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Fusion network performance experiment

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Master of Telematics - Communication Networks and Networked Services (2
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Submission date: 17th June, 2013 Trondheim

Co-supervisor: Raimena Veisllari (ITEM)

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Problem Description

The fusion concept has the main objective of combining the best properties from both circuit and packet switched networks into a hybrid solution. TransPacket is a startup-company that has implemented the novel fusion technology, also called OpMiGua integrated hybrid networks. A number of studies show that the performance properties of the OpMiGua (fusion) network are found attractive.

In the project, the student will perform a network experiment involving TransPacket H1 nodes measuring performance parameters like latency, latency variation (packet delay variation) and packet loss. Furthermore, the student will investigate and analyze the performance of TransPacket H1 node based on the result obtained from the simulation.

Assignment given: 21st January 2013
Co-supervisor: Raimena Veisllari (ITEM)
Supervisor: Prof. Steinar Bjørnstad (ITEM/Transpacket)

Abstract

Hybrid optical packet/circuit switched networking architectures are increasingly becoming an interesting research field. They integrate multiple switching techniques to achieve better quality of service and to improve resource utilization. The aim of this study was to investigate the performance of TransPacket FUSION Ethernet H1 node, which is being developed based on the original idea of OpMiGua hybrid optical network. The work was focused on several key performance elements: packet delay, packet loss rate and packet delay variation of the hybrid network.

The research background and the quality of service methods utilized in hybrid network and OpMiGua were studied in this project. The performance of H1 node was tested based on one applicable scenario. We investigated and analyzed the results obtained from the Spirent test center, and derived a mathematical model of H1 node performance respect to each aspect. Furthermore, the experiment results were verified with usability of H1 node in comparison with the ITU recommendations. The results in our experiment scenario showed that H1 node provides a high quality of service.

Acknowledgements

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I appreciate my supervisors Steinar Bjørnstad and Raimena Veisllari for their professional guidance and motivation, which have expanded my knowledge and encouraged me in my work. I also appreciate Kurosh Bozorgebrahimi and Arne Oslebo from UNINETT for their kindly support with experiment equipment.

Thanks to the Department of Telematics for providing the master program. Because of that, my two years pleasant studies were possible. Thanks to the administrative assistances, especially Mona Nordaune, for their helps during the two years.

I want to give my honest thanks to my parents for all supports for so many years.

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List of Abbreviation

3LIHON	3-Level Integrated Hybrid Optical Network
CIB	Contention induced blocking
CoS	Class of Service
CWDM	Coarse Wavelength Division Multiplexing
DMUX	DeMultiplexer
DPLR	Data Packet Loss Ratio
DWDM	Dense Wavelength Division Multiplexing
E/D	Encoder/Decoder
EDFA	Erbium Doped Fiber Amplifier
FDL	Fiber Delay Line
FDM	Frequency Division Multiplexing
FIFO	First In First Out
GST	Guaranteed Service Transport
HCT	High Class Transport
HoL	Head-of-line blocking
IP	Internet Protocol
IPDV	IP Packet Delay Variation
IPER	IP Packet Error Ratio
IPLR	IP Packet Loss Ratio
IPTD	IP Packet Transfer Delay
LAN	Local Area Network
LATW	Length Aware Time Window
MUX	Multiplexer
NCT	Normal Class Transport
OBS	Optical Burst Switching
OC	Optical Code
OCS	Optical Circuit Switching

OpMiGua	Optical Packet Switched Migration capable Network with Guaranteed service
OPS	Optical Packet Switching
ORION	Overspill Routing in Optical Networks
OXC	Optical Cross-connect
PIB	preemption induced blocking
PLR	Packet Loss Ratio
QoS	Quality of Service
RAM	Random Access Memory
RIB	Reservation induced blocking
RRGF	Round-Robin Gap Fit
SDH	Synchronous digital Hierarchy
SM	Statistical Multiplexed
SONET	Synchronous Optical Networking
SP	Service Provider
STM	Simple Time Window
VLAN	Virtual Local Area Network
WDM	Wavelength Division Multiplexing
WRON	Wavelength Routed Optical Network

Chapter 1
Introduction

1.1 Motivation

Originally, internet bandwidth was a scarce resource, certainly relative to the computing power available. Nowadays, with the large increase in data traffic due to applications such as high-resolution video streaming, internet traffic is increasing rapidly. Correspondingly, the rapid development and deployment of fiber transmission make more transmission capacity available than even specialized routers could handle [1]. An idea of all-optical network was proposed due to high reliability, low transfer delay, low jitter, and energy save. However, all-optical network differs in many aspects from the current optical-electrical-optical switching network, therefore many issues needed to be addressed [2].

Hybrid optical network combines two or more switching technologies, with purpose to utilize the advantages and improve the overall performance. Optical circuit switching (OCS) provides continuous and immediately available connection which makes it ensure the quality of service (QoS). Optical packet switching (OPS) shares available network bandwidth, which improves the network utilization. Optical burst switching (OBS) is proposed later, as a compromise between the yet unfeasible full OPS and mostly static OBS.

A number of researches have been performed with focus on the hybrid optical network, of which different technologies have been proposed and investigated in hybrid optical network architectures [3] [4] [5] [6] [7]. Based on the degree of interaction and integration of the network technologies, the hybrid optical networks are classified into three categories [1]: Client-server, Parallel and Integrated. OpMiGua [8] and Overspill Routing in Optical Networks (ORION) [9] are classified into the integrated category.

Optical Packet Switched Migration capable Network with Guaranteed service (OpMiGua) is the product by the cooperation of Telenor, Norwegian University of Science and Technology (NTNU), and Network Electronics. Circuit switching and packet switching are integrated in OpMiGua, which are used for the two different traffic types, Guaranteed Service Class (GST) and Statistical Multiplexed (SM) respectively. GST applies circuit switching that traffics are not processed in the intermediate packet switches. It ensures fix delay and no packet loss for GST traffics. Meanwhile, less powerful packet switch is required to reduce potential cost. GST traffic is suitable for broadcast-TV and mobile backhaul, which have high timing requirement. In the other hand, SM traffic applies packet switching. Packet loss and delay variation are expected. SM traffic is suitable for less demanding service.

1.2 Problem to be addressed

The FUSION ETHERNET H1 from company TransPacket (www.transpacket.com) is the product applying OpMiGua concept. A number of studies show that the performance properties of the OpMiGua (fusion) network are found to be attractive [10] [11] [12] [13]. Field trial has been conducted [14] based on H1 node. The result is quite optimistic. As a real product to be utilized in the market, it faces a series of unpredictable situations. For instance, the traffic load and traffic patterns keep changing constantly. It challenges the switch's capability of dealing with traffic and providing reliable service. Hence, more experiments should be conducted to test the performance of H1 node.

The main goal of this project is to analyze the result based on a network experiment involving TransPacket H1 nodes measuring performance parameters like latency, latency variation (packet delay variation) and packet loss rate. A prototype of real traffic will be generated and transmitted through H1 node in the experiment. A comparison of the performance with QoS requirement will be carried out to analyze the services that TransPacket H1 support. Furthermore, the potential mathematical solution will be investigated to modeling H1 performance. Results should be presented and analyzed.

