be thoroughly tested.

4.2 VoIP Test Configuration

The test configuration for testing VoIP on the Tellabs 1150 MSAP is shown in Figure 29. The VoIP telephones are connected to ONT709s. When the telephone boots up, it first authenticates to the RADIUS server using 802.1X. If the VoIP telephone is authenticated, the DHCP server sends the VoIP telephone its IP address information. When the user picks up the handset and dials, the VoIP telephone signals the Communication Manager, and the call gets set up. At that point, voice packets are sent from VoIP telephone to VoIP telephone. The signal channel connections from the Communication Manager to the VoIP telephones are maintained throughout the call to exchange feature and signal requests during the call. The actual hardware and software used is listed in Table 3.

Table 3. VoIP Hardware and Software

Hardware and Software	Model or Version
Communication Manager	
Media Server Hardware	2x Avaya S8730
Media Gateway Hardware	3x Avaya G650
Software	Avaya Version 5.2.1
VoIP Telephone	2x Avaya 9620L
VoIP Signaling Protocol	H.323 Software Version 3.1 with Patch 3.941a
Voice CODEC	G.711 mu-law
DHCP Server	
Hardware	Call Express clone box CPU - Intel Xeon @ 3.2 GHz 2 GB of RAM
Operating System	Windows Server 2003 SP2
DHCP Software	Microsoft DHCP Version 5.2.3790.3959
RADIUS Server	
Hardware	Dell PowerEdge 2950 CPU - Intel Xeon E5420 @ 2.5 GHz 4 GB RAM
Operating System	Redhat Linux 5.8
RADIUS Software	FreeRADIUS Version 2.1.12
Prognosis Server	
Hardware	Dell PowerEdge 1950 CPU - Intel Xeon 5160 @ 3.0 GHz 4 GB of RAM
Operating System	Windows Server 2003 SP2
VoIP Monitoring Software	Prognosis IP Telephony Manager Version 9.6.1

4.3 Quality of Service for VoIP

Quality of Service (QoS) is very important for VoIP. This is because voice traffic is more sensitive to latency (network delay) and jitter (variation in latency) than web traffic and email. Excessive latency and jitter will cause a poor or unintelligible voice telephone call. The International Telecommunication Union Telecommunication Standardization Sector (ITU-T) G.114 Recommendation is to have a maximum one way delay of less than 150 milliseconds [5]. There are various recommendations for jitter. Most recommend jitter to be less than 0.5 milliseconds. A third area of concern is packet loss. The more voice packets which are lost, the lower the quality of the VoIP call.

Under normal uncongested network conditions, packet loss, delay, and jitter are not an issue. The amount of bandwidth required by a single G.711 mu-law VoIP call is only 64 Kbps for the voice payload. But signaling and transport protocols will require additional bandwidth. If hundreds or thousands of calls are occurring at any one instant, more bandwidth will be required. VoIP performance is negatively impacted in times of competing traffic from heavy network congestion, packet loss, delay, and jitter. Also, if for whatever reason a VoIP telephone needed to be (re)booted, it would be affected by heavy network congestion and lack of available bandwidth. Heavy network congestion can be in the GPON section of the network or in the legacy network.

To prioritize VoIP traffic some sort of QoS scheme is needed. The Tellabs 1150 MSAP performs packet marking and prioritization for upstream frames at the ONT709. This is enabled in the Connection Profile as is illustrated in Figure 2. Untagged frames arriving at an ONT709 port can be tagged with an 802.1P Class of Service (CoS) Bit priority ranging from 0-7. Should the Type of Service byte in the IP header of the IP packet arriving at an ONT709 port be set with Differentiated Service Code Point (DSCP) bits, the Tellabs 1150 MSAP has the ability to map these DSCP bits into 802.1P CoS Bits. For downstream traffic, the Tellabs 1150 MSAP can be configured to honor and give priority to 802.1P CoS Bits. Higher 802.1P CoS Bit values get higher priority.

4.4 VoIP Test Strategy

The test strategy used for VoIP is different than the Spirent Performance Tests performed in Section 3. For those tests, the Spirent TestCenter forwarding rates of each stream was measured for a variety of tests. For VoIP testing, the Spirent TestCenter is used to generate competing network traffic. The VoIP telephones are used to call each other, and the voice quality of each call is measured with a Mean Opinion Score (MOS) value by the Prognosis IP Telephone Manager (IPTM) server. The traffic generated by the Spirent TestCenter is varied for upstream, downstream, and bidirectional flows. Then new calls are made and tested for that level of Spirent TestCenter traffic. The tests are divided into two sets. The first set tests without QoS enabled. The tests are then rerun with QoS enabled.

4.5 VoIP Testing with Competing Upstream Traffic

The first set of VoIP tests performed involved testing VoIP calls from the two VoIP telephones as shown in Figure 29. For these tests, competing traffic is generated by the Spirent TestCenter in the upstream direction as shown by the direction of the arrows. The calls are made by manually dialing each VoIP telephone from the other VoIP telephone. The call quality is measured by the Prognosis IPTM server. These calls are monitored for 5 minutes and the results are recorded. The Spirent TestCenter traffic is then increased and the test repeated. These tests are performed for 64 and 1500 byte Ethernet frame Spirent TestCenter traffic. The Ethernet frames contained IP Experimental (Protocol = 253) packets.

Figure 29. Configuration for VoIP Testing with Competing Upstream Traffic

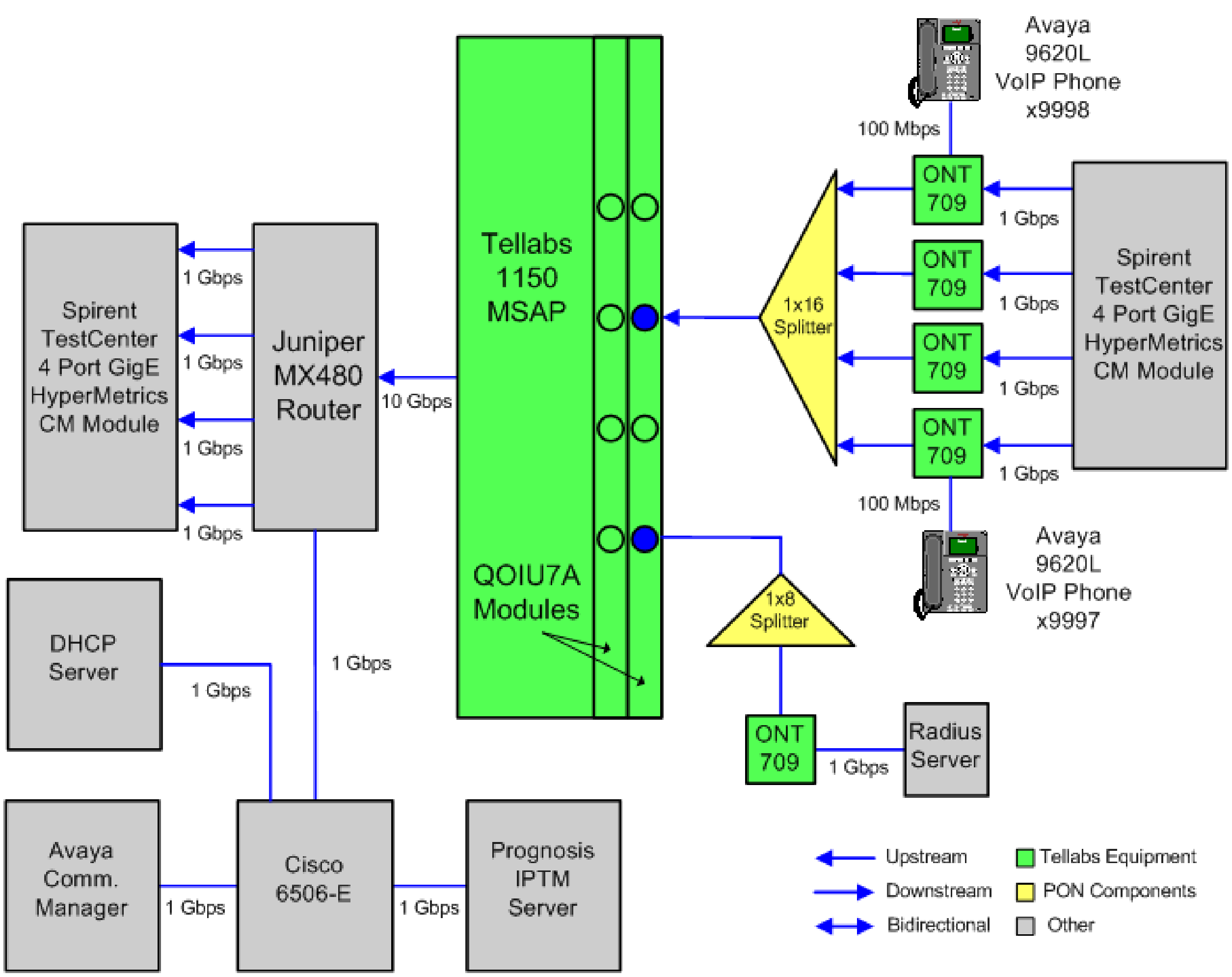


Table 4 presents the VoIP performance results with 64 byte Ethernet frame competing upstream traffic. The MOS value of 4.39 indicates a near perfect telephone call. As is shown, when the upstream is overloaded with traffic rates of 1200 Mbps or greater, MOS values decrease or the call cannot be completed if QoS is not enabled. When QoS is enabled, calls can be completed for all test loads.

Table 4. VoIP Performance Results with 64 Byte Ethernet Frame Competing Upstream Traffic

Frame Size (bytes)	Upstream Traffic Rate Aggregate (Mbps)	Downstream Traffic Rate Aggregate (Mbps)	MOS X3998 to X3997 No QoS	MOS X3998 to X3997 With QoS	MOS X3997 to X3998 No QoS	MOS X3997 to X3998 With QoS
64	1100	0	4.38	4.39	4.39	4.39
64	1200	0	3.58	4.39	3.78	4.39
64	2000	0	3.51	4.39	3.84	4.39
64	3000	0	no call	4.39	no call	4.39
64	4000	0	no call	3.67	no call	3.86

Table 5 presents the VoIP performance results with 1500 byte Ethernet frame competing upstream traffic. As is shown, when the upstream is overloaded with traffic rates of 1200 Mbps or greater, MOS values decrease or the call cannot be completed if QoS is not enabled. When QoS is enabled, calls can be completed for all test loads.

Table 5. VoIP Performance Results with 1500 Byte Ethernet Frame Competing Upstream Traffic

Frame Size (bytes)	Upstream Traffic Rate Aggregate (Mbps)	Downstream Traffic Rate Aggregate (Mbps)	MOS X3998 to X3997 No QoS	MOS X3998 to X3997 With QoS	MOS X3997 to X3998 No QoS	MOS X3997 to X3998 With QoS
1500	1100	0	4.39	4.39	4.39	4.39
1500	1200	0	3.58	4.39	3.78	4.39
1500	2000	0	2.94	4.39	2.91	4.39
1500	3000	0	2.87	4.39	2.75	4.39
1500	4000	0	no call	4.39	no call	4.39

4.6 VoIP Testing With Competing Downstream Traffic

The next set of VoIP tests performed involved testing VoIP calls from the two VoIP telephones as illustrated in Figure 30. For these tests, competing traffic is generated by the Spirent TestCenter in the downstream direction as shown by the direction of the arrows. The test procedure is the same as was described with competing upstream traffic, except that the Spirent TestCenter traffic is in the downstream direction and extra tests are performed at 2200 and 2400 Mbps to better simulate downstream congestion.

Figure 30. Configuration for VoIP Testing with Competing Downstream Traffic

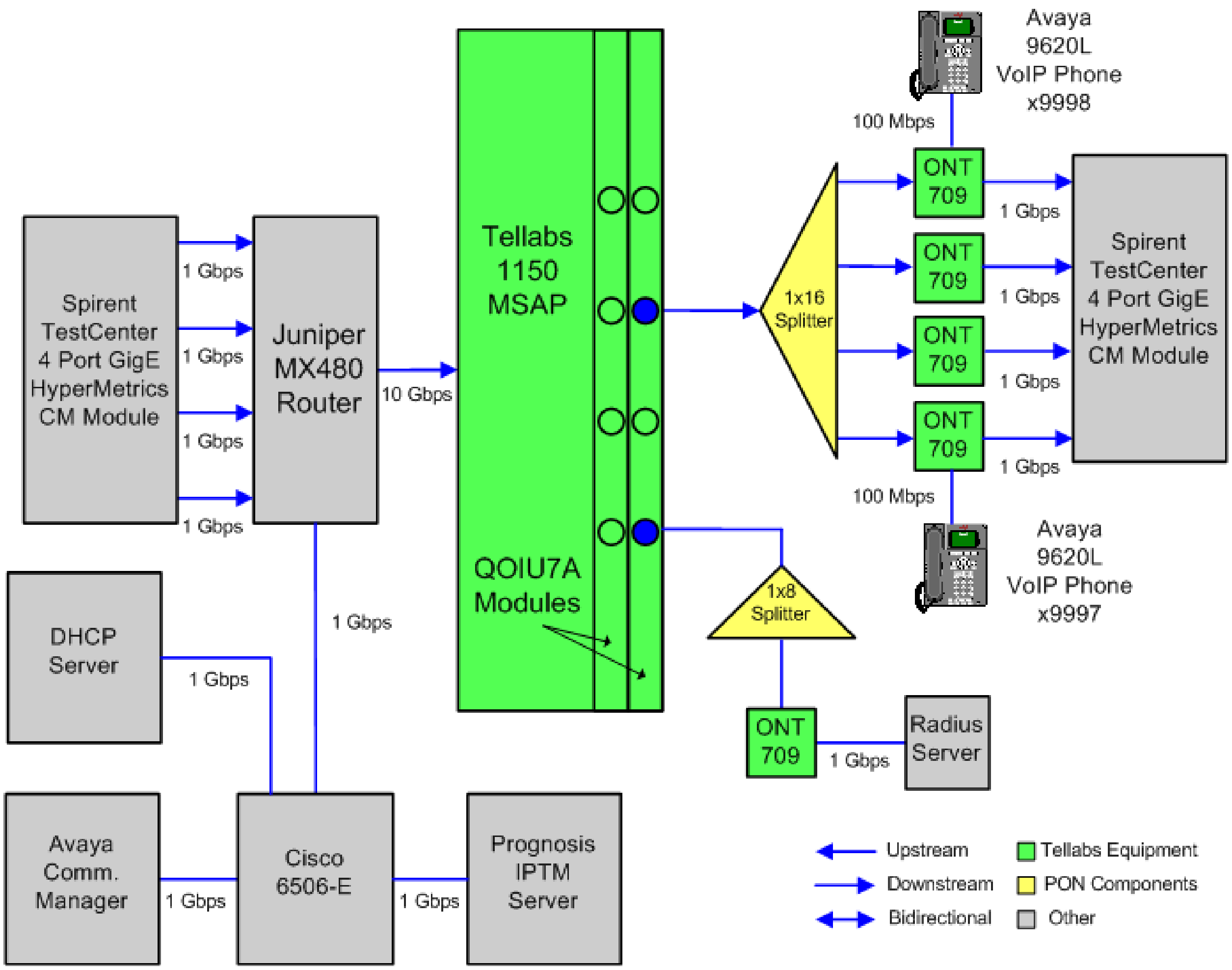


Table 6 presents the VoIP performance results with 64 byte Ethernet frame competing downstream traffic. The MOS value of 4.39 indicates a near perfect telephone call. As is shown, when the downstream is overloaded with traffic rates of greater than 2400 Mbps, the call cannot be completed if QoS is not enabled. When QoS is enabled, calls can be completed for all test loads. Note that for these tests, 4 Mbps of traffic was transmitted in the upstream direction to prevent Address Resolution Protocol (ARP) aging on the ONT709 port.

Table 6. VoIP Performance Results with 64 Byte Ethernet Frame Competing Downstream Traffic

Frame Size (bytes)	Upstream Traffic Rate Aggregate (Mbps)	Downstream Traffic Rate Aggregate (Mbps)	MOS X3998 to X3997 No QoS	MOS X3998 to X3997 With QoS	MOS X3997 to X3998 No QoS	MOS X3997 to X3998 With QoS
64	4	1000	4.39	4.39	4.39	4.39
64	4	2000	4.39	4.39	4.39	4.39
64	4	2200	4.39	4.39	4.39	4.39
64	4	2400	4.39	4.39	4.39	4.39
64	4	3000	dial tone, no call	4.39	dial tone, no call	4.39
64	4	4000	dial tone, no call	4.39	dial tone, no call	4.39

Table 7 presents the VoIP performance results with 1500 byte Ethernet frame competing downstream traffic. As is shown, when the downstream is overloaded with traffic rates of greater than 2200 Mbps, the call cannot be completed if QoS is not enabled. When QoS is enabled, calls can be completed for all test loads. Note that for these tests, 4 Mbps of traffic was transmitted in the upstream direction to prevent ARP aging on the ONT709 port.

Table 7. VoIP Performance Results with 1500 Byte Ethernet Frame Competing Downstream Traffic

Frame Size (bytes)	Upstream Traffic Rate Aggregate (Mbps)	Downstream Traffic Rate Aggregate (Mbps)	MOS X3998 to X3997 No QoS	MOS X3998 to X3997 With QoS	MOS X3997 to X3998 No QoS	MOS X3997 to X3998 With QoS
1500	4	1000	4.39	4.39	4.39	4.39
1500	4	2000	4.39	4.39	4.39	4.39
1500	4	2200	4.39	4.39	4.39	4.39
1500	4	2400	no dial tone	4.39	no dial tone	4.39
1500	4	3000	no dial tone	4.39	no dial tone	4.39
1500	4	4000	no dial tone	4.39	no dial tone	4.39

4.7 VoIP Testing with Competing Bidirectional Traffic

The final set of VoIP tests performed involved testing VoIP calls from the two VoIP telephones as illustrated in Figure 31. For these tests, competing bidirectional traffic is generated by the Spirent TestCenter as shown by the direction of the arrows. The test procedure is the same as was described with competing upstream traffic, except that the Spirent TestCenter traffic is bidirectional and some extra tests with different values of competing traffic are performed to better simulate bidirectional congestion.

Figure 31. Configuration for VoIP Testing with Competing Bidirectional Traffic

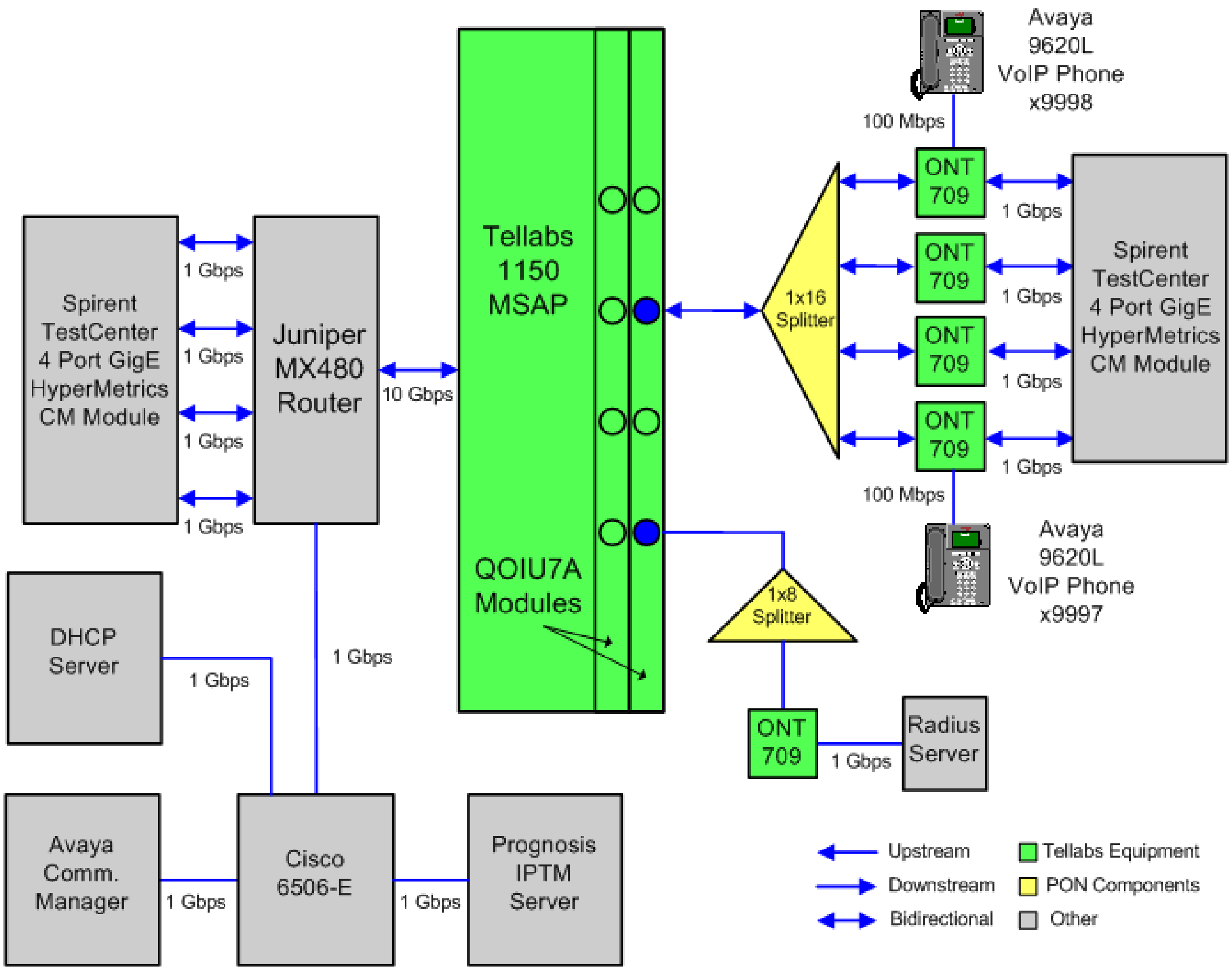


Table 8 presents the VoIP performance results with 64 byte Ethernet frame competing bidirectional traffic. The MOS value of 4.39 indicates a near perfect telephone call. As is shown, when both the upstream and the downstream have competing traffic rates of 2000 Mbps or greater, MOS values decrease or the call cannot be completed if QoS is not enabled. When QoS is enabled, calls can be completed for all test loads.

Table 8. VoIP Performance Results with 64 Byte Ethernet Frame Competing Bidirectional Traffic

Frame Size (bytes)	Upstream Traffic Rate Aggregate (Mbps)	Downstream Traffic Rate Aggregate (Mbps)	MOS X3998 to X3997 No QoS	MOS X3998 to X3997 With QoS	MOS X3997 to X3998 No QoS	MOS X3997 to X3998 With QoS
64	1100	1000	4.39	4.39	4.39	4.39
64	1200	1200	4.39	4.39	4.39	4.39
64	1200	2200	4.39	4.39	4.39	4.39
64	1200	2300	4.39	4.39	4.39	4.39
64	2000	2000	2.59	4.39	2.59	4.39
64	2200	2200	dial tone, calls, rings, cannot connect	4.39	dial tone, calls, rings, cannot connect	4.39
64	2400	2400	dial tone, no call	3.99	dial tone, no call	3.98
64	3000	3000	no dial tone	4.39	no dial tone	4.39
64	4000	4000	no dial tone	4.39	no dial tone	4.39

Table 9 presents the VoIP performance results with 1500 byte Ethernet frame competing bidirectional traffic. As is shown, when both the upstream and the downstream have competing traffic rates of 1200 Mbps or greater, MOS values will decrease or the call cannot be completed if QoS is not enabled. When QoS is enabled, calls can be completed for all test loads.

Table 9. VoIP Performance Results with 1500 Byte Ethernet Frame Competing Bidirectional Traffic

Frame Size (bytes)	Upstream Traffic Rate Aggregate (Mbps)	Downstream Traffic Rate Aggregate (Mbps)	MOS X3998 to X3997 No QoS	MOS X3998 to X3997 With QoS	MOS X3997 to X3998 No QoS	MOS X3997 to X3998 With QoS
1500	1100	1000	4.39	4.39	4.39	4.39
1500	1200	1200	3.90	4.39	3.73	4.39
1500	1200	2200	3.75	4.39	3.74	4.39
1500	1200	2300	dial tone, no call	4.39	dial tone, no call	4.39
1500	2000	2000	3.02	4.39	2.91	4.39
1500	2200	2200	2.83	4.39	3	4.39
1500	2400	2400	no dial tone	4.39	no dial tone	4.39
1500	3000	3000	no dial tone	4.39	no dial tone	4.39
1500	4000	4000	no dial tone	4.39	no dial tone	4.39

4.8 VoIP Testing Summary

Based on the results presented in this section, the following conclusions can be reached:

- Without QoS enabled, VoIP will work well until the GPON port is overloaded in the upstream direction with competing traffic near or exceeding 1200 Mbps for 64 byte and 1500 byte Ethernet frames.
- Without QoS enabled, VoIP will work well until the GPON port is overloaded in the downstream direction with competing traffic exceeding 2400 Mbps for 64 byte Ethernet frames or 2200 Mbps for 1500 byte Ethernet frames.
- Without QoS enabled, VoIP will work well until the GPON port is overloaded with bidirectional traffic at rates exceeding 1200 Mbps for 64 byte Ethernet frames or near 1200 Mbps for 1500 byte Ethernet frames.
- When QoS is enabled, VoIP works very well at all tested competing traffic rates.

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5. STREAMING VIDEO TESTING

5.1 Streaming Video at Sandia National Laboratories

The ability to provide streaming video is an important capability of any user network. Streaming video has a variety of informational and instructional uses at Sandia National Laboratories. GPON is touted as being capable of providing "triple play" which is voice, video, and data. This section presents the results of the streaming video testing using the Tellabs 1150 MSAP.

5.2 Streaming Video Test Configuration

The test configuration for testing streaming video on the Tellabs 1150 MSAP is shown in Figure 33. The computer acting as the video server for this test is on the legacy network. The computer acting as the video client is connected to an ONT709. Using the Remote Desktop Protocol (RDP), the video client connects to the video server using the Remote Desktop Connection application. A MPEG video is played on the video server and the video is displayed on the video client. It should be noted that the video server is not on a general user LAN. Also, before applying competing traffic with the Spirent TestCenter, tests were performed under nominal conditions as to assure that there was no other competing traffic or video server usage which would skew the results. The hardware and software used for these tests are presented in Table 10.

Table 10. Streaming Video Hardware and Software

Hardware and Software	Model or Version
Video Server	
Hardware	Hewlett-Packard Z400 CPU - Intel Xeon W3530 @ 2.67 GHz 16 GB RAM
Operating System	Windows 7 Enterprise, 64 Bit
Video Player	Microsoft Windows Media Player Version 12.0.7601.17514
Video Client	
Hardware	Dell Precision M6500 CPU - Intel Core i7 X 920 @ 2.00 GHz 16 GB RAM
Operating System	Windows 7 Enterprise, 64 Bit
Video Player	Microsoft Windows Media Player Version 12.0.7600.16667

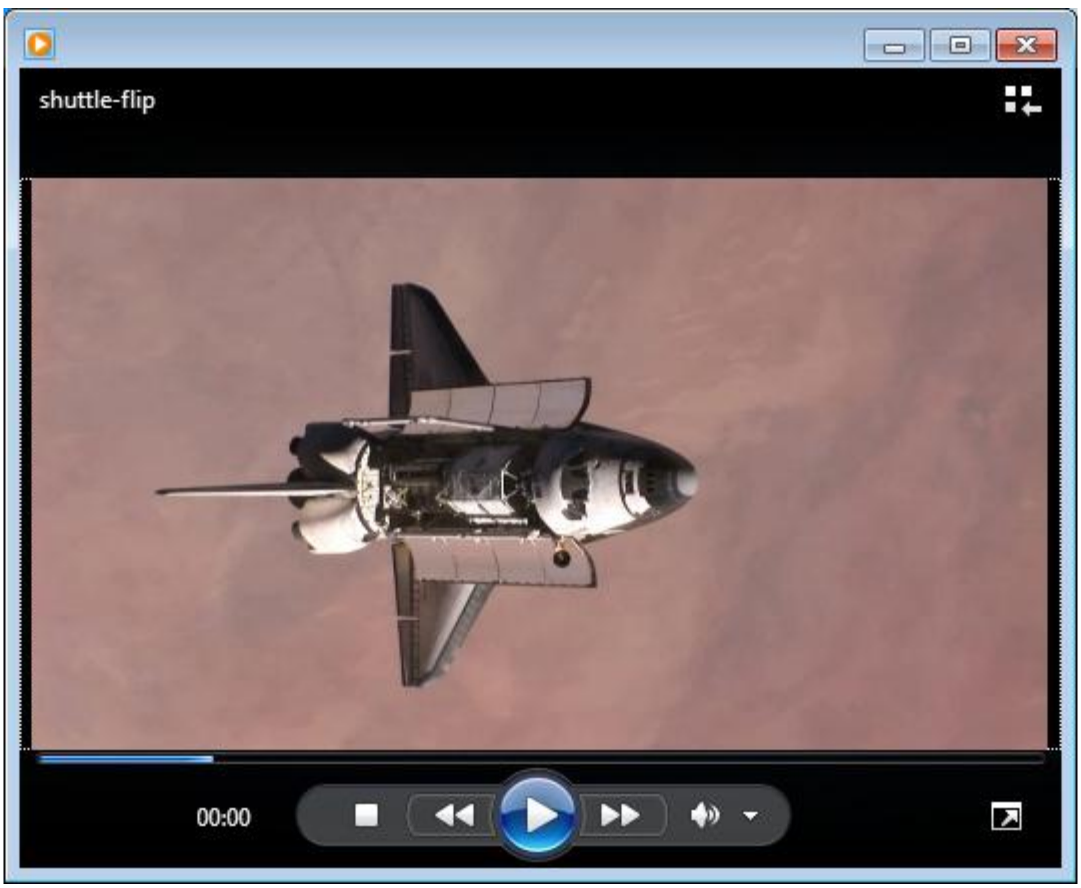
The video that was played on the video server was a NASA video clip of a space shuttle doing a flip. Table 11 presents the space shuttle flip video properties. Actual monitoring of the bandwidth utilization during playback of this video showed network usage peaking at 21 Mbps, although the total bit rate of the video is listed as 18.5 Mbps.

Table 11. Space Shuttle Flip Video Properties

Video Properties	Value
Video Format	MPEG
Length	4 seconds
Frame Width	1280 pixels
Frame Height	720 pixels
Data Rate	18.5 Mbps
Total Bit Rate	18.5 Mbps
Frame Rate	29 frames per second

For completeness, Figure 32 presents a space shuttle flip video screen capture used for streaming video testing.

Figure 32. Space Shuttle Flip Video Screen Capture Used for Streaming Video Testing



5.3 Quality of Service for Streaming Video

QoS is very important for streaming video. Lost frames, excessive delay and jitter will cause a poor quality video. Video buffering can provide some help. However, it does have its limits such as when buffer starvation occurs.

Under normal uncongested network conditions, neither packet loss, delay, or jitter is an issue. Heavy network congestion can be in the GPON section of the network or in the legacy network.

To prioritize streaming video traffic, some sort of QoS scheme is needed. The same QoS mechanism used to prioritize VoIP traffic was used to prioritize streaming video traffic. For a review of the QoS mechanism, please see Section 4.3.

5.4 Streaming Video Test Strategy

The test strategy used for streaming video is the same as for VoIP testing. For streaming video tests, the Spirent TestCenter was used to generate competing network traffic while an attempt was made to connect to the video server from the video client using the Remote Desktop Connection application. If the connection was successful, the MPEG video is played. The quality of the video displayed on the server was then empirically rated as presented in Table 12. The traffic generated by the Spirent TestCenter is varied for upstream, downstream, and bidirectional flows. Then a new connection is attempted and the streaming video quality is rated for that level of Spirent TestCenter traffic. The tests are divided into two sets. The first set tests without QoS enabled. The tests are then rerun with QoS enabled.

Table 12. Video Quality Rating Scale

Video Rating	Video Quality
0	Video does not play
1	Video starts but is not usable
2	Video plays but is of low quality
3	Video plays and is usable
4	Video plays very good but not quite perfect
5	Video plays perfectly

5.5 Streaming Video Testing with Competing Upstream Traffic

The first set of streaming video tests performed involved testing video quality between the video server and client as shown in Figure 33. For these tests, traffic is generated by the Spirent TestCenter in the upstream direction as shown by the direction of the arrows. This Spirent TestCenter traffic is used to provide competing traffic for the streaming video that was sent from the video server to the video client. The Spirent TestCenter traffic is then increased and the test repeated. These tests are performed for 64 and 1500 byte Ethernet frame Spirent TestCenter traffic. The Ethernet frames contained IP Experimental (Protocol = 253) packets.

Figure 33. Configuration for Streaming Video Testing with Competing Upstream Traffic

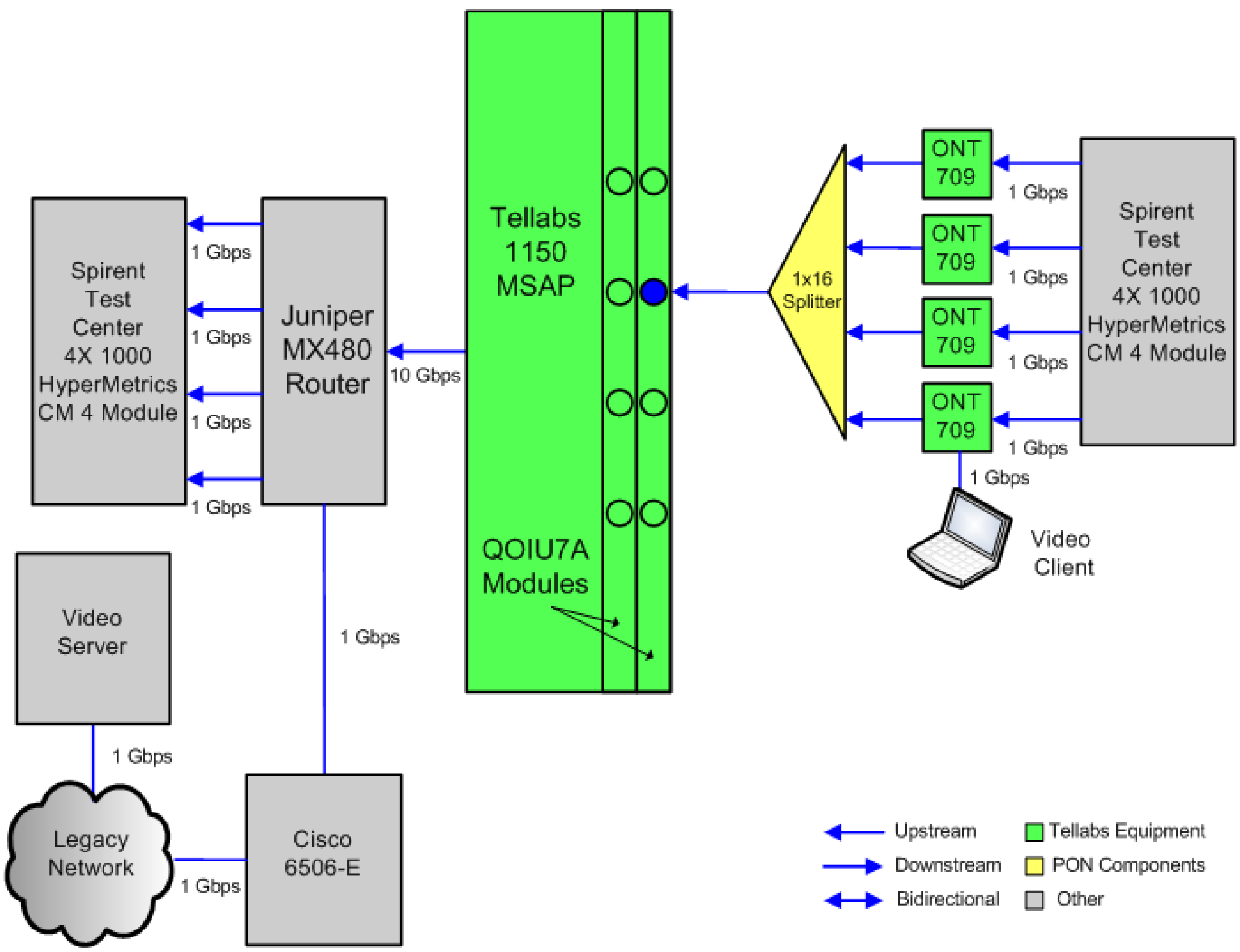


Table 13 presents the streaming video quality results with 64 byte Ethernet frame competing upstream traffic. As is presented, when the upstream is overloaded with traffic rates greater than 1200 Mbps, a Remote Desktop Connection can either not be completed or maintained if QoS is not enabled. When QoS is enabled, a Remote Desktop Connection is possible at 4000 Mbps and perfect streaming video is displayed at any value of competing upstream traffic.