1.3 Methods and outline

The background knowledge of hybrid optical network and OpMiGua were obtained from publications, standards and white papers. The experiment was carried on the TransPacket H1 nodes located in UNINETT lab in Trondheim. Spirent TestCenter was the monitoring and measuring instrument used in the experiment.

In this paper, the background materials are described in chapter 2 to 4, including the principle of hybrid optical network (chapter 2) ,OpMiGua hybrid network (chapter 3), and the quality of service requirement of internet application (chapter 4). Hybrid network QoS methods are illustrated, as well as the technologies used in OpMiGua. The experiment set up is described in chapter 5, consisting of the equipment materials, physical connection and experiment configuration. A comprehensive study of experiment results is presented in chapter 6. Analysis of the results, discussion, conclusion, and future work are presented in chapter 7, 8 and 9, respectively.

Chapter 2
Hybrid Optical network

Hybrid optical network and its characteristics are described in this chapter. First, Wavelength Division Multiplexing (WDM), one key multiplexing technique in hybrid optical network, is illustrated. And then, three switching techniques, OCS, OPS and OBS, are discussed in details.

2.1 Characteristic

Optical network is the network with all optical fiber as the transmission media. Comparing to the other transmission media, optical fiber provides larger bandwidth capacity and immune to noise and interference. Optical network combining with two or more switching technologies is called as hybrid optical network. OCS and OPS are two main switching technologies widely accepted in current hybrid optical network. OBS is proposed as a compromise between the unfeasible full OPS and the mostly static OCS.

Wavelength Division Multiplexing (WDM) multiplexes a number of optical carrier signals onto a single optical fiber by using different wavelength of laser light. It enables bidirectional communications over one strand of fiber, as well as multiplication of capacity. By dividing the optical spectrum into wavelength channels, it's possible to reach much higher fiber utilization. Also, data transport in a wavelength channel is protocol independent enabling signals of different protocols

[15]. All the above factors make WDM the current favorite multiplexing technology for long-haul communication in optical communication networks [16].

WDM is essentially the frequency division multiplexing (FDM) technology in optical domain. Every channel is realized by dividing the frequency domain and every channel occupies a period of bandwidth.

The basic principle of a four channel WDM is indicated in Figure 2.1:

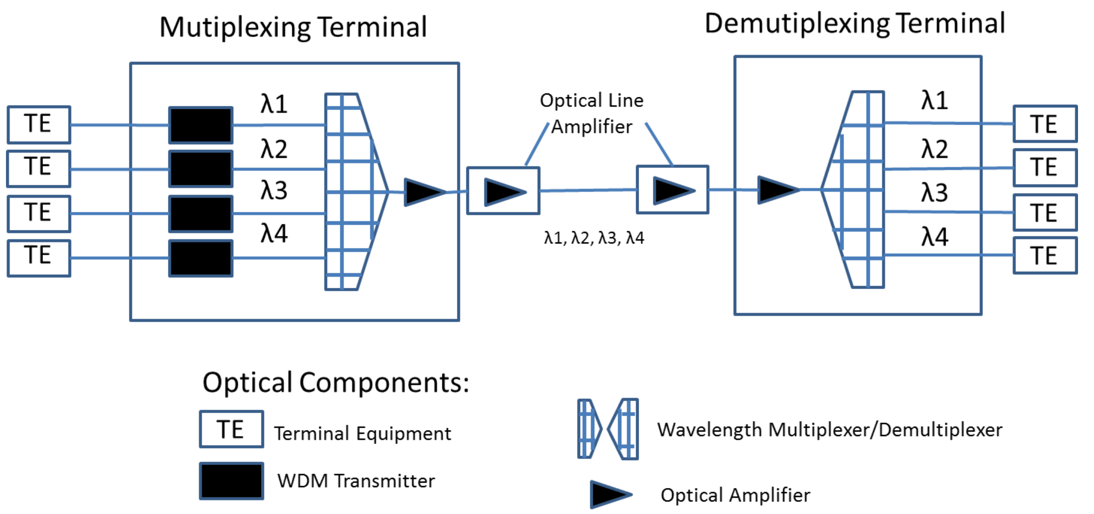


Figure 2.1: Four channel point-to-point WDM transmission system with amplifier [16]

Figure 2.1 is an example of WDM system. WDM Multiplexer (MUX) combines four independent data streams from terminal equipment (TE), each on a unique wavelength, and sends them on a fiber. Optical signals are amplified by the optical amplifier without O/E/O signal transform. A DeMultiplexer (DMUX) at the fiber's receiving end separates out these data streams.

According to the difference of channel spacing, WDM can be divided into two divisions [15]: Coarse Wavelength Division Multiplexing (CWDM), and Dense Wavelength Division Multiplexing (DWDM).

DWDM is the technology of choice for transporting extremely large amounts of data traffic over metro or long distances in telecom networks. Typically, DWDM is able to provide up to 40 or 80 channels spacing. Channel spacing of DWDM ranges from 0.2 nm to 1.2 nm. The dense channel spacing requires tight control of wavelengths. DWDM takes advantage of the operating window of the Erbium Doped Fiber Amplifier (EDFA) to amplify the optical channels and extend the operating range of the system to over 1500 kilometers [17].

CWDM is the cost efficiently technology for transporting large data of traffic. In comparison with DWDW, CWDM has fewer numbers of channels. Typically, CWDM is able to transport up to 16 channels (wavelengths) in the spectrum grid from 1270 nm to 1610 nm with a 20 nm channel spacing [18]. CWDM provides high access bandwidth with low cost. It can be applied for point-to-point, Ethernet and SONET ring network structure. CWDM is particularly suitable for short-distance, high-bandwidth and intensive access points applications, such as intra/inter building network communication.

2.2 Switching techniques

Switching technology is the fundamental technique in network operation. Network is composed with many nodes, which connect by links. There might be multiple links from sender to receiver. Switching technique is the key aspect of defining hybrid network. Circuit switching and packet switching are the original techniques introduced into optical hybrid network. Optical burst switching (OBS) is also proposed later as a promising technique to improve the overall performance [3] [5] [6] [19]. A comparison between OBS and the other optical switching techniques [19] indicated that OBS is the cost-effective and viable solution for next generation of optical networks.

2.2.1 Optical Circuit Switching

Circuit switching implementing the network in which two network nodes establish a dedicated communication channel through the network before the nodes may communicate. Once a connection is established, a dedicated path exists between both ends until the connection is terminated. The set of dedicated resource allocated for connection is called a circuit, as depicted in Figure 2.2

Optical Circuit Switching (OCS) integrates circuit switching into optical technology. In OCS, the network is configured to establish a circuit, from an entry to an exit node. Optical cross connect circuits in the core routers. The optical form signal can travel in an all-optical manner from the entry to the exit node.