Table 13. Streaming Video Quality Results with 64 Byte Ethernet Frame Competing Upstream Traffic

Frame Size (bytes)	Upstream Traffic Rate Aggregate (Mbps)	Downstream Traffic Rate Aggregate (Mbps)	Remote Desktop Connection? No QoS	Video Quality No QoS	Remote Desktop Connection? With QoS	Video Quality With QoS
64	1100	0	Yes	5	Yes	5
64	1200	0	Yes	5	Yes	5
64	2000	0	No	0	Yes	5
64	3000	0	No	0	Yes	5
64	4000	0	No	0	Yes	5

Table 14 presents the streaming video quality results with 1500 byte Ethernet frame competing upstream traffic. For competing traffic exceeding 1200 Mbps, a Remote Desktop Connection can either not be completed or maintained and therefore streaming video is not possible if QoS is not enabled. When QoS is enabled, a Remote Desktop Connection is possible and perfect streaming video was displayed for all competing test traffic.

Table 14. Streaming Video Quality Results with 1500 Byte Ethernet Frame Competing Upstream Traffic

Frame Size (bytes)	Upstream Traffic Rate Aggregate (Mbps)	Downstream Traffic Rate Aggregate (Mbps)	Remote Desktop Connection? No QoS	Video Quality No QoS	Remote Desktop Connection? With QoS	Video Quality With QoS
1500	1100	0	Yes	5	Yes	5
1500	1200	0	Yes	5	Yes	5
1500	2000	0	No	0	Yes	5
1500	3000	0	No	0	Yes	5
1500	4000	0	No	0	Yes	5

5.6 Streaming Video Testing with Competing Downstream Traffic

The next set of streaming video tests performed involved testing video quality between the video server and client as shown in Figure 34. For these tests, traffic is generated by the Spirent TestCenter in the downstream direction as shown by the direction of the arrows. The Spirent TestCenter traffic is used to provide competing traffic for the video playback that was sent using the Remote Desktop Protocol from the video server to the video client. The Spirent TestCenter traffic is then increased and the test repeated. These tests are performed for 64 and 1500 byte Ethernet frame Spirent TestCenter traffic.

Figure 34. Configuration for Streaming Video Testing with Competing Downstream Traffic

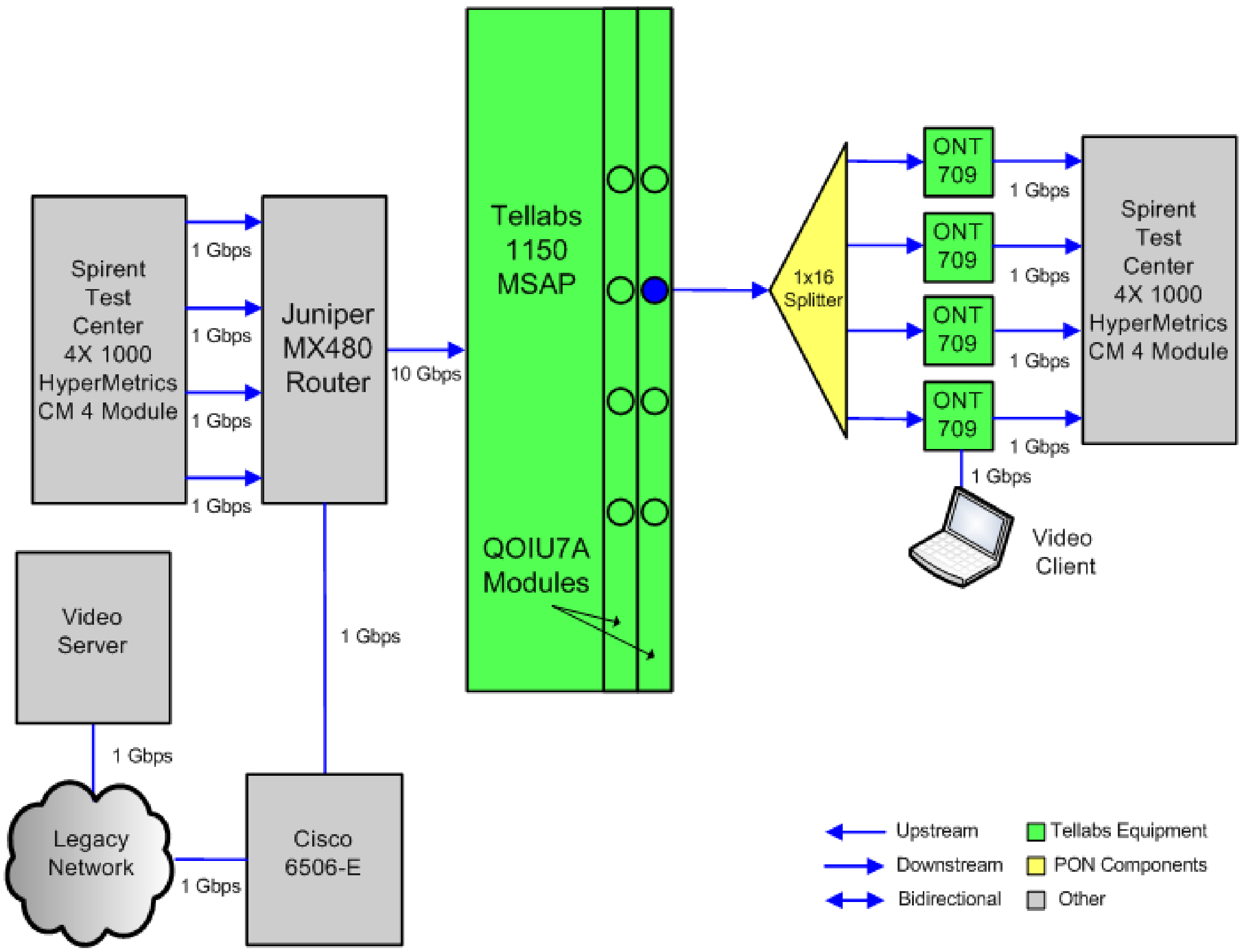


Table 15 presents the streaming video quality results with 64 byte Ethernet frame competing downstream traffic. As is presented, when the downstream is overloaded with traffic rates of greater than 2400 Mbps, a Remote Desktop Connection can either not be completed or maintained or the streaming video will not play if QoS is not enabled. When QoS is enabled, a Remote Desktop Connection is possible at 4000 Mbps and perfect streaming video is displayed at any value of competing downstream traffic. Note that for these tests, 4 Mbps of traffic was transmitted in the upstream direction to prevent ARP aging on the ONT709 port.

Table 15. Streaming Video Quality Results with 64 Byte Ethernet Frame Competing Downstream Traffic

Frame Size (bytes)	Upstream Traffic Rate Aggregate (Mbps)	Downstream Traffic Rate Aggregate (Mbps)	Remote Desktop Connection? No QoS	Video Quality No QoS	Remote Desktop Connection? With QoS	Video Quality With QoS
64	4	1000	Yes	5	Yes	5
64	4	2000	Yes	5	Yes	5
64	4	2200	Yes	5	Yes	5
64	4	2400	Yes	5	Yes	5
64	4	3000	Yes	0	Yes	5
64	4	4000	No	0	Yes	5

Table 16 presents the streaming video quality results with 1500 byte Ethernet frame competing downstream traffic. As is shown, when the downstream is overloaded with traffic rates exceeding 2200 Mbps or greater, streaming video quality values decrease or the Remote Desktop Connection cannot be completed if QoS is not enabled. When QoS is enabled, a Remote Desktop Connection is possible at 4000 Mbps and perfect streaming video is displayed at any value of competing downstream traffic. Note that for these tests, 4 Mbps of traffic was transmitted in the upstream direction to prevent ARP aging on the ONT709 port.

Table 16. Streaming Video Quality Results with 1500 Byte Ethernet Frame Competing Downstream Traffic

Frame Size (bytes)	Upstream Traffic Rate Aggregate (Mbps)	Downstream Traffic Rate Aggregate (Mbps)	Remote Desktop Connection No QoS	Video Quality No QoS	Remote Desktop Connection With QoS	Video Quality With QoS
1500	4	1000	Yes	5	Yes	5
1500	4	2000	Yes	5	Yes	5
1500	4	2200	Yes	5	Yes	5
1500	4	2400	Yes	1	Yes	5
1500	4	3000	Yes > 60 sec.	0	Yes	5
1500	4	4000	No	NA	Yes	5

5.7 Streaming Video Testing with Competing Bidirectional Traffic

The next set of streaming video tests performed involved testing video quality between the video server and client as shown in Figure 35. For these tests, bidirectional traffic is generated by the Spirent TestCenter as shown by the direction of the arrows. The Spirent TestCenter traffic is used to provide competing traffic for the streaming video that was sent using the Remote Desktop Protocol from the video server to the video client. The Spirent TestCenter traffic is then increased and the test repeated. These tests are performed for 64 and 1500 byte Ethernet frame Spirent TestCenter traffic.

Figure 35. Configuration for Streaming Video Testing with Competing Bidirectional Traffic

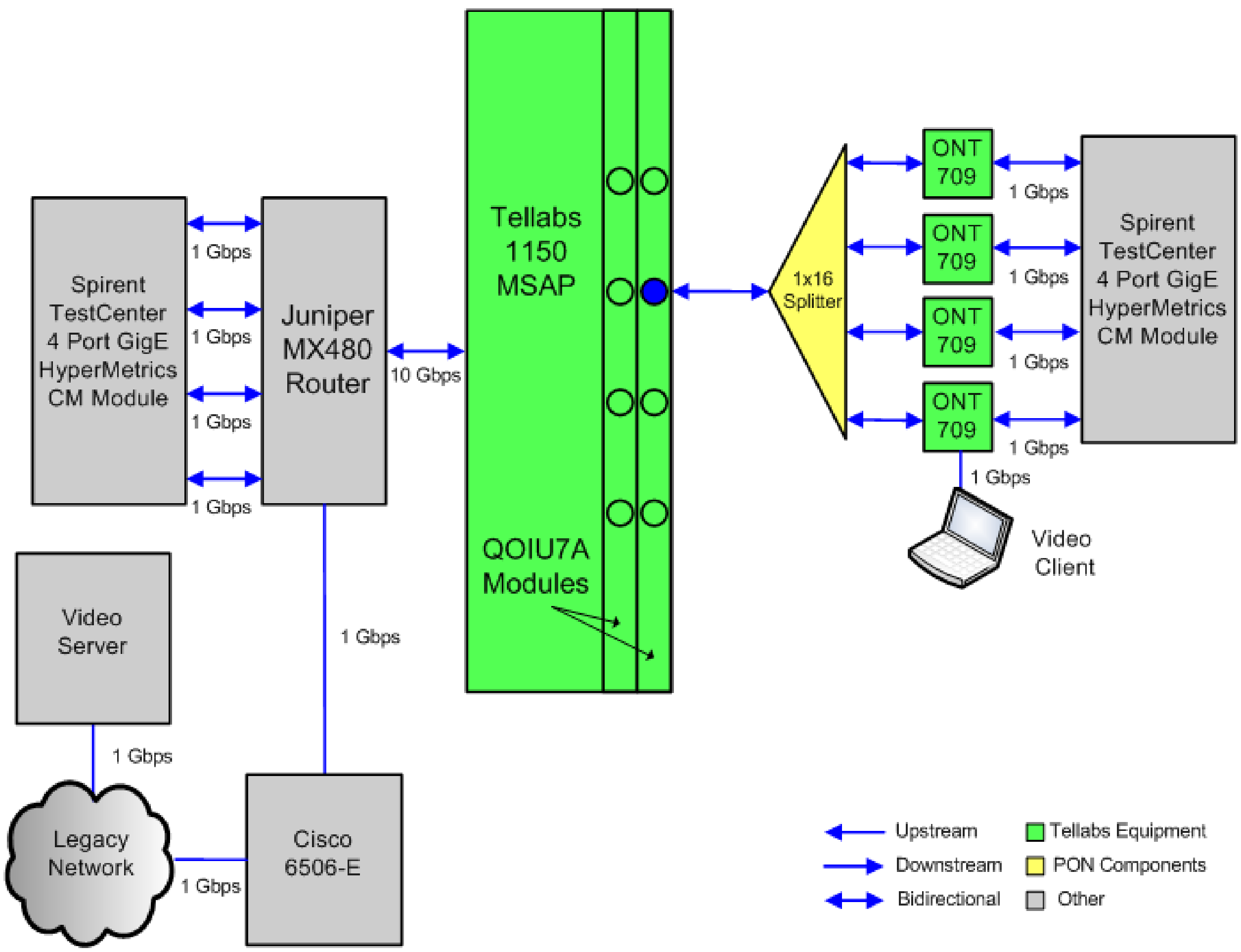


Table 17 presents the streaming video quality results with 64 byte Ethernet frame competing bidirectional traffic. As is presented, without QoS enabled, when there is competing bidirectional traffic at rates of 2000 Mbps, a Remote Desktop Connection can either not be completed and maintained or the streaming video quality will be poor. When QoS is enabled, a Remote Desktop Connection is possible at 4000 Mbps and perfect streaming video is displayed at any value of competing bidirectional traffic.

Table 17. Streaming Video Quality Results with 64 Byte Ethernet Frame Competing Bidirectional Traffic

Frame Size (bytes)	Upstream Traffic Rate Aggregate (Mbps)	Downstream Traffic Rate Aggregate (Mbps)	Remote Desktop Connection No QoS	Video Quality No QoS	Remote Desktop Connection With QoS	Video Quality With QoS
64	1100	1000	Yes	5	Yes	5
64	1200	1200	Yes	5	Yes	5
64	1200	2200	Yes	5	Yes	5
64	1200	2300	Yes	5	Yes	5
64	2000	2000	Yes	1	Yes	5
64	2200	2200	No	NA	Yes	5
64	2400	2400	No	NA	Yes	5
64	3000	3000	No	NA	Yes	5
64	4000	4000	No	NA	Yes	5

Table 18 presents the streaming video quality results with 1500 byte Ethernet frame competing bidirectional traffic. As is shown, when the upstream is overloaded with traffic rates of 2000 Mbps or greater, the Remote Desktop Connection cannot be completed when QoS is not enabled. When QoS is enabled, a Remote Desktop connection is possible at 4000 Mbps and perfect streaming video is displayed at any value of competing bidirectional traffic.

Table 18. Streaming Video Quality Results with 1500 Byte Ethernet Frame Competing Bidirectional Traffic

Frame Size (bytes)	Upstream Traffic Rate Aggregate (Mbps)	Downstream Traffic Rate Aggregate (Mbps)	Remote Desktop Connection? No QoS	Video Quality No QoS	Remote Desktop Connection? With QoS	Video Quality With QoS
1500	1100	1000	Yes	5	Yes	5
1500	1200	1200	Yes	5	Yes	5
1500	1200	2200	Yes	5	Yes	5
1500	1200	2300	Yes	5	Yes	5
1500	2000	2000	No	0	Yes	5
1500	2200	2200	No	0	Yes	5
1500	2400	2400	No	0	Yes	5
1500	3000	3000	No	0	Yes	5
1500	4000	4000	No	0	Yes	5

5.8 Streaming Video Testing Summary

Based on the results presented in this section, the following conclusions can be reached:

- Without QoS enabled, streaming video will work well until the GPON port is overloaded in the upstream direction with traffic exceeding 1200 Mbps for 64 byte and 1500 byte Ethernet frames.
- Without QoS enabled, streaming video will work well until the GPON port is overloaded in the downstream direction with traffic exceeding 2400 Mbps for 64 byte Ethernet frames or 2200 Mbps for 1500 byte Ethernet frames.
- Without QoS enabled, streaming video will work well until the GPON port is overloaded with bidirectional traffic at rates of 2000 Mbps for 64 byte and 1500 byte Ethernet frames.
- When QoS is enabled, streaming video works very well at all tested competing traffic rates.

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6. ZERO CLIENT TESTING

6.1 Zero Clients at Sandia National Laboratories

Sandia National Laboratories is also deploying Zero Clients. These Zero Clients offer the potential to reduce costs by eliminating the need for individual PCs for many users. They also allow a much more secure environment by having security patches installed to a central server which maintains the Zero Client images. Because they use the PC over IP (PCoIP) protocol, the only bandwidth needed between the server and desktop of the user is to drive the display of the user and send keyboard strokes and mouse clicks to the server. Finally, like GPON, Zero Client computing is a green technology as the Zero Client being deployed uses under 15.5 watts. Because both GPON and Zero Clients are new technologies, it was very important to test the ability of the Tellabs 1150 MSAP to support Zero Clients. This section describes the tests performed and the results.

6.2 Zero Client Test Configuration

The architecture used for the Zero Client is the VMware Virtual Desktop Infrastructure (VDI). The test configuration for testing Zero Clients on the Tellabs 1150 MSAP is shown in Figure 36. The VMware View server for this test is located on the legacy network. The rationale was to attempt to characterize the Zero Client performance on the Tellabs 1150 MSAP as accurately as was possible without having to install another VMware View server that was dedicated for testing. The Zero Client is physically connected to an ONT709. The hardware and software used for these tests are presented in Table 19.

Table 19. Zero Client Hardware and Software

Hardware and Software	Model or Version
VMware View Server	
Hardware	Dell PowerEdge 2950 CPU - Intel Xeon X5550 @ 2.99 GHz
Operating System	Windows Server 2008, 64 bit
Video Player	Microsoft Windows Media Player Version 12.0.7600.16667
Web Browser	Internet Explorer 8.0
Wyse Zero Client	
Hardware	Wyse Model D200 P20
Software	Firmware Version 3.4.1

6.3 Quality of Service for Zero Clients

The Zero Clients used for this test use the PCoIP protocol. This protocol is only used to connect between the VMware View server and the Zero Client. Actual data transfers never occur to or from the desktop of the user. Therefore, not much bandwidth is needed. For a user performing general tasks such as email with 1024x768 resolution only 3 Mbps is needed. At the other end of the scale, the extreme bandwidth user would require 200 Mbps for high quality graphics at 1920 x 1200 resolution [3].

Because the Zero Client does no local processing, it is totally dependent on the network connection. Under normal uncongested network conditions, neither packet loss, delay, or jitter is an issue. However, during heavy network congestion, the Zero Client user can be adversely affected.

The solution to this problem is to prioritize PCoIP traffic with a QoS scheme. The same QoS mechanism used to prioritize VoIP traffic and streaming video traffic can be used. For a review of the QoS mechanism, please see Section 4.3.

6.4 Zero Client Test Strategy

The test strategy used for Zero Clients is the same as for VoIP and streaming video testing. For Zero Client tests, the Spirent TestCenter is again used to generate competing network traffic while an attempt was made to connect to the VMware View server from the Zero Client. If the connection was successful and the virtual desktop of the user is displayed, the time for this connection to occur was recorded. After this, the Space Shuttle Flip MPEG video is played. The quality of the video displayed on the Zero Client was then empirically rated as presented in Table 12. Next, Internet Explorer was started and the time to display the Sandia Restricted Network (SRN) Home Page is recorded. The competing network traffic generated by the Spirent TestCenter is then varied for upstream, downstream, and bidirectional flows. Then a new Zero Client connection is attempted, and if successful, the video and web browser tests are repeated. The tests are divided into two sets. The first set of tests are run without QoS enabled. The second set of tests are then run with QoS enabled. For all tests, the Spirent TestCenter competing network traffic was IP Experimental (Protocol = 253) packets. Due to network traffic or server loading, which at any instant during the testing could influence the test results, tests were performed on a weekend.

6.5 Zero Client Baseline Testing

Before running any tests with competing network traffic, Zero Client baseline testing was performed to measure Zero Client performance on both the legacy network and Tellabs 1150 MSAP with no competing traffic. Table 20 presents the Zero Client baseline performance results. As is shown, both the legacy network and Tellabs 1150 MSAP network have similar performance. Note that the video quality is not perfect. Because these tests were conducted without competing traffic, there was no need to test with QoS enabled. Also, QoS has not been implemented in the legacy network, so it was not possible to test in that mode. Therefore, QoS columns have Not Applicable (NA) entries.

Table 20. Zero Client Baseline Performance Results

Network	US Traffic Rate Agg. (Mbps)	DS Traffic Rate Agg. (Mbps)	Server Conn. Time No QoS (s)	Home Page Display Time No QoS (s)	Video Quality No QoS	Server Conn. Time With QoS (s)	Home Page Display Time With QoS (s)	Video Quality With QoS
Legacy	0	0	8	4	3	NA	NA	NA
Tellabs 1150 MSAP	0	0	8	4	3	NA	NA	NA

6.6 Zero Client Testing with Competing Upstream Traffic

The next set of Zero Client tests performed involved testing the performance between the VMware View server and Zero Client as shown in Figure 36. For these tests, traffic is generated by the Spirent TestCenter in the upstream direction as shown by the direction of the arrows. This Spirent TestCenter traffic is used to provide competing traffic for the Zero Client connection attempt to the VMware View server, video playback, and web browser display that was sent using the PCoIP protocol from the VMware View server to the Zero Client. The Spirent TestCenter traffic is then increased and the test repeated. These tests are performed for 64 and 1500 byte Ethernet frame Spirent TestCenter traffic. The Ethernet frames contained IP Experimental (Protocol = 253) packets.

Figure 36. Configuration for Zero Client Testing with Competing Upstream Traffic

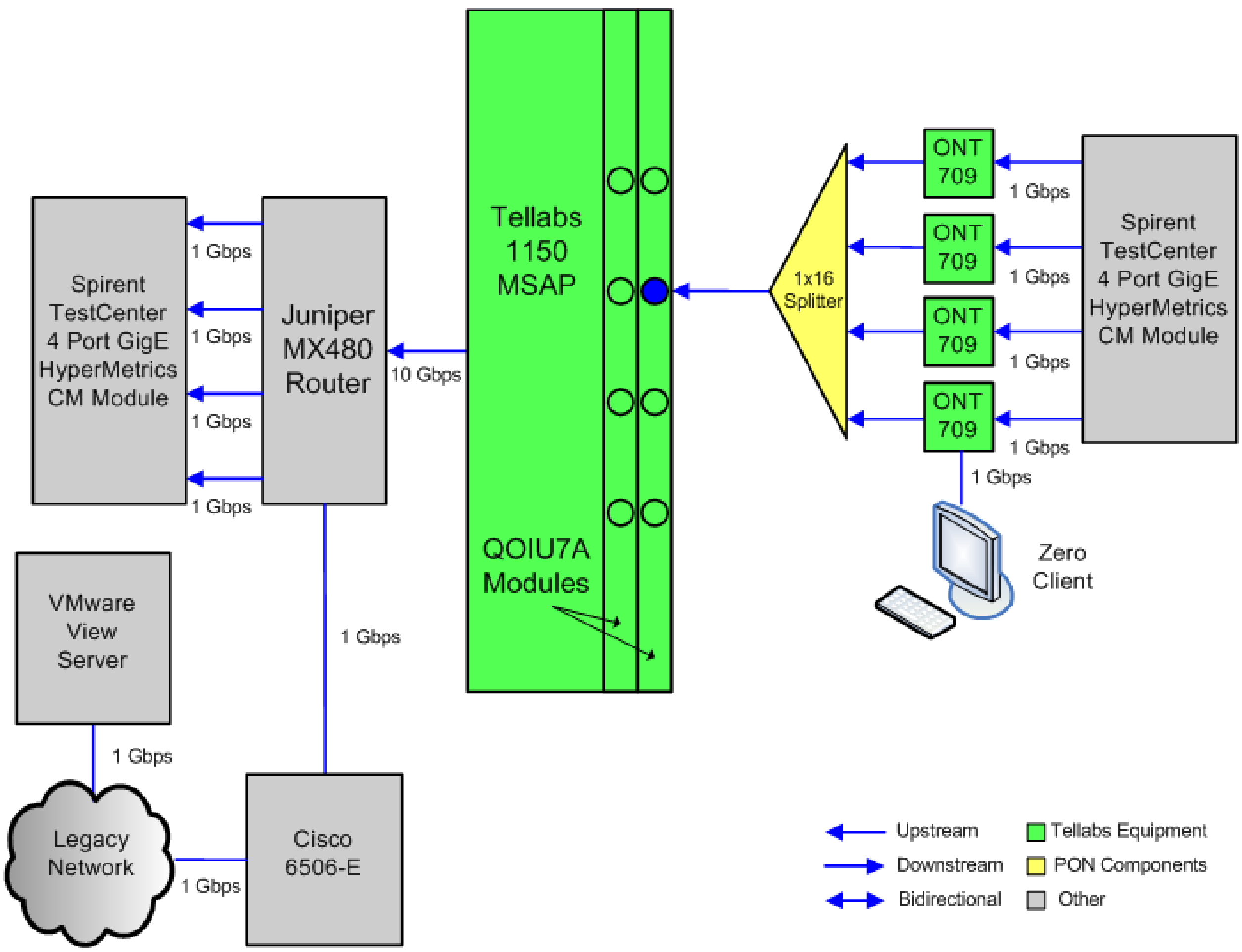

Table 21 presents the Zero Client performance results with 64 byte Ethernet frame competing upstream traffic. With competing traffic of 2000 Mbps, the Zero Client connection to the VMware View server can still be made. However, keyboard entry and mouse actions respond slowly. Video quality is also degraded. Although 2000 Mbps well exceeds the ITU-T G.984 recommendations of 1.244 Gbps in the upstream direction, enough of the upstream connection frames are protected with the Committed Information Rate of 5 Mbps, as illustrated in the connection profile in Figure 2, to permit a successful connection. When the upstream is overloaded with traffic rates of greater than 2000 Mbps, a Zero Client connection can either not be completed or maintained if QoS is not enabled. When QoS is enabled, a Zero Client connection is possible at 4000 Mbps with acceptable streaming video.

Table 21. Zero Client Performance Results with 64 Byte Ethernet Frame Competing Upstream Traffic

Frame Size (bytes)	US Traffic Rate Agg. (Mbps)	DS Traffic Rate Agg. (Mbps)	Server Conn. Time No QoS (s)	Home Page Display Time No QoS (s)	Video Quality No QoS	Server Conn. Time With QoS (s)	Home Page Display Time With QoS (s)	Video Quality With QoS
64	1100	0	8	4	3	9	9	3
64	1200	0	9	6	3	9	10	3
64	2000	0	19	9	2	10	9	3
64	3000	0	cannot connect	NA	NA	11	9	3
64	4000	0	cannot connect	NA	NA	10	9	3

Table 22 presents the Zero Client performance results with 1500 byte Ethernet frame competing upstream traffic. The results are the same as for 64 byte Ethernet frame competing upstream traffic. With competing traffic of 2000 Mbps, the Zero Client connection to the VMware View server can still be made. However, keyboard entry and mouse actions respond slowly. Video quality is also degraded. Although 2000 Mbps well exceeds the ITU-T G.984 recommendations of 1.244 Gbps in the upstream direction, enough of the upstream connection frames are protected with the Committed Information Rate of 5 Mbps, as illustrated in the connection profile in Figure 2, to permit a successful connection. When the upstream is overloaded with traffic rates of greater than 2000 Mbps, a Zero Client connection can either not be completed or maintained if QoS is not enabled. When QoS is enabled, a Zero Client connection is possible at 4000 Mbps with slightly degraded streaming video.

Table 22. Zero Client Performance Results with 1500 Byte Ethernet Frame Competing Upstream Traffic

Frame Size (bytes)	US Traffic Rate Agg. (Mbps)	DS Traffic Rate Agg. (Mbps)	Server Conn. Time No QoS (s)	Home Page Display Time No QoS (s)	Video Quality No QoS	Server Conn. Time With QoS (s)	Home Page Display Time With QoS (s)	Video Quality With QoS
1500	1100	0	9	9	3	6	5	3
1500	1200	0	10	9	3	9	9	3
1500	2000	0	10	17	2	9	11	3
1500	3000	0	cannot connect	NA	NA	9	5	3
1500	4000	0	cannot connect	NA	NA	10	5	2

6.7 Zero Client Testing with Competing Downstream Traffic

The next set of Zero Client Tests performed involved testing the performance between the VMware View server and Zero Client as shown in Figure 37. For these tests, traffic is generated by the Spirent TestCenter in the downstream direction as shown by the direction of the arrows. This Spirent TestCenter traffic is used to provide competing traffic for the Zero Client connection attempt to the VMware View server, video playback, and web browser display that was sent using the PCoIP protocol from the VMware View server to the Zero Client. The Spirent TestCenter traffic is then increased and the test repeated. These tests are performed for 64 and 1500 byte Ethernet frame Spirent TestCenter traffic.

Figure 37. Configuration for Zero Client Testing with Competing Downstream Traffic

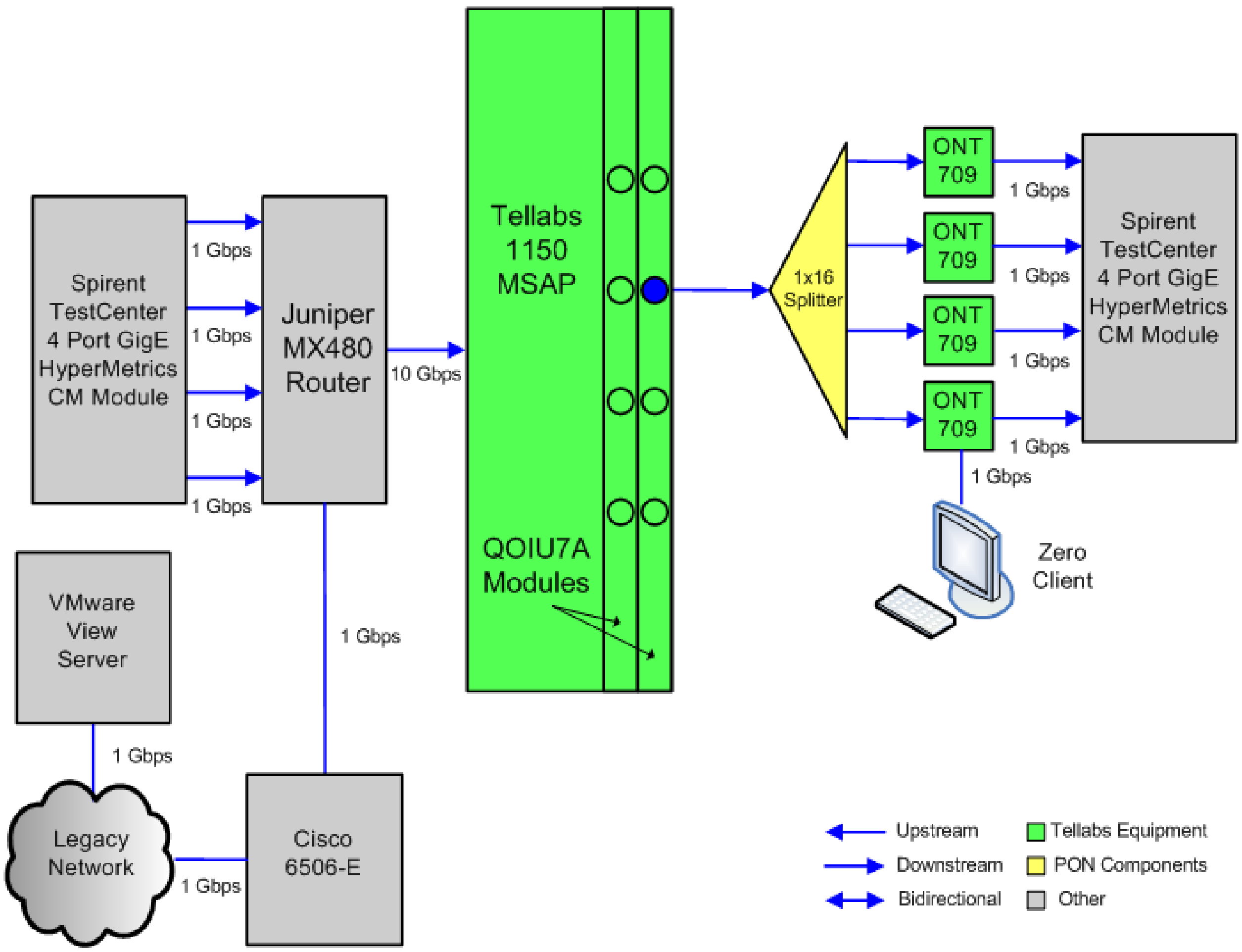

Table 23 presents the Zero Client performance results with 64 byte Ethernet frame competing downstream traffic. With competing traffic of 4000 Mbps, the Zero Client connection to the VMware View server can still be made. Although 4000 Mbps well exceeds the ITU-T G.984 recommendations of 2.488 Gbps in the downstream direction, the upstream connection packets have no competing traffic, so a connection is possible. Even with competing traffic at 4000 Mbps, enough of the PCoIP packets sent from the VMware View server to the Zero Client are protected with the Committed Information Rate of 5 Mbps to permit some Zero Client usage. However, video quality is degraded when competing traffic is greater than 2400 Mbps if QoS is not enabled. When QoS is enabled, a Zero Client connection is possible at 4000 Mbps with acceptable streaming video. Note that for these tests, 4 Mbps of traffic was transmitted in the upstream direction to prevent ARP aging on the ONT709 port.