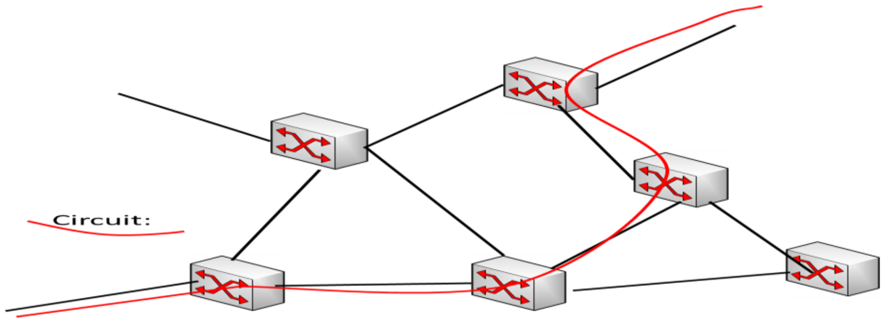


Figure 2.2: Circuit switching

Since circuit switching has dedicated channel, it guarantees the quality of service. However, because of dedication, the bandwidth resource cannot be fully utilized. Each time the new end systems need to communicate, a dedicated path should be connected, which make it more expensive than the other switching techniques. Meanwhile, the establishment of a new connection takes time. Therefore, circuit switching is well suited for long-lasting connections which also has high traffic load.

2.2.2 Optical Packet Switching

Packet switching is connectionless transmission, which aims to optimize the utilization of the available channel capacity in network. Packet switching introduces the idea of fragment, which cuts data into packets and transmit over a network without any pre-allocated resource, as depicted in Figure 2.3. Packet switching only utilizes the resource when it is available and there is packet data to send, so that no resources are wasted.

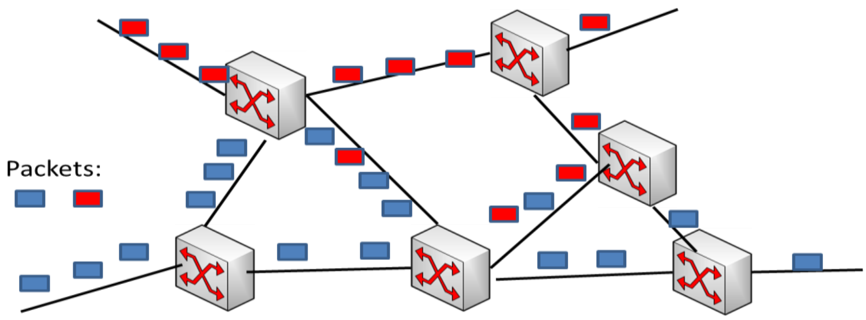


Figure 2.3: Packet switching

The switches (routers) have to make a lookup in the forwarding table, called routing table, for each incoming packet. A routing table contains a mapping between the possible final destinations of packets and the outgoing link on their path to the destination. Routing tables can be very large because they are indexed by possible destinations, which makes lookups and routing decisions computationally expensive, and the forwarding process relatively slow compare to circuit switching.

The architecture of OPS node is shown in Figure 2.4 which consists of a set of Multiplexers and DeMultiplexers, an input and an output interface, a space switch fabric with associated optical buffers and wavelength converters, and a switch control unit. Each packet consists of the payload and an optical header which is used for routing in the optical domain. The packet are first de-multiplexed into individual wavelengths and sent to the input interface. The input interface is responsible for extracting the optical packet header and forwarding it to the switch control unit for processing. The switch control unit processes the header information, determines and appropriate output port and wavelength for the packet. In routing the packet, the switch may need to buffer it and/or convert it to a new wavelength. The switch controller also determines a new header for the packet, and forwards it to the output interface. When the packet arrives at the output interface, the new header is attached, and the packet is forwarded on the outgoing fiber link to the next node in its path [20].

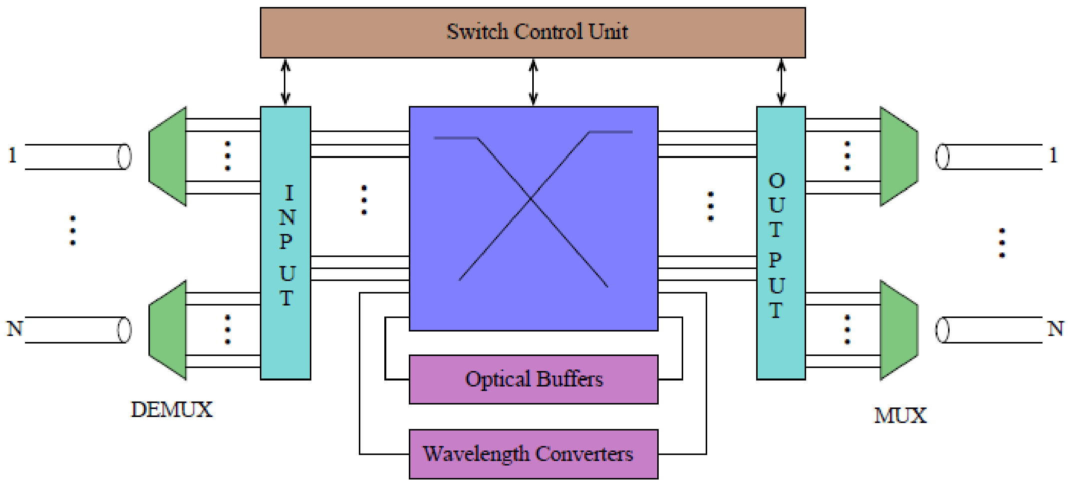


Figure 2.4: OPS node architecture [20]

Optical packet switching (OPS) promises almost arbitrarily fine transmission and switching granularity, evoking the vision of a bandwidth-efficient, flexible, data-centric all-optical Internet [20]. The challenge of OPS is the optical buffering and packet level parsing. Hence it needs a practical and cost-effective implementation.

2.2.3 Optical Burst Switching

Optical burst switching (OBS) is viewed as a compromise between the yet unfeasible full OPS and the mostly static OCS. It has been proposed to improve the utilization of a network of optical cross connect (OXCs).

OBS can be viewed as fast wavelength switching where the holding time of a wavelength is in the order of an optical burst. An important feature of OBS is the separation of control and data. A control packet is sent over a separate control channel ahead of the optical burst to perform channel reservation.

OBS dynamically provide sub-wavelength granularity by optimally combining electronics and optics. In OBS network, various types of client data are aggregated at the ingress (en edge node) and transmitted as data burst. Edge node detail is depicted in Figure 2.5. Client data goes through burst assembly/disassembly at the edge of an OBS network. Data and control signals are transmitted separately on different channels.