Table 23. Zero Client Performance Results with 64 Byte Ethernet Frame Competing Downstream Traffic

Frame Size (bytes)	US Traffic Rate Agg. (Mbps)	DS Traffic Rate Agg. (Mbps)	Server Conn. Time No QoS (s)	Home Page Display Time No QoS (s)	Video Quality No QoS	Server Conn. Time With QoS (s)	Home Page Display Time With QoS (s)	Video Quality With QoS
64	4	1000	6	5	3	10	5	3
64	4	2000	10	5	3	10	6	3
64	4	2200	9	6	3	10	5	3
64	4	2400	9	4	3	9	9	2
64	4	3000	9	5	2	11	8	3
64	4	4000	11	8	2	9	9	3

Table 24 presents the Zero Client performance results with 1500 byte Ethernet frame competing downstream traffic. The results are the same as for 64 byte Ethernet frame competing downstream traffic. With competing traffic of 4000 Mbps, the Zero Client connection to the VMware View server can still be made. Although 4000 Mbps well exceeds the ITU-T G.984 recommendations of 2.488 Gbps in the downstream direction, the upstream connection packets have no competing traffic, so a connection is possible. Even with competing traffic at 4000 Mbps, enough of the PCoIP packets sent from the VMware View server to the Zero Client are protected with the Committed Information Rate of 5 Mbps to permit some Zero Client usage. However, video quality is degraded when competing traffic is greater than 2400 Mbps if QoS is not enabled. When QoS is enabled, a Zero Client connection is possible at 4000 Mbps with acceptable streaming video. Note that for these tests, 4 Mbps of traffic was transmitted in the upstream direction to prevent ARP aging on the ONT709 port.

Table 24. Zero Client Performance Results with 1500 Byte Ethernet Frame Competing Downstream Traffic

Frame Size (bytes)	US Traffic Rate Agg. (Mbps)	DS Traffic Rate Agg. (Mbps)	Server Conn. Time No QoS (s)	Home Page Display Time No QoS (s)	Video Quality No QoS	Server Conn. Time With QoS (s)	Home Page Display Time With QoS (s)	Video Quality With QoS
1500	4	1000	9	9	3	6	6	3
1500	4	2000	9	9	3	10	9	3
1500	4	2200	10	9	3	8	5	3
1500	4	2400	9	9	3	11	5	3
1500	4	3000	9	9	2	10	9	3
1500	4	4000	9	11	2	9	5	3

6.8 Zero Client Testing with Competing Bidirectional Traffic

The next set of Zero Client Tests performed involved testing the performance between the VMware View server and Zero Client as shown in Figure 38. For these tests, bidirectional traffic is generated by the Spirent TestCenter as shown by the direction of the arrows. This Spirent TestCenter traffic is used to provide competing traffic for the video playback and web browser display that was sent using the PCoIP protocol from the VMware View server to the Zero Client. The Spirent TestCenter traffic is then increased and the test repeated. These tests are performed for 64 and 1500 byte Ethernet frame Spirent TestCenter traffic.

Figure 38. Configuration for Zero Client Testing with Competing Bidirectional Traffic

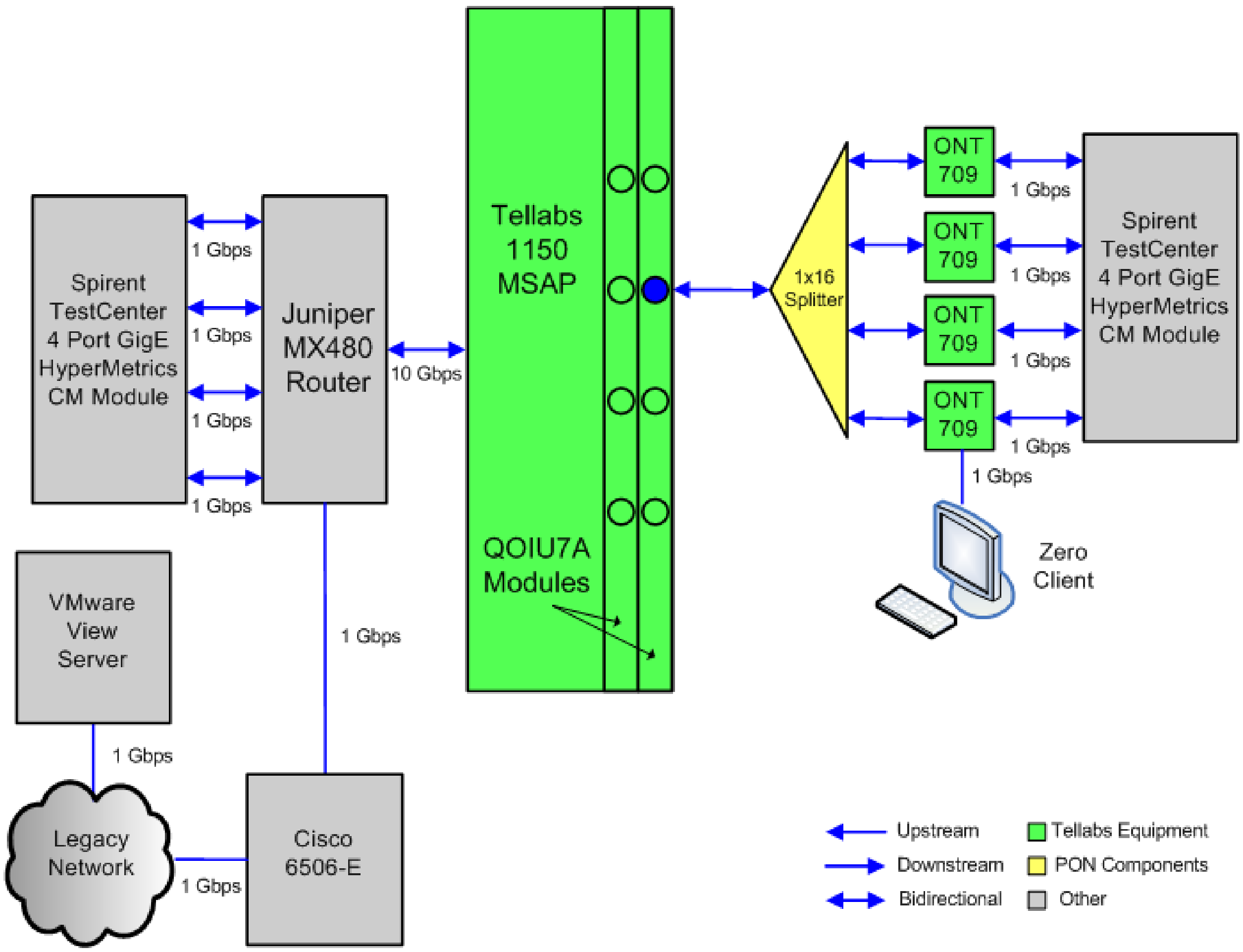

Table 25 presents the Zero Client performance results with 64 byte Ethernet frame competing bidirectional traffic. As is presented, when both the upstream and downstream are overloaded with traffic rates of 2200 Mbps or greater, video quality is degraded or a Zero Client connection can either not be completed or maintained if QoS is not enabled. When QoS is enabled, a Zero Client connection is possible at 4000 Mbps with acceptable streaming video.

Table 25. Zero Client Performance Results with 64 Byte Ethernet Frame Competing Bidirectional Traffic

Frame Size (bytes)	US Traffic Rate Agg. (Mbps)	DS Traffic Rate Agg. (Mbps)	Server Conn. Time No QoS (s)	Home Page Display Time No QoS (s)	Video Quality No QoS	Server Conn. Time With QoS (s)	Home Page Display Time With QoS (s)	Video Quality With QoS
64	1100	1000	8	4	3	10	10	3
64	1200	1200	12	4	3	6	8	3
64	1200	2200	11	4	3	9	10	3
64	1200	2300	11	8	3	10	9	3
64	2000	2000	11	4	3	11	5	3
64	2200	2200	11	8	2	10	6	2
64	2400	2400	14	8	2	13	8	2
64	3000	3000	cannot connect	NA	NA	10	8	3
64	4000	4000	cannot connect	NA	NA	10	6	3

The results for the tests with 1500 byte Ethernet frame competing bidirectional traffic are presented in Table 26. As is presented, when both the upstream and downstream are overloaded with traffic rates of 2000 Mbps or greater, video quality is degraded or a Zero Client connection can either not be completed or maintained if QoS is not enabled. When QoS is enabled, a Zero Client connection is possible at 4000 Mbps with acceptable streaming video.

Table 26. Zero Client Performance Results with 1500 Byte Ethernet Frame Competing Bidirectional Traffic

Frame Size (bytes)	US Traffic Rate Agg. (Mbps)	DS Traffic Rate Agg. (Mbps)	Server Conn. Time No QoS (s)	Home Page Display Time No QoS (s)	Video Quality No QoS	Server Conn. Time With QoS (s)	Home Page Display Time With QoS (s)	Video Quality With QoS
1500	1100	1000	9	9	3	5	5	3
1500	1200	1200	8	7	3	10	9	3
1500	1200	2200	9	9	3	10	5	3
1500	1200	2300	9	7	3	9	5	3
1500	2000	2000	16	9	2	10	9	3
1500	2200	2200	14	7	2	11	9	3
1500	2400	2400	cannot connect	NA	NA	10	6	3
1500	3000	3000	cannot connect	NA	NA	10	8	3
1500	4000	4000	cannot connect	NA	NA	10	9	3

6.9 Zero Client Testing Summary

Based on the results presented in this section, the following conclusions can be reached:

- Under normal conditions without competing traffic causing GPON port overload, Zero Clients work well and display acceptable video.
- Without QoS enabled, Zero Clients work well until the GPON port is overloaded in the upstream direction with traffic at rates greater than 1200 Mbps for 64 byte and 1500 byte Ethernet frames.
- Without QoS enabled, Zero Clients work well until the GPON port is overloaded in the downstream direction with traffic at rates greater than 2400 Mbps for 64 byte and 1500 byte Ethernet frames.
- Without QoS enabled, Zero Clients will work well until the GPON port is overloaded with bidirectional traffic at rates of 2200 Mbps for 64 byte Ethernet frames and 2000 Mbps for 1500 byte Ethernet frames.

- When QoS is enabled, Zero Clients work well at all tested competing traffic rates on the Tellabs 1150 MSAP.

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7. SECURITY TESTING

7.1 Security Testing Introduction

An important aspect of any network device or system is security. Testing the security for the Tellabs 1150 MSAP consisted of tests of the Tellabs implementation of GPON. The Panorama INM was also analyzed and tested for vulnerabilities with administrative management. Vulnerabilities to GPON systems in general are beyond the scope of this document and are not covered.

7.2 Tellabs 1150 MSAP GPON Implementation

The Tellabs 1150 MSAP in combination with the Panorama INM offers several features which enhance network security. These features include the following:

- No Network Eavesdropping
- Security in the Case of Improper ONT709 Relocation
- Host Authentication with 802.1X
- Access Control Lists
- Equipment Inventory

7.2.1 No Network Eavesdropping

All network topologies must address the potential for network neighbors. Network neighbors are systems with potential access to the physical transport layer shared with other systems. With Ethernet, for example, this is mitigated by switched topology. Wi-Fi utilizes encryption and access keys. In the case of GPON, downstream traffic is broadcast yet protected by AES-128 encryption and addressed to specific ONTs. Upstream traffic is sent unencrypted.

For a user to capture and decode another user's traffic, either upstream or downstream, it would be necessary to capture upstream traffic or at least the upstream key exchange sent by another ONT709 on the same GPON port or splitter. There are several difficulties which make this technically difficult and currently beyond the reach of most users. GPON uses a wavelength of 1310 nanometers for upstream traffic and a wavelength of 1490 nanometers for downstream traffic. A specially modified ONT709 or other device capable of capturing and decoding GPON would be needed to listen to the upstream transmission wavelength at 1310 nanometers. Also, the splitter would need to have a high reflection index. An ONT709 cannot be configured to listen at the upstream wavelength of 1310 nanometers. Therefore, any network eavesdropping by a user on the same GPON port or splitter would require special hardware and software.

The Tellabs 1150 MSAP does permit an administrator to disable downstream encryption to an ONT709 port. This is accomplished in the Connection Profile as shown in Figure 2. Thus, a user would need administrator privileges to perform this. This user would also need to capture and decode the GEM frames which are intended for another ONT709.

The connection from the Tellabs 1150 MSAP to the network uses an 802.1Q trunk. Therefore, this link is no different than any other 802.1Q trunk and must be protected as such. However, only Ethernet frames in VLANs which are provisioned on the Tellabs 1150 MSAP will be able to be sent or received by the Tellabs 1150 MSAP.

7.2.2 Security in the Case of Improper ONT Relocation

In examining the GPON architecture, a series of related questions arose regarding the ONT709s. The ONT709s are the only part of the GPON infrastructure which are located in the office space of an individual and thus potentially outside of the physical control of administrative processes. More specifically, the question became that of "What happens during a rogue ONT709 move?" If a user carries an ONT709 to a different location (or network drop) which is configured for a different VLAN or subnet, what happens then? Will the ONT709 come online, and if so, with what functionality and on what VLAN or subnet?

The Tellabs 1150 MSAP in combination with the Panorama INM handles this situation in a secure fashion. When a new ONT709 is added to a splitter which is connected to a particular GPON port on a Tellabs 1150 MSAP GPON module, it will not provide any user network connectivity until the serial number of the unit is entered. Also, each port on the ONT709 that is going to be active must also be placed in a VLAN that is provisioned on the Tellabs 1150 MSAP. The port must also be assigned a traffic profile. Until that occurs, the ONT709 port(s) will not provide any service. Should the ONT709 be moved to another GPON port, it will no longer be provisioned and the previous steps will need to be repeated. Also, the Panorama INM will report that there is an Unexpected ONT on that GPON port and will display the serial number of the ONT709.

Should the ONT709 be moved to another connection on the same GPON port and splitter, it will not be listed as an Unexpected ONT. This is because the ONT709s are on a Passive Optical Network and there is no fixed address for a particular physical cable. This is not a real serious problem, as GPON ports and splitters service a limited geographic area; thus a rogue ONT709 move will not be able to move very far before service is lost and the Panorama INM reports an Unexpected ONT.

Testing these scenarios was performed by adding a new ONT709 to a GPON port. The Panorama INM reported the ONT709 to be an Unexpected ONT.

7.2.3 Host Authentication with 802.1X

If desired, end user devices such as PCs and VoIP telephones can be authenticated using 802.1X. If 802.1X authentication is desired, it is enabled on a per ONT709 port basis. The Panorama INM allows up to four Radius servers to be configured per Tellabs 1150 MSAP. The four Radius servers are for redundancy, but a specific Radius server cannot be chosen to authenticate a specific ONT709 port. Host authentication was tested and verified in the laboratory for both PCs and VoIP telephones.

7.2.4 Access Control Lists

Another security enhancing feature is the ability to apply an access control list (ACL) to an ONT709 port. Up to 16 MAC addresses can be permitted or denied depending upon how the ACL is configured. ACLs are useful when it is necessary to restrict access to a particular ONT709 port for whatever reason. An ACL may also be applied to a port to permit any MAC address. Unless an ONT709 port has an ACL applied to it, the Panorama INM will not report the MAC address of the machine that is connected to it. Having the Panorama INM report the MAC address is a very useful tool for troubleshooting.

If a switch or hub is connected to an ONT709 port, up to 16 MAC addresses are permitted. This means that if a 24 port switch is connected, only 16 network connections can be active. Thus, if User 17 attempts to connect when 16 connections are active, User 17 will not be able to connect until one of the existing 16 active MAC addresses ages out.

ACLs have been tested and verified to work in laboratory tests.

7.2.5 Equipment Inventory

The Panorama INM has an Equipment Inventory utility which lists all the equipment for a Tellabs 1150 MSAP. This provides a means to check physical inventory for missing or inoperative components. By performing inventory checks on a periodic basis, actual equipment deployed can be verified with what equipment is believed to be deployed.

7.3 Tellabs 1150 MSAP Management

Management of the Tellabs 1150 MSAP consists of two main methods:

- GPON Management
- Administrative Network Management

7.3.1 GPON Management

Tellabs 1550 MSAP to ONT709 management is accomplished by the Physical Layer Operations, Administration, and Maintenance (PLOAM) field in the upstream and downstream GEM frames as specified in the ITU-T G.984 recommendations. Although it uses the same fiber and frames, it is considered an administrative channel and therefore can be considered out-of-band. These PLOAM messages are not directly configurable by the administrator and are necessary for all GPON platforms.

7.3.2 Administrative Network Management

The Tellabs 1150 MSAP can be managed using the Panorama INM. All operations except the basic startup of the Tellabs 1150 MSAP can be performed via the Panorama INM. It is also possible to perform many operations when directly connected to the Tellabs 1150 MSAP via the command line interface (CLI). Any person, such as an administrator who has access to these management applications, can provision or change any ONT709 to have different parameters such as the VLAN or its QoS settings. However, this is no different than current network gear.

7.3.2.1 Management via the Panorama INM

Almost all of the configuration and management operations for the Tellabs 1150 MSAP can be performed by the Panorama INM application. This software consists of a server and one or more clients. The Panorama INM server runs on a Sun Solaris platform. Therefore, all authentication features that are supported by Solaris are available for the Panorama INM administrator. In addition, the Panorama server application is password protected and supports multiple logins. Each Panorama INM user can be assigned different levels of privileges.

The remote client sends an encrypted username and password to the server for authentication. This has been verified in laboratory tests.

7.3.2.2 Management via the Tellabs 1150 MSAP CLI

It is also possible to perform many management functions via the Tellabs 1150 MSAP CLI. The administrator who is performing these functions will only have access to the equipment on the 1150 MSAP to which he or she is currently logged on to. The 1150 MSAP is password protected and will temporarily disable the login for one minute after 5 unsuccessful login attempts.

7.4 Security Testing Summary

The Tellabs 1150 MSAP and Panorama INM have many features which enhance security. These include encryption, no network eavesdropping, 802.1X authentication, and ACLs. It also detects and prevents the operation of ONT709s that were moved or relocated without proper provisioning. Panorama INM users can be given different levels of privileges. All of these security features were verified by laboratory testing.

However, good security practices should be followed and the Panorama INM server and Tellabs 1150 MSAP CLI should be protected by placing them on a management network with restricted access.

8. END USER FIELD TESTING

8.1 The Importance of End User Field Testing

Although laboratory testing of GPON as implemented by the Tellabs 1150 MSAP is useful, the end user field testing is really the ultimate test. That is because GPON is designed to be deployed at the access layer of the network. This is where the end user gains access to the network. Because Sandia National Laboratories has deployed over 13,000 ONT709s, it was possible to test the Tellabs 1150 MSAP in a production environment as well as a laboratory environment. This section presents the field test results for many of the applications that are used every day.

8.2 Tests Performed and Results

The tests performed included a wide variety of applications used in daily tasks. These included web access, DHCP, multicast, diskless booting, email, file transfers to and from corporate storage systems, Secure Copy, corporate streaming video, streaming audio, and printing.

8.2.1 Web Access

Users accessed both corporate internal web sites and external web sites using Firefox 14.0, Microsoft Internet Explorer 8.0, and Google Chrome 21.0. All browsers worked well.

8.2.2 DHCP

This test was performed by having hosts running Windows, Linux, Solaris, and Mac OS, which were connected to ONT709s in production, send a DHCP request to a DHCP server and obtain an IP address. DHCP worked fine for all hosts.

8.2.3 Multicast

Hosts running Windows, Linux, Solaris, and Mac OS, which were connected to ONT709s in production acting as multicast subscribers, were all able to receive corporate multicast transmissions.

8.2.4 Diskless Booting

In addition to laboratory testing of Zero Clients, production testing was also performed. There were no issues in production testing. The Zero Clients worked well.

8.2.5 Email

These tests used Microsoft Outlook clients on Windows 7, Windows Vista, and Windows XP to send and receive email from the corporate email server. All clients worked well.

8.2.6 File Transfers to and from Corporate Storage Systems

This test used Windows clients to save and retrieve files from the corporate storage systems. There were some problems in performance which were traced back to the firewall that was being used on the clients. Disabling the firewall improved performance. There were also issues with users retrieving files from the Internet. These were problems which were not related to the Tellabs 1150 MSAP.

8.2.7 Secure Copy (SCP)
This test used a SCP client to connect to a Linux or Solaris server and perform file transfers from client to server. The client was connected to a production ONT709. The server was connected to the corporate network. There were no problems. All transfers performed well.

8.2.8 Corporate Streaming Video
In addition to laboratory testing of streaming video, production testing of corporate streaming video was also performed. There were no issues in production testing. Corporate streaming video worked well.

8.2.9 Streaming Audio
This test used Microsoft Windows Media Player Version 11.0 to test streaming audio from external streaming audio sites. Streaming audio was also tested with Firefox 14.0, Microsoft Internet Explorer 8.0, and Google Chrome 21.0. Streaming audio worked well.

8.2.10 Printing
Many network printers from Hewlett-Packard, Dell, Konica Minolta, and others were connected to ONT709s throughout the Sandia National Laboratories campus in Albuquerque, NM. All work well.

8.3 End User Field Testing Summary

A large number of user applications were tested using the Tellabs 1150 MSAP due to the fact that Sandia National Laboratories has deployed over 13,000 ONT709s. All of the user applications tested on the Tellabs 1150 MSAP worked well.

9. TELLABS 1150 MSAP MANAGEMENT

9.1 Tellabs 1150 MSAP Management Overview

There are two main methods of managing the Tellabs 1150 MSAP. The easiest and most complete method is to use the Panorama INM. The other method is to use the CLI on the Tellabs 1150 MSAP. Both methods have their advantages. This chapter will give an overview of both methods.

9.2 The Panorama INM

9.2.1 Panorama INM Description and Operation

The Panorama INM is a full featured network manager capable of performing all of the functions needed to manage a Tellabs 1150 MSAP once initial startup is performed. The Panorama INM is used to perform the following functions:

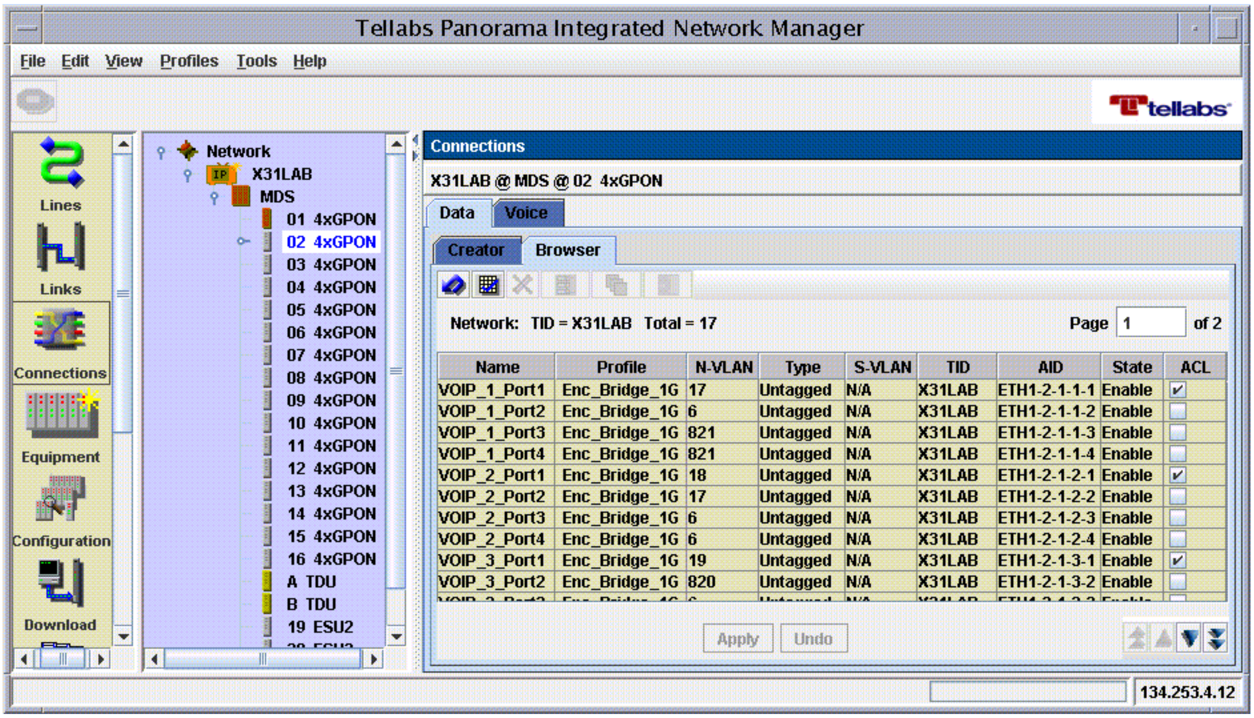
- Alarm Reporting
- OLT and ONT provisioning
- Report Generation
- Backup and Restore
- Inventory

The Panorama INM is a server running the Panorama application. An important component of the Panorama INM server application is the Oracle database. The server runs on a Sun workstation running the Solaris OS. It is also possible to run a Windows Panorama INM server. To access the Panorama INM server, a Panorama client is required. There are clients for both Windows-based systems and Solaris-based systems. Information is exchanged between the client and server using XML commands. It is possible to run both the server and a client on the same machine. This has been verified in laboratory tests.

9.2.2 Panorama INM Screenshots

In this section, screenshots for two important Panorama functions will be presented. Before a port on an ONT709 can be placed into service, it must be provisioned. Figure 39 is a screenshot of the Connections utility.

Figure 39. The Panorama INM Connections Utility



The columns have the following definitions:

Name An administrator defined name of the port. There can be multiple entries with the same name.

Profile The traffic profile used by this connection. An example is presented in Figure 2.

N-VLAN The VLAN for this port.

Type The host connected to this port will be sending and receiving untagged traffic.

S-VLAN Because type is untagged, this is not applicable. Otherwise it denotes the type of VLAN used.

TID Name of the network element or Tellabs 1150 MSAP that is being provisioned.

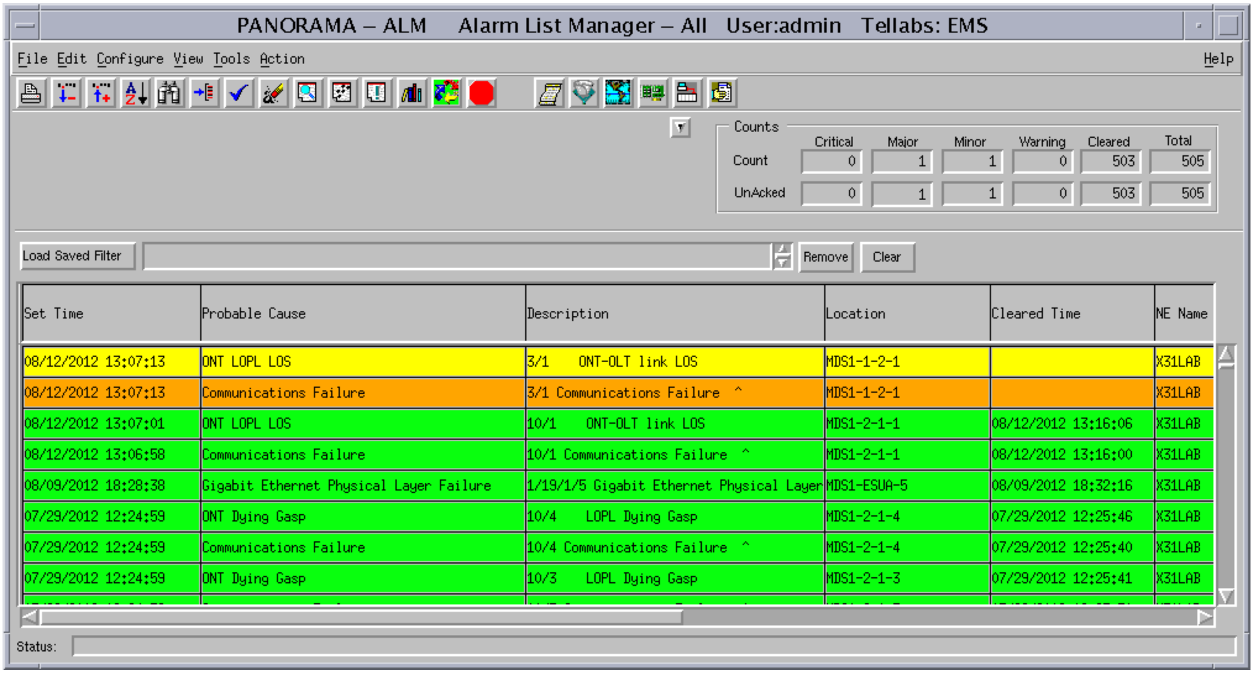
AID Port of the network element being provisioned.

State Indicates if the port is active or not.

ACL Indicates if the port has an ACL on it.

For monitoring of the Tellabs 1150 MSAP, the Alarm List Manager utility is used. A screenshot of the Alarm List Manager utility is presented in Figure 40.

Figure 40. The Panorama INM Alarm List Manager



Alarms are color coded by the Alarm List Manager. These colors are:

Red Critical. Not shown in this example.
Orange Major.
Yellow Minor.
Green Cleared.

The Alarm List Manager has the following columns. Note that these columns can be rearranged at the discretion of the user. Also, due to space limitations, not all columns are shown.

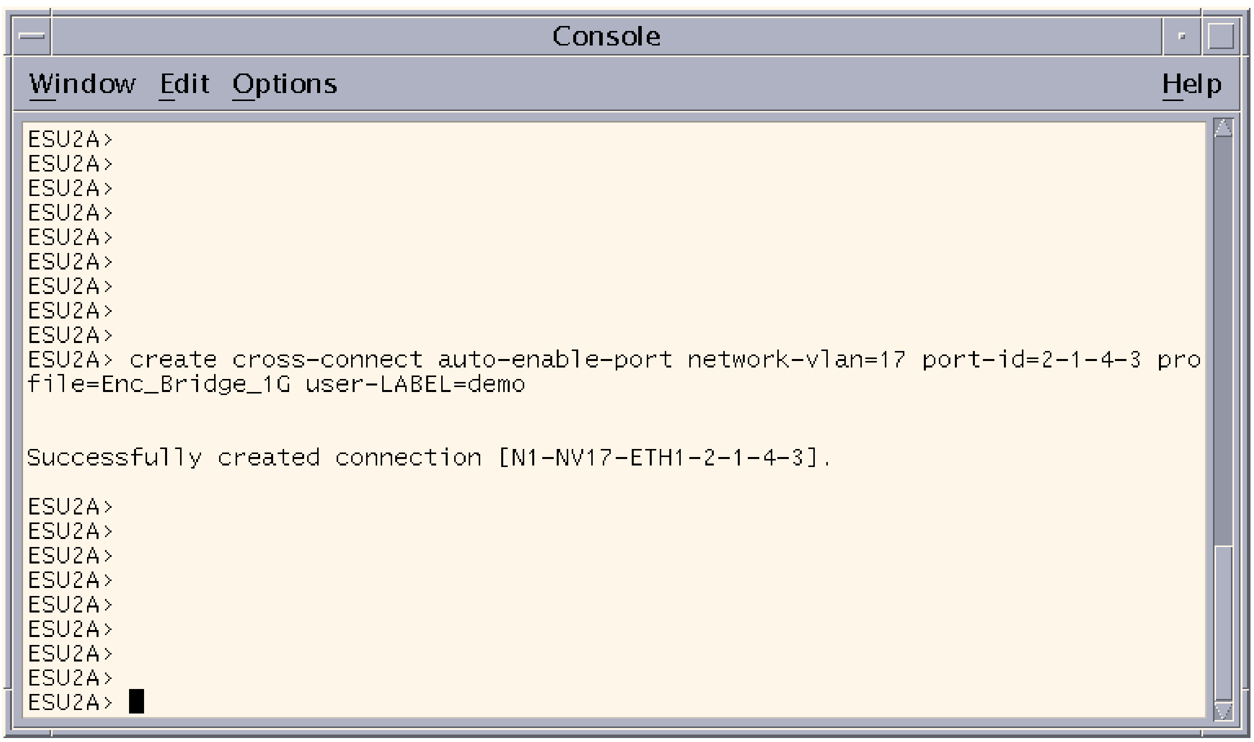
Set Time The time the alarm occurred.
Probable Cause Most likely cause of the alarm.
Description More information on the alarm, if available.
Location The module number (i.e. the slot that it is located in, port number (if the module has ports), and number of the device on the GPON port.
Cleared Time When the alarm was cleared.
NE Name The network element, i.e. the name of the Tellabs 1150 MSAP.

9.3 Command Line Interface

The CLI is also used to manage the Tellabs 1150 MSAP. This is performed by connecting to the Tellabs 1150 MSAP by using its management address using GPON or a serial port. Many functions can be performed with the CLI.

The CLI is quite useful for provisioning. A large (more than a few hundred) deployment of ONT709s would require a technician to make various selections and entries into the Panorama INM GUI for each ONT709. Although this is possible, this has the potential to be slow and error prone. Most provisioning functions, with the exception of an ACL, can be performed using the CLI. An example of provisioning a cross-connect (needed for all ONT709 ports) is presented in Figure 41.

Figure 41. CLI Provisioning Example



In this example, an ONT709 connected to a GPON module in slot 2 on GPON port 1 with an ID of 4 will have port 3 configured to use VLAN 17. It will use the ENC_Bridge_1G profile. The port will become automatically enabled when the command completes.

The advantages of the CLI are that these commands can be generated by scripts. The output of these scripts can be copied and pasted into a terminal window when connected to a Tellabs 1150 MSAP or the Panorama INM. At that point, they are executed. Sandia National Laboratories has deployed most of their 13,000 ONT709s using this method. It has saved a great deal of time and effort.

9.4 Management Testing Summary

The Tellabs 1150 MSAP has several options for management. These include the Panorama INM and the CLI. Both were tested in the laboratory and field tested and verified to work. For most daily operations the Panorama INM will be sufficient. However, for large deployments, the CLI can be quite useful.

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10. CONCLUSION

This report presents the results of extensive laboratory and field testing of the Tellabs 1150 MSAP. The tests performed included Spirent performance tests, VoIP tests, streaming video tests, Zero Client tests, security tests, management tests, and end user field tests.

The results of the testing confirm that the Tellabs 1150 MSAP performs at the ITU-T G.984 recommendations with specified performance levels of 1.244 Gbps in the upstream direction and 2.448 Gbps in the downstream direction minus protocol overhead. The Tellabs 1150 MSAP was proven to support QoS for VoIP, streaming video, and Zero Clients.

The Tellabs 1150 MSAP provides two main methods for management. These methods are the Panorama INM and the CLI. Both were tested and worked well. The CLI enabled Sandia National Laboratories to deploy over 13,000 ONT709s via scripts.

The Tellabs 1150 MSAP was also tested for security. It provides encryption in the downstream direction as defined in the ITU-T G.984 recommendations, protects the user from network eavesdropping, supports 802.1X authentication, and has access control lists. All of these features were tested and worked well.