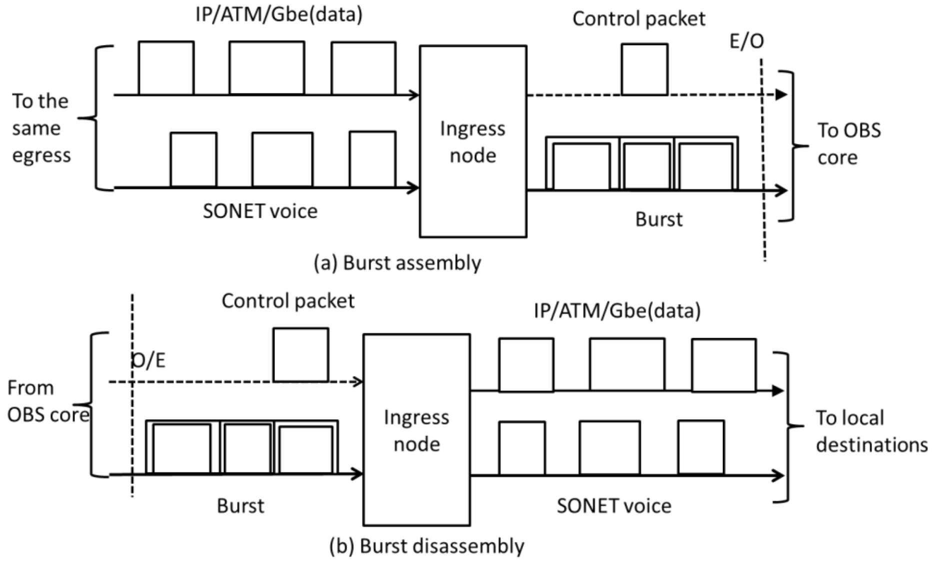


Figure 2.5: Burst assembly/disassembly at the edge of OBS network [19]

For each burst, there is a control packet contains the information of the burst. Since the control is significantly smaller than the burst, one control channel is sufficient to carry control packets associated with multiple data channels. Control packet goes through O/E/O conversions at each intermediate OBS node and is processed electronically to configure the underlying switching fabric, thus the costly O/E/O conversions are only required on a few control channels.

An offset time was introduced in OBS. Offset time is the time between control packet and corresponding data burst that used to compensate the processing/configuration delay. Each time the burst passes an intermediate OBS node, the time between control packet and corresponding data burst becomes smaller. If the offset time is big enough, the data burst will be switched all optical way and in a cut-through manner, which is without delay at any intermediate node. In this way, no RAM or fiber delay line (FDL) is need in any intermediate node.

Chapter 3
OpMiGua

3.1 Motivation

The application demand pushes the increase of network capacity. The multiple applications, for instance, telephony, file transfer and TV broadcast desire a converged network serving multiple services. The converged network should utilize the efficiency of packet switching and the QoS of circuit switching. All of these elements motivated the development of OpMiGua.

OpMiGua aims to enable the network provide absolute service guarantee and high throughput. It combines optical circuit and optical packet switching that brings the best of QoS and cost efficiency. OpMiGua is classified as the integrated hybrid optical network [1].

3.2 Design Principle

The design of OpMiGua follows the principle:

- Packet based transport but circuit/packet switched
- ORION [9] Related principle and project
- Time multiplexed packet and circuit switched network
  - Some packets follow wavelength paths (circuits)
  - Some packets are switched by packet switches
- Packets are tagged to decide: Wavelength path or packet switching
  - OpMiGua uses polarizations state as tag

In OpMiGua network, the traffics are classified in to two classes: guaranteed service transport (GST) and statistically multiplexed (SM). GST uses circuit switching and SM uses packet switching. GST traffics pass through the middle nodes, SM packets are extracted out in every intermediate node, aggregated into new SM traffic and find proper time slot to re-insert.

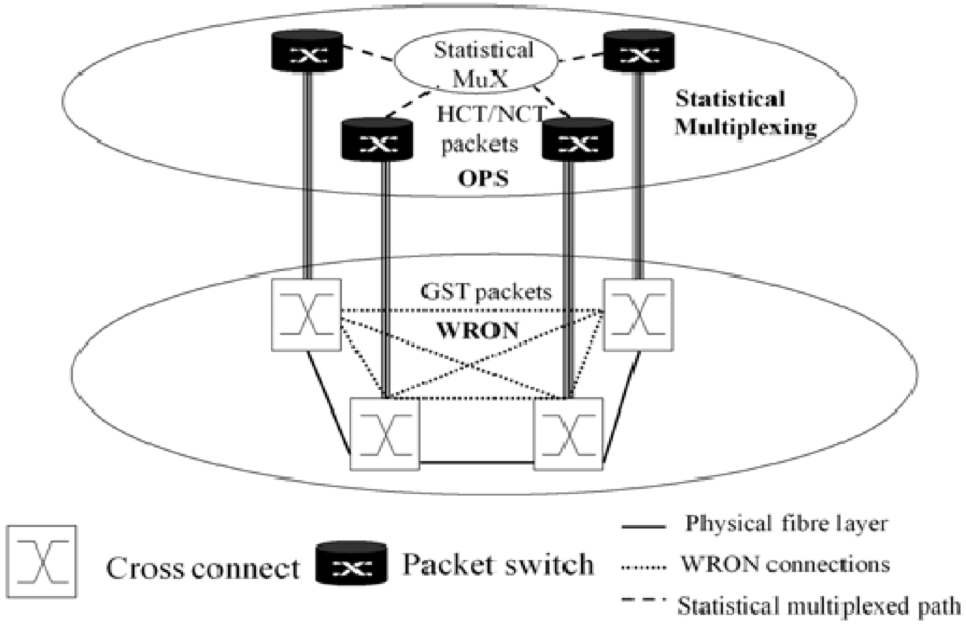


Figure 3.1: The OpMiGua hybrid network model [8]

The OpMiGua network model is shown in Figure 3.1. GST packets follow pre-assigned paths through the wavelength routed optical network (WRON), while SM packets are switched according to their header information in OPS. GST packets have no contention with other GST packets because of pre-assigned wavelength paths. Meanwhile, GST packets do not require head processing. The node design gives GST traffic absolutely priority over SM traffic. High throughput efficiency is ensured through interleaving the SM packets in OPS network and GST packets following the WRON. The WRON capacity between these nodes is the maximum allowed GST traffic. GST traffic between each of the nodes in the network can be transported by one or more wavelength.

According to the design principle, SM and GST traffics share the transmission fiber as optical signals. SM signals need to be extracted and pass through the O/E/O transform. Therefore, SM packets and GST packets need to be separated when arrival the network node. Optical code (OC) is used to differentiate between GST and SM packets. A multiport Encoder/Decoder (E/D) can be used to generate optical labels to be appended to optical packets.

Figure 3.2 illustrates the application of optical code in OpMigua. Figure 3.2 (a) and (b) are the OC encoding and decoding part respectively. Figure 3.2 (c) shows the modified OC decoder part for OpMiGua node. The modified OC labeling in OpMiGua do not label GST. On the other hand, all SM packets are marked by an OC, both in headers and tails; the tail OC allows to handle variable length SM packets [21]. At the ingress node, encoders generate OC to label SM packets. At the switching node, incoming signal is split into two parts and a copy is sent to the decoder. The detected signal controls the state of gates to split the traffics into two different directions. Therefore, the separation of GST and SM packets in switching node is accomplished.

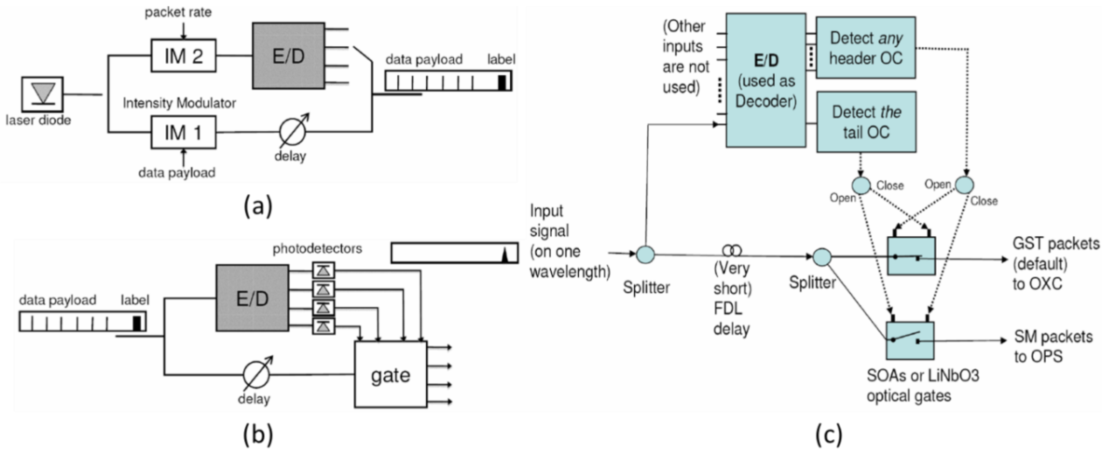


Figure 3.2: Optical code and modification in OpMiGua. (a) OC encoding, (b) OC decoding, (c) Modified part for OpMiGua node [21]

Figure 3.3 is the detailed OpMiGua node design. Polarization beam splitters (PBSs) separate SM and GST packets at the input. SM traffic are converted to the electronic domain and buffered to the output queue. Fiber delay line (FDL) is used to delay the GST packet for a time corresponding to the maximum length SM packet. This ensures the control electronics have time to monitor the available gaps on all output wavelength so that the gap-filling scheduler can successfully transmit SM packets without preemption and without disturbing the GST traffic. The gap-filling scheduler may use different reservation techniques [12] [22], such as SM traffic include simple time window (STM), length aware time window (LATW), preemptive (PRE) and combined (COMB). The efficiency of each reservation technique related to the GST traffic load [12]. GST traffic pattern is another element which may influence the utilization of the gaps.

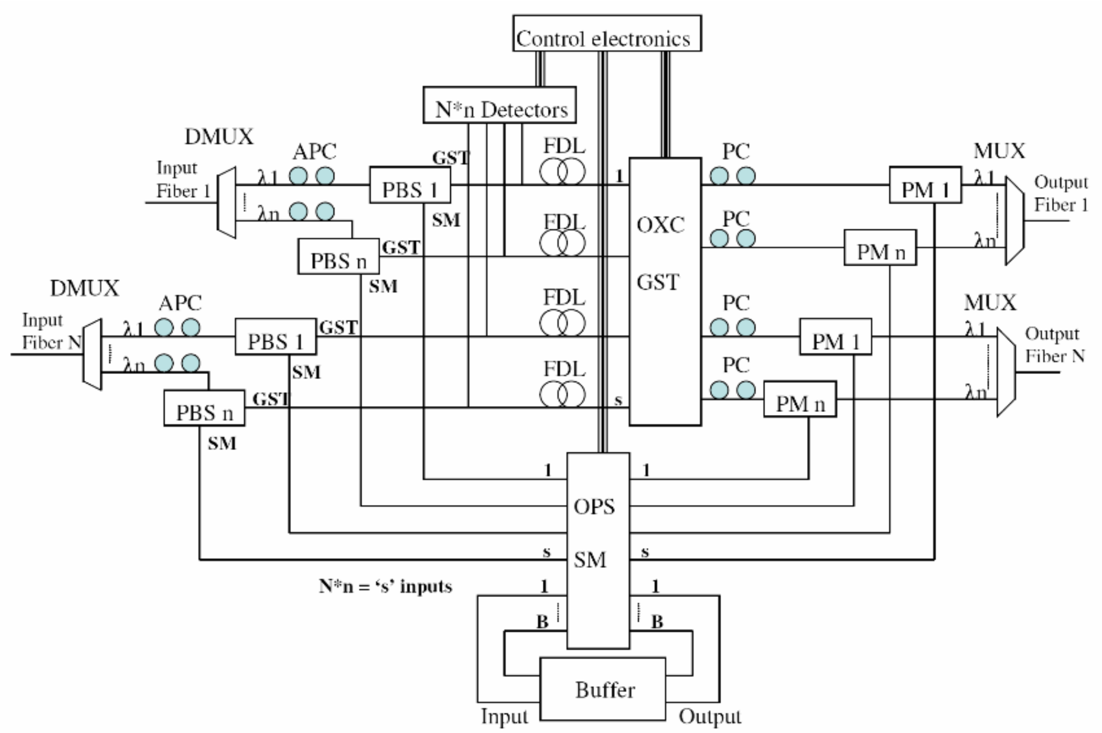


Figure 3.3: General node design for original OpMiGua [21]

Figure 3.4 indicates the sharing of physical fiber layer between GST traffic and SM traffic.

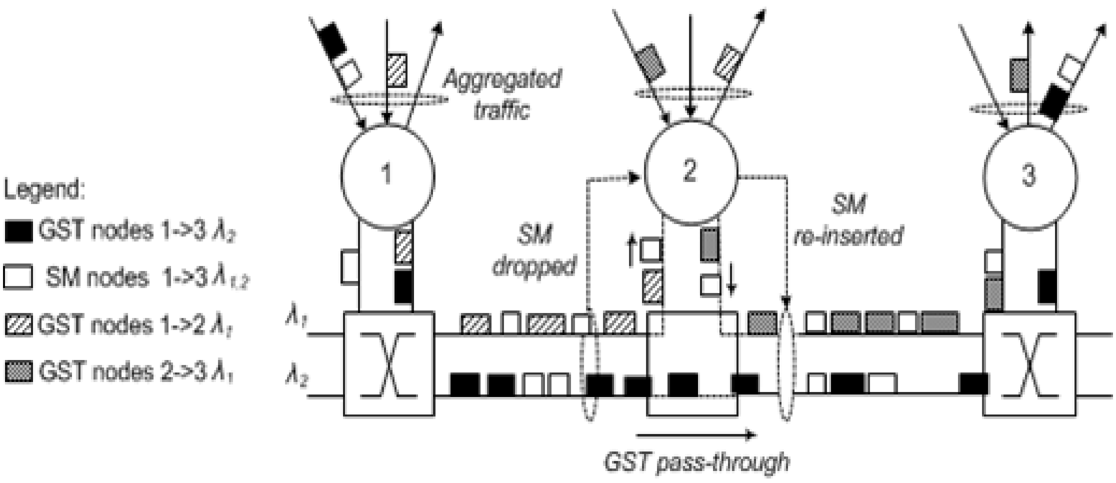


Figure 3.4: A hybrid network model illustrating the sharing of the physical fiber layer [22]

In the middle node, GST traffics pass through the node directly. SM traffics are extracted first, aggregated into the queue and re-insert into lightpath when find the proper time slot. The utilization of the whole lightpath mostly depends on how much percent of the gap between GST packets can be utilized by SM traffic. The utilization of the gaps varies according to many aspects, such as GST traffic load, GST packet length, SM scheduling techniques.