Because of the large production deployment, the Tellabs 1150 MSAP was extensively field tested for numerous corporate applications including web access, DHCP, multicast, diskless booting, email, file transfers to and from corporate storage systems, SCP transfers between clients and servers, corporate streaming video, streaming audio, and printing. All of these applications worked well.

The Tellabs 1150 MSAP has performed well in all testing. The Tellabs 1150 MSAP will allow Sandia National Laboratories to offer the “triple play” of voice, video, and data to its users.

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APPENDIX A: UPSTREAM PERFORMANCE RESULTS

The configuration for these tests is illustrated in Figure 4. Mean latency is unidirectional and includes the latency of the Juniper MX480. Forwarding rate is the number of frames per second (fps) that were successfully sent and received by the Spirent TestCenter without any frame loss occurring.

Table 27. Upstream Performance Results for 1 Stream

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	1	234.42	337146	358075	358073	347610	337146	347610	9359	177976300
128	1	182.16	304186	327941	322002	304186	327940	317251	10885	324864883
256	1	220.50	242727	249096	255463	280939	239542	253553	14745	519277359
512	1	142.81	220095	193661	196965	215138	216790	208530	10959	854137520
1024	1	124.61	118890	118890	118891	118890	118891	118890	0	973950337
1500	1	132.02	81659	81659	81659	81659	81659	81659	0	979906464
1518	1	134.33	80703	80703	80703	80703	80703	80703	0	980059685

Table 28. Upstream Performance Results for 2 Streams

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	2	376.16	569653	402247	590588	611515	590584	552917	76490	283093642
128	2	399.61	442089	453970	465843	548987	548983	491974	47151	503781782
256	2	204.80	364441	402657	370811	326228	389918	370811	26105	759420760
512	2	222.77	271676	271674	271676	271674	271675	271675	1	1112782152
1024	2	238.94	136756	136756	136756	136756	136756	136756	0	1120303464
1500	2	274.52	93930	93930	93930	93930	93930	93930	0	1127157936
1518	2	271.94	92831	92830	92831	92831	92831	92831	0	1127336482

Table 29. Upstream Performance Results for 3 Streams

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	3	427.76	540592	540592	509210	477815	446422	502926	36607	257498249
128	3	327.40	609689	449343	574057	449348	520603	520608	64728	533102713
256	3	229.58	508448	508447	508447	508450	508448	508448	1	1041301844
512	3	267.34	273695	273693	273695	273695	273695	273695	1	1121053729
1024	3	270.71	136944	136943	136943	136943	136943	136943	0	1121838662
1500	3	309.11	94058	94058	94058	94058	94059	94058	0	1128700320
1518	3	313.16	92958	92957	92957	92957	92957	92957	0	1128874714

Table 30. Upstream Performance Results for 4 Streams

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	4	248.47	1934514	1976367	1934513	1934514	1348578	1825697	239109	934756891
128	4	252.11	1050459	1050458	1050458	1050458	1050459	1050458	0	1075669479
256	4	248.96	537814	537814	537814	537814	537814	537814	0	1101443514
512	4	258.40	272408	272408	272408	272408	272408	272408	0	1115783250
1024	4	276.61	135446	135446	135446	135446	135446	135446	0	1109572927
1500	4	310.37	93030	93030	93030	93030	93030	93030	0	1116359232
1518	4	307.66	91941	91941	91941	91941	91941	91941	0	1116533131

APPENDIX B: DOWNSTREAM PERFORMANCE RESULTS

The configuration for these tests is illustrated in Figure 6. Mean latency is unidirectional and includes the latency of the Juniper MX480. Forwarding rate is the number of frames per second (fps) that were successfully sent and received by the Spirent TestCenter without any frame loss occurring.

Table 31. Downstream Performance Results for 1 Stream

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	1	29.67	807989	1216053	1216053	1216053	807989	1052827	199910	539047615
128	1	32.96	844595	844595	844595	844595	844595	844595	0	864864840
256	1	36.69	452899	443345	452899	452899	452899	450988	3821	923623170
512	1	45.11	234962	234962	234962	234962	234962	234962	0	962405990
1024	1	60.44	119732	119732	119732	119732	119732	119732	0	980842906
1500	1	74.29	82237	82237	82237	82237	82237	82237	0	986842080
1518	1	74.86	81274	81274	81274	81274	81274	81274	0	986996071

Table 32. Downstream Performance Results for 2 Streams

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	2	31.37	2432105	2432105	2432105	2432105	2432105	2432105	0	1245237999
128	2	34.88	1689189	1689189	1689189	1689189	1689189	1689189	0	1729729552
256	2	38.65	905797	905797	905797	491820	905797	823002	165591	1685507105
512	2	47.65	469925	469925	469925	469925	469925	469925	0	1924811858
1024	2	63.81	234412	239464	239464	239464	239464	238453	2020	1953409876
1500	2	78.10	164474	164474	164474	164474	164474	164474	0	1973684160
1518	2	78.41	162549	156834	162549	162549	162549	161406	2286	1960112521

Table 33. Downstream Performance Results for 3 Streams

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	3	32.80	3710937	3710937	3710937	3710937	3710937	3710937	0	1899999835
128	3	34.38	2106208	1945867	2106208	2106208	2106208	2074139	64136	2123918780
256	3	39.44	1081649	1081649	1081649	1081649	1043436	1074006	15285	2199565087
512	3	48.87	541331	541331	541331	541331	382732	509611	63440	2087368270
1024	3	65.84	270800	270800	270800	270800	270800	270800	0	2218390716
1500	3	80.02	184262	184262	23283	184262	184262	152066	64391	1824794520
1518	3	80.81	182105	182105	182105	182105	182105	182105	0	2211488075

Table 34. Downstream Performance Results for 4 Streams

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	4	31.34	3692336	3692336	3692336	3692336	3692336	3692336	0	1890476045
128	4	33.40	2095650	2095650	2095650	2095650	2095650	2095650	0	2145945811
256	4	40.01	1085541	1085541	1085541	1085541	1085541	1085541	0	2223188255
512	4	49.44	543351	543351	543351	543351	543351	543351	0	2225563787
1024	4	64.70	270145	270145	270145	270145	270145	270145	0	2213026841
1500	4	82.60	185547	185547	185547	185547	185547	185547	0	2226562440
1518	4	83.32	183375	183375	183375	183375	183375	183375	0	2226909959

APPENDIX C: BIDIRECTIONAL PERFORMANCE RESULTS

The configuration for these tests is illustrated in Figure 8. Mean latency is bidirectional and includes the latency of the Juniper MX480. Forwarding rate is the number of frames per second (fps) that were successfully sent and received by the Spirent TestCenter without any frame loss occurring.

Table 35. Bidirectional Performance Results for 1 Stream

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	1	129.62	653361	799847	674293	757997	653360	707772	60071	362379102
128	1	125.89	620248	584617	691510	572739	667757	627374	46061	642431107
256	1	158.64	479082	466338	491820	479081	491818	481628	9534	986373272
512	1	76.85	393929	456708	426971	443491	446795	433579	22017	1775939199
1024	1	92.90	237780	237780	237780	237780	237780	237780	0	1947891630
1500	1	103.35	163317	163317	163317	163317	163317	163317	0	1959805656
1518	1	104.44	161406	161406	161406	161406	161406	161406	0	1960111477

Table 36. Bidirectional Performance Results for 2 Streams

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	2	199.80	1432279	1139300	1181171	971909	1139317	1172795	148324	600471164
128	2	189.92	1097968	1097969	836674	931690	955445	983949	101227	1007564024
256	2	129.02	576028	818044	818045	677930	805307	739071	97141	1513617420
512	2	133.46	543349	543349	543349	543348	543348	543349	0	2225555513
1024	2	151.31	273511	273511	273511	273512	273511	273511	0	2240605258
1500	2	178.09	187859	187859	187859	187859	187859	187859	0	2254309464
1518	2	177.16	185660	185661	185660	185660	185660	185660	0	2254660432

Table 37. Bidirectional Performance Results for 3 Streams

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	3	202.98	955632	1081183	1143963	955623	955631	1018406	79408	521424028
128	3	174.77	1219380	1183747	934316	1005584	934318	1055469	122610	1080800172
256	3	134.23	1016894	1016894	1016894	1016893	1016893	1016894	1	2082598822
512	3	157.74	547386	547386	547386	547386	547387	547386	0	2242094604
1024	3	167.94	273885	273885	273885	273885	273885	273885	0	2243667083
1500	3	193.31	188116	188116	188116	188116	188116	188116	0	2257390056
1518	3	194.37	185914	185914	185914	185914	185914	185914	0	2257742919

Table 38. Bidirectional Performance Results for 4 Streams

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	4	210.79	1274175	1190469	1692699	1525282	1357859	1408097	180306	720945620
128	4	274.86	1340767	1293276	1293268	1293262	1293259	1302766	19000	1334032787
256	4	144.08	1050153	1050153	1050152	1050152	1050152	1050153	0	2150712336
512	4	154.47	531600	531599	531599	531599	531600	531599	0	2177431159
1024	4	186.97	270892	270892	270892	270892	270892	270892	0	2219144790
1500	4	191.80	181434	181434	181434	181434	181434	181434	0	2177208288
1518	4	192.92	179311	179311	179311	179311	179311	179311	0	2177548776

APPENDIX D: GPON PORT TO GPON PORT USING DIFFERENT GPON MODULES PERFORMANCE RESULTS

The configuration for these tests is illustrated in Figures 10 and 12. Mean latency is unidirectional for the unidirectional tests and bidirectional for the bidirectional tests and does not include the latency of the Juniper MX480. Forwarding rate is the number of frames per second (fps) that were successfully sent and received by the Spirent TestCenter without any frame loss occurring.

Table 39. Unidirectional Performance Results for 1 Stream Using Different GPON Modules

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	1	244.04	263905	305757	295294	326683	140440	266416	66166	136404858
128	1	209.05	280432	333880	274493	256679	221046	273306	36685	279865426
256	1	226.94	223618	198143	268202	201329	249092	228077	27141	467101622
512	1	177.02	201921	182095	165575	182096	180444	182426	11560	747217355
1024	1	91.05	112156	112156	112156	112155	112155	112156	0	918778036
1500	1	160.52	81659	81656	81659	81659	81659	81658	1	979901328
1518	1	159.30	80703	80704	80703	80703	80703	80703	0	980059685

Table 40. Bidirectional Performance Results for 1 Stream Using Different GPON Modules

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	1	233.50	527808	485955	674288	674289	653363	603141	80067	308808064
128	1	196.59	560860	442089	548986	477723	477723	501476	45692	513511571
256	1	173.59	530033	453606	498184	389917	517294	477807	51014	978548097
512	1	147.55	334454	364191	344366	357581	334455	347009	12076	1421349700
1024	1	84.38	222626	222627	222626	222627	222626	222626	0	1823755698
1500	1	148.89	163317	163318	163318	163317	163317	163317	0	1959808776
1518	1	152.07	161406	161406	161406	161406	161406	161406	0	1960115654

Table 41. Unidirectional Performance Results for 2 Streams Using Different GPON Modules

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	2	309.45	402251	360398	465029	423170	485957	427361	44687	218808812
128	2	321.66	347074	418339	323321	347070	382707	363702	33257	372430977
256	2	211.11	351704	332599	358073	364442	364441	354252	11812	725507383
512	2	196.58	241939	241939	241937	241937	235330	240616	2643	985564668
1024	2	262.82	123287	123286	123286	123284	123286	123286	1	1009957011
1500	2	246.81	83522	83522	80052	83521	83522	82828	1388	993934728
1518	2	248.39	82545	82544	82545	82544	82545	82544	0	1002419315

Table 42. Bidirectional Performance Results for 2 Streams Using Different GPON Modules

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	2	254.36	930047	930047	846350	930050	971908	921680	41006	471900332
128	2	264.09	670391	789164	741654	860428	599123	732152	90892	749723560
256	2	227.56	677929	652456	690666	716144	170968	581633	206357	1191183757
512	2	190.95	483874	483874	483874	483874	483874	483874	0	1981948412
1024	2	239.42	246572	246572	246572	246572	246572	246572	0	2019916497
1500	2	237.90	167043	167043	167043	167043	167043	167043	0	2004516576
1518	2	238.95	165088	165088	165088	165088	165088	165088	0	2004829716

Table 43. Unidirectional Performance Results for 3 Streams Using Different GPON Modules

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	3	402.35	477818	697539	697537	697537	603377	634762	86532	324998021
128	3	255.04	556246	538428	467162	609688	556246	545554	45908	558647276
256	3	268.46	479789	479790	479790	479790	128225	409477	140626	838608978
512	3	235.53	248914	248914	248912	248912	248912	248913	1	1019547238
1024	3	275.19	126840	126841	126841	126841	126840	126841	0	1039079424
1500	3	297.16	87120	87119	87119	87117	87119	87119	1	1045426728
1518	3	299.27	86100	86100	86100	86100	86100	86100	0	1045599177

Table 44. Bidirectional Performance Results for 3 Streams Using Different GPON Modules

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	3	295.77	1269524	1395071	1395065	1206745	955631	1244407	161764	637136402
128	3	246.67	1219378	1041213	1041218	1041220	1005576	1069721	76091	1095394390
256	3	221.74	959574	959574	959575	959577	959575	959575	1	1965209194
512	3	230.55	497824	497824	497824	497824	497824	497824	0	2039087538
1024	3	263.85	253677	253681	253681	253680	253680	253680	2	2078145528
1500	3	286.81	174239	174238	174238	174239	174238	174239	0	2090862288
1518	3	287.72	172199	172199	172199	172199	172199	172199	0	2091187959

Table 45. Unidirectional Performance Results for 4 Streams Using Different GPON Modules

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	4	400.29	678941	720797	762646	637084	762638	712421	48808	364759568
128	4	414.10	670387	741655	622880	599127	622884	651387	50726	667019872
256	4	240.87	499605	499605	499601	499605	499603	499604	1	1023188144
512	4	254.92	252585	252584	252585	252583	252583	252584	1	1034583859
1024	4	295.51	128712	128712	128711	128712	128711	128711	0	1054404592
1500	4	330.07	88404	88404	88404	88404	88405	88404	0	1060853568
1518	4	360.51	87370	87370	87370	87370	87370	87370	0	1061018560

Table 46. Bidirectional Performance Results for 4 Streams Using Different GPON Modules

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	4	302.42	1357857	1274161	1274161	1608979	1274173	1357866	129673	695227547
128	4	316.32	1150748	1245759	1388284	1435803	1198261	1283771	109989	1314581473
256	4	238.32	999201	999201	999201	999202	999202	999202	0	2046364672
512	4	250.70	505167	505167	505166	505166	505166	505166	0	2069161394
1024	4	283.77	257422	257422	257421	257422	257422	257422	0	2108797485
1500	4	311.85	176808	176808	176808	176808	176808	176808	0	2121699024
1518	4	328.29	174739	174739	174739	174739	174737	174739	1	2122024660

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APPENDIX E: GPON PORT TO GPON PORT USING THE SAME GPON MODULE PERFORMANCE RESULTS

The configuration for these tests is illustrated in Figures 14 and 16. Mean latency is unidirectional for the unidirectional tests and bidirectional for the bidirectional tests and does not include the latency of the Juniper MX480. Forwarding rate is the number of frames per second (fps) that were successfully sent and received by the Spirent TestCenter without any frame loss occurring.

Table 47. Unidirectional Performance Results for 1 Stream Using the Same GPON Module

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	1	230.41	326683	358073	316223	305757	358075	332962	21545	170476696
128	1	219.73	292309	369512	304186	304186	322002	318439	27240	326081300
256	1	209.73	274570	274571	233173	245912	236356	252916	18171	517972554
512	1	180.18	210181	210182	193661	195312	198617	201591	7194	825715515
1024	1	99.82	115523	117206	116365	118049	118049	117038	982	958777491
1500	1	143.21	81659	81659	81659	81659	81659	81659	0	979908816
1518	1	143.05	80703	80704	80703	80703	80703	80703	0	980060049

Table 48. Bidirectional Performance Results for 1 Stream Using the Same GPON Module

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	1	228.38	695219	695218	653366	716145	799850	711960	48448	364523407
128	1	171.38	691512	655881	655879	608371	632124	648753	27702	664323414
256	1	204.23	498188	472713	491819	466340	485452	482902	11813	988983591
512	1	138.98	423667	384016	387320	390624	417059	400537	16455	1640600822
1024	1	128.77	232729	232729	232729	232729	231045	232392	674	1903755723
1500	1	174.98	163318	163317	163317	163317	163317	163317	0	1959805632
1518	1	173.84	161406	161406	161406	161406	161406	161406	0	1960112570

Table 49. Unidirectional Performance Results for 2 Streams Using the Same GPON Module

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	2	404.74	444103	527803	569650	548736	527803	523619	42679	268092841
128	2	293.87	525233	548984	442091	453970	548988	503853	46549	515945507
256	2	234.17	383549	396287	288012	332596	338967	347882	38763	712462627
512	2	217.66	271674	271674	271675	271676	271675	271675	1	1112781578
1024	2	238.76	136756	136757	136756	136756	136756	136756	0	1120306070
1500	2	274.92	93930	93930	93930	93930	93930	93930	0	1127158416
1518	2	275.44	92831	92831	92830	92831	92831	92831	0	1127334904

Table 50. Bidirectional Performance Results for 2 Streams Using the Same GPON Module

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	2	283.11	1264877	1097466	1055612	1097467	1264874	1156059	90153	591902321
128	2	237.43	1121721	884180	1097972	1097969	1121726	1064714	90890	1090266845
256	2	183.91	792570	677928	830785	754357	741619	759452	51333	1555357278
512	2	208.36	543350	543349	543349	543349	543349	543349	0	2225557684
1024	2	230.49	273512	273511	273511	273512	273512	273511	0	2240605929
1500	2	257.76	187859	187859	187859	187859	187859	187859	0	2254309224
1518	2	260.52	185661	185661	185657	185661	185661	185660	1	2254653437

Table 51. Unidirectional Performance Results for 3 Streams Using the Same GPON Module

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	3	392.83	603365	446430	571982	477816	509205	521760	58215	267140982
128	3	320.83	484978	609685	520605	556245	574059	549114	43054	562292947
256	3	222.37	508450	508450	508448	508448	508450	508449	1	1041303937
512	3	258.44	273694	273695	273695	263781	273695	271712	3965	1112931213
1024	3	304.44	33899	136943	136939	136943	136943	116333	41217	953002869
1500	3	307.37	94058	94058	94058	94058	94058	94058	0	1128696432
1518	3	309.36	92958	92958	92957	92957	92958	92958	0	1128876026

Table 52. Bidirectional Performance Results for 3 Streams Using the Same GPON Module

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	3	287.70	1143962	1081176	1018397	955632	955631	1030960	73209	527851321
128	3	270.08	1041210	1148106	1148104	1076852	1219375	1126729	62126	1153770916
256	3	219.52	1016894	1016893	1016893	1016894	1016894	1016894	0	2082598257
512	3	250.29	547387	547386	547382	547386	547386	547385	2	2242090951
1024	3	262.94	273885	273885	273885	273885	273885	273885	0	2243667001
1500	3	294.81	188116	188116	188116	188116	188116	188116	0	2257390320
1518	3	295.12	185914	185914	185914	185914	185914	185914	0	2257743065

Table 53. Unidirectional Performance Results for 4 Streams Using the Same GPON Module

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	4	392.16	804496	637089	678935	720789	762639	720790	59187	369044355
128	4	480.82	622883	646635	599128	646634	622884	627633	17775	642696114
256	4	244.08	525079	525078	525080	525078	525078	525078	1	1075360346
512	4	256.27	265801	265800	265800	265801	265801	265801	1	1088720314
1024	4	305.87	135446	135446	135447	135446	135447	135446	0	1109577056
1500	4	305.56	90717	90717	90717	90718	90717	90717	0	1088607888
1518	4	306.79	89656	89656	89656	89655	89655	89656	0	1088777048

Table 54. Bidirectional Performance Results for 4 Streams Using the Same GPON Module

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	4	289.95	1274152	1357857	1357859	1274156	1274158	1307637	41006	669509916
128	4	345.63	1198258	1150739	1245763	1293278	1293271	1236262	55407	1265932126
256	4	239.63	1050152	1050152	1050152	1050152	1050152	1050152	0	2150711714
512	4	250.60	531599	531600	531599	531599	531599	531599	0	2177430970
1024	4	288.79	270892	270892	270892	270892	270892	270892	0	2219145527
1500	4	297.85	181434	181434	181434	181434	181434	181434	0	2177208720
1518	4	298.91	179311	179311	179311	179311	179311	179311	0	2177549384

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APPENDIX F: UPSTREAM SINGLE ONT PERFORMANCE RESULTS

The configuration for these tests is illustrated in Figure 18. Mean latency is unidirectional and includes the latency of the Juniper MX480. Forwarding rate is the number of frames per second (fps) that were successfully sent and received by the Spirent TestCenter without any frame loss occurring. Upstream performance results for 1 stream using a single ONT709 are presented in Table 27.

Table 55. Upstream Performance Results for 2 Streams Using a Single ONT709

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	2	212.24	381327	360398	339472	318548	318545	343658	24404	175952914
128	2	216.40	299569	299567	335198	299567	275813	301943	19003	309189550
256	2	226.48	243434	237062	268908	237064	237064	244707	12350	501159272
512	2	56.48	212202	228722	232026	232026	232026	227400	7706	931431834
1024	2	79.22	118236	118236	118235	118236	118236	118236	0	968587428
1500	2	98.50	81209	81209	81209	81209	81209	81209	0	974511024
1518	2	99.34	80258	80259	80259	80259	80258	80259	0	974662211

Table 56. Upstream Performance Results for 3 Streams Using a Single ONT709

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	3	212.26	345982	320871	345984	345982	320871	335938	12302	172000293
128	3	191.08	324641	271194	289010	306826	324641	303262	20776	310540657
256	3	233.89	240957	288724	240957	240954	240956	250510	19107	513043935
512	3	87.81	194396	229089	219176	214220	224133	216203	11977	885566792
1024	3	85.04	119264	119265	119265	119265	119265	119265	0	977017209
1500	3	106.01	81916	81916	81916	81916	81916	81916	0	982991232
1518	3	106.79	80957	80957	80957	80957	80957	80957	0	983143702

Table 57. Upstream Performance Results for 4 Streams Using a Single ONT709

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	4	207.51	293899	327379	293899	327381	394348	327381	36679	167619161
128	4	190.02	318834	337837	318837	299832	299829	315034	14221	322594658
256	4	197.38	244849	232112	283062	283062	232112	255039	23348	522320437
512	4	189.49	193110	186501	193111	193111	186502	190467	3238	780152988
1024	4	87.78	118609	118609	118610	118609	118610	118610	0	971649532
1500	4	110.62	81466	81466	81467	81466	81466	81466	0	977594400
1518	4	111.58	80513	80513	80513	80513	80513	80513	0	977747662

APPENDIX G: DOWNSTREAM SINGLE ONT PERFORMANCE RESULTS

The configuration for these tests is illustrated in Figure 20. Mean latency is unidirectional and includes the latency of the Juniper MX480. Forwarding rate is the number of frames per second (fps) that were successfully sent and received by the Spirent TestCenter without any frame loss occurring. Downstream performance results for 1 stream using a single ONT709 are presented in Table 31 .

Table 58. Downstream Performance Results for 2 Streams Using a Single ONT709

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	2	46.18	1197452	1197452	1218375	1218378	1218377	1210006	10251	619523298
128	2	33.70	834037	834037	834037	834037	834037	834037	0	854054007
256	2	38.25	447237	389917	447237	447237	447237	435773	22928	892463731
512	2	46.26	232025	232025	232025	232025	232025	232025	0	950375916
1024	2	63.19	118235	118235	118235	118235	118235	118235	0	968582349
1500	2	79.46	81209	81209	81209	81209	81209	81209	0	974506560
1518	2	80.15	80258	80258	80258	80258	80258	80258	0	974658617

Table 59. Downstream Performance Results for 3 Streams Using a Single ONT709

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	3	33.41	1199777	1199777	1199777	1199777	1199777	1199777	0	614285670
128	3	34.72	841295	841295	841295	841295	841295	841295	0	861486438
256	3	39.83	451129	451129	432023	451129	451129	447308	7643	916086923
512	3	48.56	234045	234045	234045	234045	234045	234045	0	958646600
1024	3	68.31	119264	119264	119264	119264	119264	119264	0	977011507
1500	3	86.96	81916	81916	81916	81916	81916	81916	0	982987224
1518	3	87.71	80957	80957	80957	23011	80957	69368	23178	842401179

Table 60. Downstream Performance Results for 4 Streams Using a Single ONT709

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	4	31.93	561756	1181176	1181176	1181176	1181176	1057292	247768	541333310
128	4	34.96	836676	836676	836676	836676	836676	836676	0	856756722
256	4	38.60	448653	448653	448653	448653	448653	448653	0	918840574
512	4	49.89	232760	232760	232760	232760	232760	232760	0	953383444
1024	4	72.39	118609	118609	118609	118609	118609	118609	0	971647468
1500	4	92.73	81466	81466	81466	81466	81466	81466	0	977590440
1518	4	93.46	80512	80512	80512	80512	80512	80512	0	977743071

APPENDIX H: BIDIRECTIONAL SINGLE ONT PERFORMANCE RESULTS

The configuration for these tests is illustrated in Figure 22. Mean latency is bidirectional and includes the latency of the Juniper MX480. Forwarding rate is the number of frames per second (fps) that were successfully sent and received by the Spirent TestCenter without any frame loss occurring. Bidirectional performance results for 1 stream using a single ONT709 are presented in Table 35.

Table 61. Bidirectional Performance Results for 2 Streams Using a Single ONT709

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	2	116.81	678943	637091	678943	678943	678942	670572	16741	343333040
128	2	133.84	599134	599131	575374	717905	717905	641890	62670	657295258
256	2	118.23	486866	512341	486860	512341	486864	497055	12482	1017967665
512	2	63.47	424401	444226	378142	437617	417792	420436	23120	1722104308
1024	2	71.39	236470	236470	236470	236470	236470	236470	0	1937163928
1500	2	89.32	162418	162418	162418	162418	162418	162418	0	1949012544
1518	2	90.08	160517	160517	160517	160517	160517	160517	0	1949316796

Table 62. Bidirectional Performance Results for 3 Streams Using a Single ONT709

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	3	122.34	691962	641738	641738	691963	591518	651784	37583	333713291
128	3	130.50	613648	649281	578019	542385	613649	599396	36337	613781948
256	3	134.65	481911	481912	481911	577446	462804	497197	40801	1018258821
512	3	67.27	408614	458177	438352	398699	438352	428439	21718	1754884350
1024	3	76.97	238528	238528	238528	238528	238528	238528	0	1954022539
1500	3	97.11	163831	163831	163831	163831	163831	163831	0	1965974112
1518	3	97.92	161914	161914	161914	161914	161914	161914	0	1966280677

Table 63. Bidirectional Performance Results for 4 Streams Using a Single ONT709

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	4	118.53	788684	654760	721724	587796	721721	694937	68289	355807826
128	4	124.48	675675	599661	561655	675675	561651	614863	51556	629619950
256	4	101.11	464216	515171	515172	515171	489697	499885	20382	1023765328
512	4	90.72	399436	386219	452303	373001	452303	412652	33436	1690223960
1024	4	80.75	237219	237218	237219	237219	237219	237219	0	1943294476
1500	4	102.43	162932	162932	162932	162932	162932	162932	0	1955180496
1518	4	103.23	161025	161025	161025	161025	161025	161025	0	1955485414

APPENDIX I: PERFORMANCE RESULTS WITH ENCRYPTION DISABLED AND FEC

The configuration for these tests is illustrated in Figures 4, 6 and 8. Mean latency is unidirectional for the unidirectional tests and bidirectional for the bidirectional tests and includes the latency of the Juniper MX480. Forwarding rate is the number of frames per second (fps) that were successfully sent and received by the Spirent TestCenter without any frame loss occurring.

Table 64. Upstream Performance Results for 1 Stream with Encryption Disabled and FEC

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	1	226.25	368536	358073	326683	316221	337147	341332	19406	174761934
128	1	174.81	327940	333881	292309	298249	310126	312501	16199	320000961
256	1	243.86	245910	233174	233172	252278	274572	247821	15286	507537773
512	1	100.78	225051	193662	213485	211834	216791	212164	10312	869025522
1024	1	133.78	118890	118890	118891	118891	118890	118890	0	973950599
1500	1	137.48	81659	81659	81659	81659	81659	81659	0	979909584
1518	1	140.87	80704	80703	80703	80704	80703	80703	0	980060997

Table 65. Downstream Performance Results for 1 Stream with Encryption Disabled and FEC

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	1	29.98	1216053	1216053	1216053	1216053	1216053	1216053	0	622619040
128	1	32.93	844595	844595	844595	844595	844595	844595	0	864864840
256	1	36.93	452899	452899	452899	452899	452899	452899	0	927536210
512	1	44.82	234962	230006	234962	234962	234962	233971	1982	958345839
1024	1	60.44	119732	119732	119732	119732	119732	119732	0	980842906
1500	1	73.99	82237	82237	63155	82237	82237	78421	7633	941046432
1518	1	74.85	81274	81274	81274	81274	81274	81274	0	986996071

Table 66. Bidirectional Performance Results for 1 Stream with Encryption Disabled and FEC

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	1	129.84	674293	757995	799848	695218	695219	724515	46978	370951514
128	1	115.90	596494	608369	655880	596492	620247	615496	22029	630268336
256	1	127.78	606457	485451	536402	485445	485449	519841	47592	1064633819
512	1	74.82	426971	390624	453404	446796	430275	429614	21858	1759698182
1024	1	94.26	237780	237780	237780	237780	237780	237780	0	1947891630
1500	1	105.58	163317	163317	163317	163317	163317	163317	0	1959805632
1518	1	106.40	161406	161406	161406	161406	161406	161406	0	1960111452

APPENDIX J: PERFORMANCE RESULTS WITH ENCRYPTION AND NO FEC

The configuration for these tests is illustrated in Figures 4, 6 and 8. Mean latency is unidirectional for the unidirectional tests and bidirectional for the bidirectional tests and includes the latency of the Juniper MX480. Forwarding rate is the number of frames per second (fps) that were successfully sent and received by the Spirent TestCenter without any frame loss occurring.

Table 67. Upstream Performance Results for 1 Stream with Encryption and No FEC

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	1	156.72	713821	682431	692895	682431	661505	686616	17001	351547634
128	1	121.90	607053	583299	523913	565483	559544	567858	27498	581487002
256	1	106.46	386025	386025	398763	370103	392394	386662	9532	791884009
512	1	152.23	231659	231659	231658	231659	231658	231659	0	948873773
1024	1	176.66	118890	118890	118890	118890	118890	118890	0	973948191
1500	1	205.19	81659	81658	81659	81659	81659	81659	0	979904952
1518	1	201.14	80703	80703	80703	80703	80703	80703	0	980056309

Table 68. Downstream Performance Results for 1 Stream with Encryption and No FEC

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	1	33.89	1226516	1216053	1216053	1226516	1216053	1220238	5126	624761899
128	1	35.55	648622	844595	844595	844595	844595	805400	78389	824729719
256	1	40.01	452899	452899	452899	452899	452899	452899	0	927536230
512	1	48.60	234962	234962	234962	234962	234962	234962	0	962405990
1024	1	65.08	119732	119732	119732	119732	119732	119732	0	980842906
1500	1	79.96	82237	82237	82237	82237	82237	82237	0	986842080
1518	1	80.56	81274	81274	81274	81274	81274	81274	0	986996071

Table 69. Bidirectional Performance Results for 1 Stream with Encryption and No FEC

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	1	92.76	1302080	1302080	1323006	1343932	1323007	1318821	15659	675236303
128	1	79.42	1154716	1012191	1035946	1095330	1012191	1062075	55404	1087564597
256	1	76.44	708362	791156	835738	861214	784787	796251	52271	1630722879
512	1	100.66	463316	463316	463316	463316	463316	463316	0	1897741206
1024	1	121.27	237779	237779	237779	237779	237779	237779	0	1947889418
1500	1	143.44	163317	163317	163317	163317	163317	163317	0	1959803400
1518	1	140.56	161406	161406	161406	161406	161406	161406	0	1960109242

APPENDIX K: PERFORMANCE RESULTS WITH ENCRYPTION DISABLED AND NO FEC

The configuration for these tests is illustrated in Figures 4, 6 and 8. Mean latency is unidirectional for the unidirectional tests and bidirectional for the bidirectional tests and includes the latency of the Juniper MX480. Forwarding rate is the number of frames per second (fps) that were successfully sent and received by the Spirent TestCenter without any frame loss occurring.

Table 70. Upstream Performance Results for 1 Stream with Encryption Disabled and No FEC

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	1	227.15	358073	358073	347610	326683	316222	341332	17000	174762164
128	1	184.69	304186	333880	316063	327940	322001	320814	10217	328513665
256	1	250.56	245911	242726	239541	287307	233172	249731	19254	511449678
512	1	71.86	210182	201921	208529	223398	225050	213816	8952	875790713
1024	1	128.39	118890	118890	118891	118890	118890	118890	0	973947535
1500	1	134.63	81659	81659	81659	81659	81659	81659	0	979905384
1518	1	156.88	80703	80703	62416	80703	80703	77046	7315	935644195

Table 71. Downstream Performance Results for 1 Stream with Encryption Disabled and No FEC

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	1	28.71	807989	1216053	1216053	1216053	1216053	1134440	163225	580833327
128	1	31.69	844595	844595	844595	844595	844595	844595	0	864864840
256	1	35.40	452899	452899	452899	452899	347812	431881	42035	884492734
512	1	43.51	234962	220094	234962	234962	234962	231989	5947	950225543
1024	1	58.99	119732	119732	119732	119732	119732	119732	0	980842906
1500	1	72.47	82237	82237	81080	82237	82237	82006	463	984066600
1518	1	73.29	81274	81274	81274	81274	81274	81274	0	986996071

Table 72. Bidirectional Performance Results for 1 Stream with Encryption Disabled and No FEC

Frame Size (bytes)	Number of Streams	Mean Latency (µs)	Forwarding Rate Trial 1 (fps)	Forwarding Rate Trial 2 (fps)	Forwarding Rate Trial 3 (fps)	Forwarding Rate Trial 4 (fps)	Forwarding Rate Trial 5 (fps)	Mean Forwarding Rate (fps)	Std. Dev. Forwarding Rate (fps)	Mean Forwarding Rate (bps)
64	1	125.60	611512	757998	695214	716144	716145	699402	48449	358094057
128	1	121.73	667757	644002	644001	572739	548986	615497	46061	630269196
256	1	141.01	479082	485451	485451	549139	466343	493093	28878	1009854263
512	1	55.83	463316	456708	423666	420362	436883	440187	17232	1803006779
1024	1	92.56	237780	237780	237780	237780	237777	237779	1	1947887026
1500	1	118.29	163317	163317	163317	135562	163317	157766	11102	1893193560
1518	1	104.93	161406	161406	161406	161406	161406	161406	0	1960111428

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