SM traffic suffers loss and delay because of the absolutely GST traffic priority. Three different blocking factors are defined [23] which induce the SM traffic loss and queuing delay.

a) Reservation induced blocking (RIB)
b) Contention induced blocking (CIB)
c) Head-of-line blocking (HoL)

RIB of SM is caused by the reservation scheme for the GST traffic. When the gap between consecutive GST packets is smaller than the SM packet in the head of the queue, the gap will not be utilized and thus increased the buffer overflow probability as well as the delay of SM packets. CIB is caused by multiple packets destined to the same output at the same time. Electronic buffer reduces the CIB effect. HoL is caused in FIFO buffer, when the packet in the head is too long and cannot fill the gap. The head packet stays in the queue and blocks the possibility of serving the short packets in the queue.

Electronic buffer enables a novel scheduling technique Round-Robin Gap Fit (RRGF) [22] to increase the utilization of lightpath when traffic pass one node. RRGF is the idea of adding additional SM traffic in one node to increase the probability of finding the suitable gap. Meanwhile, It has been proved lightpath utilization is rising with an added number of nodes [14].

3.3 Performance Evaluation

A set of experimental demonstrations were conducted to test the performance of OpMiGua hybrid network [10] [11] [13] [14] [24]. Experimental demonstrations confirm zero packet loss and no jitter for GST traffic, regardless of the load of SM traffic on the network. Having SM traffic increases lightpath utilization. The utilization could reach 98% with SM packet loss probability of less than 10^{-6} [13].

For the pragmatic use of OpMiGua hybrid network, the demonstration and analysis of TV and data transport [10] indicates that with video streaming in the GST path, OpMiGua hybrid network supports broadcast quality video. Furthermore, the analysis of the network capability of high data traffic indicates that the packet switched SM Class of Service (CoS) is suitable for internet applications [10].

The company Transpacket (http://www.transpacket.com) has developed the OpMiGua fusion node product. A field trial connection has been set up for the performance test. The trial connection is illustrated in the figure below. It includes three fusion nodes from TransPacket, two FreeBSD servers with Iperf traffic generators and Spirent SPT-2000 packet generator/tester. Xe0 and xe1 are 10GE interfaces while ge0 to ge9 are GE interfaces.

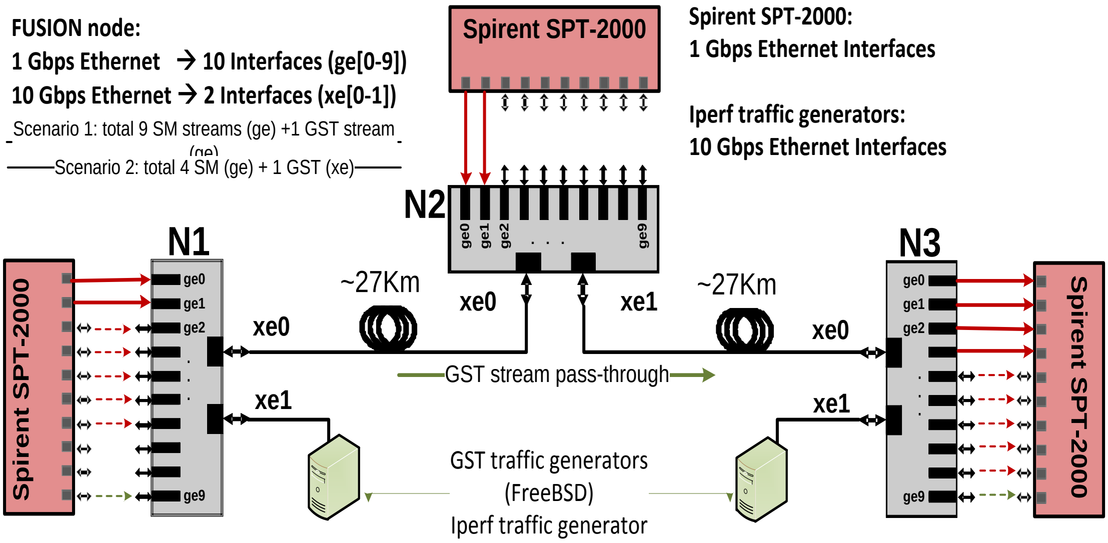


Figure 3.5: Field-trial setup in the carrier network of UNINETT [14]

The three nodes are setup in the carrier network of UNINETT. Fiber distance between each node is fixed. First field trial has been detailed described in [14], traffics are generated in N1, pass through N2 and received by N3. Two different scenarios are set up for different purposes. The first scenario aims to accurately measure the GST traffic performance, while the second scenario is to emulate the router offload and the effective increase in network throughput by adding/dropping SM traffic. The results of two scenarios are depicted in Figure 3.6 and Figure 3.7.

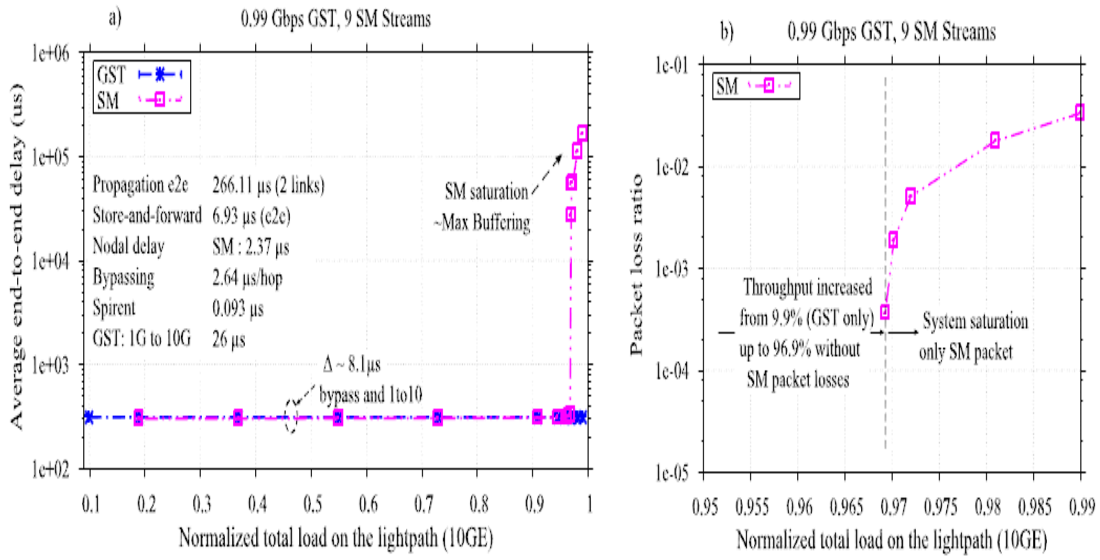


Figure 3.6: Simulation result of 0.99 Gbps GST, 9 SM Streams [14]

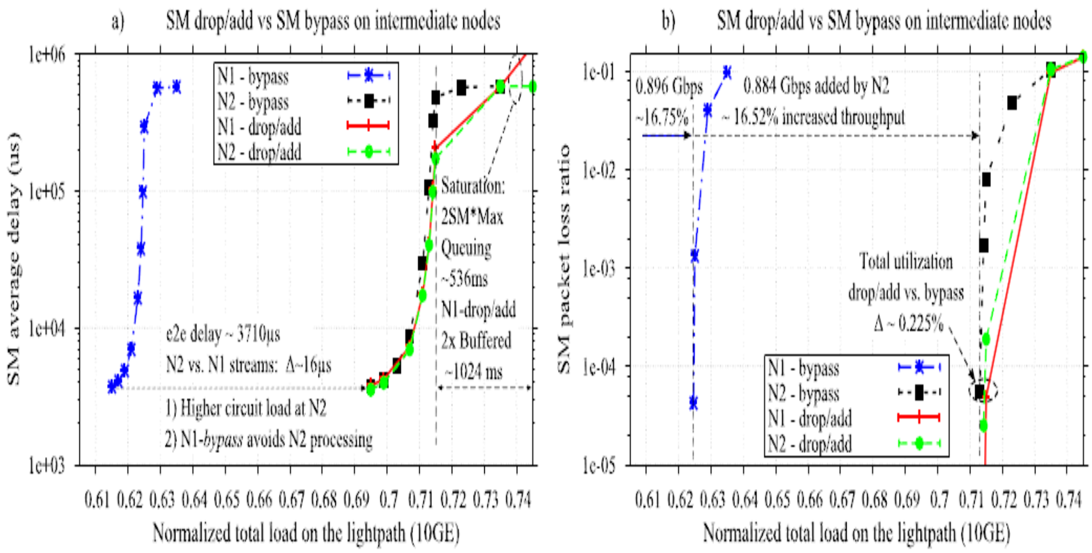


Figure 3.7: Simulation result of 5.35 Gbps GST, add/drop SM traffic [14]

Figure 3.6 is the result of first scenario, with average 0.99 Gbps GST from one GE interface and 9 SM traffic from the other 9 GE interface. The result indicates that with 10% circuit traffic, the maximum ligthpath utilization can reach 96.9% without any packet losses using SM. SM traffic does not experience delay until the congestion happens.

Figure 3.7 is the result of second scenario, with 53.5% load GST traffic generated by Iperf network generator on 10GE interface. Result indicates that with the increasing of circuit traffic, 53.5% in the scenario, the threshold of not causing SM packet loss decreased. However, additional SM traffic added in the nodes increases the lightpath load, and lightpath utilization is rising with an added number of nodes [14].

Chapter 4
QoS Requirement and improvement Methods

4.1 Introduction

The internet history has shown a trend of higher speed and wider range applications among heterogeneous users. For users, the most fundamental needs for service are performance related, i.e. delay, bandwidth, dependability and security. Since different applications have various requirements for the performances, QoS recommendations are proposed for differentiating the services.

In OpMiGua hybrid network, Traffics are generally classified into two types, GST and SM traffic. Thus, the QoS are generally differentiated into two options. GST offers a fully predictable transport with full transparency, including time transparency [25]. This enables transparent transport with a minimum of Packet Delay Variation (PDV) and low latency. GST transport can reach zero packet loss and network end-to-end delay less than 1us. However, the existing dimensioning rules in H1 node restrict the overall performance of the switch. When GST and SM traffic are aggregated, GST traffic aggregation follows the principle of aggregation in circuit switched systems and may never be oversubscribed. SM traffic aggregation on the other hand follows the principles know from packet switching with statistical multiplexing allowing efficient oversubscribed traffic aggregation.

An oversubscription of SM traffic may occur if SM traffic is aggregated from

GE interfaces on top of GST traffic bypassing between the 10GE interfaces. SM packets loss may occur if the traffic load is too heavy. A rule applied here is the larger the load-share of the GST traffic, the lower the total load. As a rule of thumb, if SM traffic shall be added to a 10GE interface, the total load of the GST traffic should not exceed 0.5. At a load of 0.5 an additional SM load of approximately 0.2 may be added without packet loss, giving a total load of 0.7 [25].

When a small amount of GST traffic is aggregated into a 10GE interface, a larger total load is allowed with aggregating additional SM traffic. The additional SM traffic may not suffer packet loss. The total load may reach 0.9 on the 10GE interface with proper percentage of GST and SM traffic. The high utilization of network resources comes with the price of low GST traffic, which means low QoS guaranteed traffic.

As described in the previous chapters, the SM packets share the wavelength resources on a packet-by-packet basis by inserting the packets into the variable time gaps between circuit-switched packers. Hence, the integrated approach results in resource utilization that is close to that of packet-switched systems [26]. Especially when the network system is in high utilization situation, most of the traffics are SM traffic, which is not QoS guaranteed.

In this chapter, the QoS requirements of different applications are analyzed based on the recommendation of International Telecommunication Union (ITU). The other QoS methods for improving OPS SM packets transmission are studied and compared with the current applied scheduling mechanisms in OpMiGua.

4.2 QoS Requirement

ITU has been working on a series of recommendations in internet protocol aspects. ITU Y.1541 Recommendation [27] is the one in quality of service and network performance. It defines classes of network QoS with objectives for Internet Protocol network performance parameters. The network QoS classes defined here are intended to be the basis of agreements between end-users and network service providers, and between service providers. The recommendation of QoS classes performance parameters are regarded as the threshold for testing a new technology or product. In a constantly changing network, the performance of the product should within the recommended range to deliver a satisfactory service. As a user, the quality of service is intuitively reflected on the performance of application, i.e. video definition, fluency, sound delay, music fluency.

QoS classes defined in ITU Y.1541 Recommendation [27] support an extremely wide range of applications, including the following: conversational telephony, multimedia conferencing, digital video, and interactive data transfer. Adding new classes or revise classes is possible for other applications. However, they should be balanced with the requirement of feasible implementation, and the number should be limited for implementations to global network scalability

Table 4-1 presents the bounds on the network performance between user network interfaces, which comes from the recommendation [27]. As long as the users a path is available, network providers should collaboratively support these bounds for the lifetime of the flow to provide a certain quality of the application services.

Table 4-1: IP network QoS classes definition and network performance objectives [27]

Network performance parameter	**Nature of network performance objects**	**QoS Class**					
		Class 0	**Class 1**	**Class 2**	**Class 3**	**Class 4**	**Class 5 Unspecified**
IPTD	Upper bound on the mean IPTD	100ms	400ms	100ms	400ms	1s	U
IPDV	Upper bound on the 1-10^-3 quantile of IPTD minus the minimum IPTD	50ms	50ms	U	U	U	U
IPLR	Upper bound on the packet loss probability	1*10^-3	1*10^-3	1*10^-3	1*10^-3	1*10^-3	U
IPER	Upper bound	1*10^-5					U

Table 4-2 is a summary that matches the real application of QoS classes. The actual network QoS offered to a given flow will depend on the distance and complexity of the path traversed. The pragmatic performance will often be better than the upper bound that recommended in the QoS classes definitions.

Table 4-2: QoS targets for reference service classes [7]

Service Class	Y.1541 QoS Class	Upper bound Packet Loss Rate	Upper bound Delay	Upper bound jitter	Bandwidth need
i.Video streaming	6 or 7	10^-5	100ms or 400ms	50ms	High
ii.Vido conversational	0 or 1	10^-3	100ms or 400ms	50ms	High
iii.Music streaming	6 or 7	10^-5	100ms or 400ms	50ms	Low to medium
iv.Voice conversational	0 or 1	10^-3	100ms or 400ms	50ms	Low
v.Interative messaging	3 (or2)	10^-3	400ms or 100ms	Undef.	Low
vi.Control traffic	2	10^-3	100ms	Undef.	Low
vii.General data transfer	4 or 5	10^-3 or undef.	1s or undef.	Undef.	Low to high

The basic QoS classes are listed in Table 4-2. Additional services may be needed with combination of these classes. OpMiGua architecture considers two types of transport services, carried by the same set of shared optical wavelengths. In order to improve the utilization, most of the service classes will be transported by SM service. Method to ensure the transmission of SM packets is crucial to the overall performance.

4.3 QoS Improvement Methods

As described above, when OpMiGua switch is in high utilization, most of the traffics are SM packets. It means that most of the traffics are transported by OPS. In an OPS network, contention occurs at a switching node whenever two or more packets try to leave the switch fabric on the same output port, on the same wavelength, at the same time [28]. The contentions block the packet transportation that induces the loss and queuing delay of SM packets. There are many researches in contention resolution in OPS network. A unified study of contention-resolution schemes [28] brings us the current most commonly used technologies to mitigate the contention in OPS network. Redundancy Schemes [26] are also proposed as an alternatives to the commonly used schemes [28].

4.3.1 Contention-Resolution in OPS network

Contention-resolution schemes have different effects in slotted and unslotted networks. OpMiGua is an unslotted network which utilizes packets of variable lengths. It requires no synchronization of packets at the input of the switching fabric. Since the integration results in utilization in OpMiGua is close to packet-switched system, the schemes used purely OPS network may also be utilized in OpMiGua network. Three schemes are analyzed and compared by Shun, Y., *et al.*, [28]: Optical Buffering, Wavelength Conversion and Space Deflection.

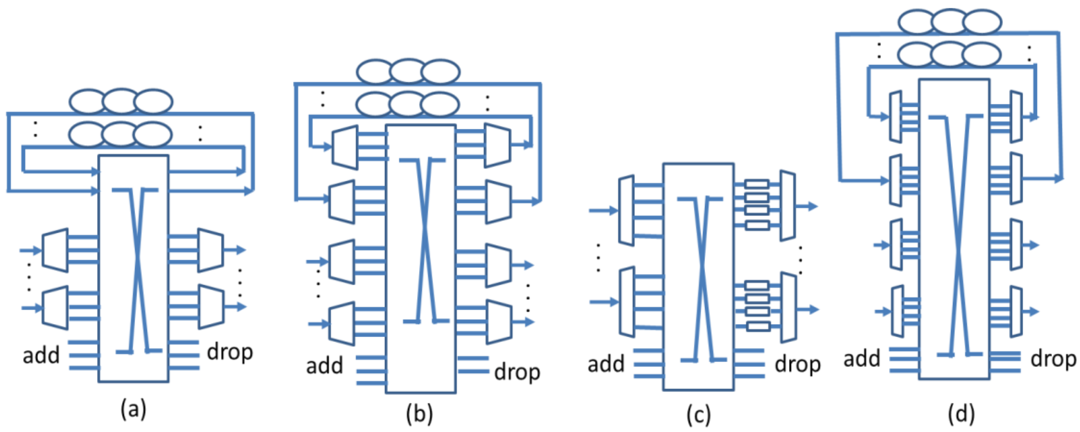


Figure 4.1: Node architecture for contention-resolution [28]

Figure 4.1 lists four node architectures for contention-resolution: (a) Optical buffering, (b) Wavelength conversion, (c) Space deflection, (d) Combinational scheme

Optical Buffering:

Optical buffering utilizes one or more optical fiber delay lines, which loops the signal form the output back to the input of switch. The contention packet enters the fiber delay line at the output and travel through the entire delay line. The packets reenter the switch fabric, mitigate the time domain contention. The length of delay line is generally designed according to the largest packet.

Wavelength Conversion:

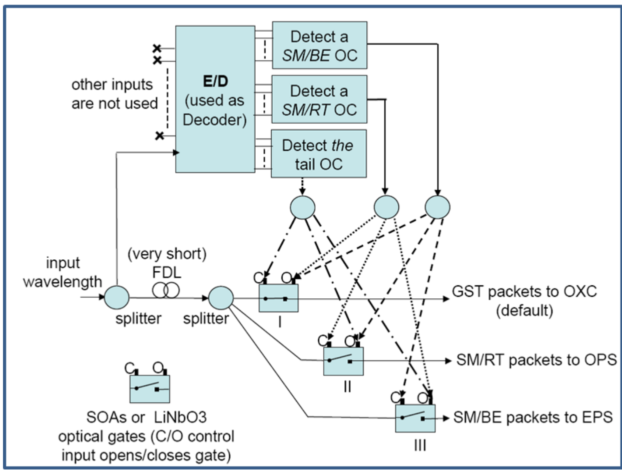
In wavelength conversion, signals come from input side of each wavelength are de-multiplexed first and sent into the switch. The switch is capable of recognizing the contention and assigning a converter to the signal which leads the signal to the desired output fiber. The wavelength converters are able to convert any incoming or several pre-determined wavelength to a fixed wavelength.

Space Deflection:

Space deflection relies on the neighboring node to route the packets when contention occurs. The space deflection comes with the price of switching capacity of another node and the network capacity. Adoption of any node architecture between optical Buffering and wavelength conversion is possible. Comparing with the first two methods, space deflection always has the lowest priority to be utilized.

4.3.2 3-Level Integrated Hybrid Optical Network

3-Level Integrated Hybrid Optical Network (3LIHON) is an evolved version of OpMiGua. In 3LIHON, the two level OpMiGua network are further divided into three levels (Figure 4.2). The new architecture aims giving at least three advantages: (i) better QoS for short packets with high real-time demands; (ii) better bandwidth resource utilization; (iii) cheaper overall switch architecture [7].



OpMiGua			3LIHON		
1	GST		GST		1
2	SM		SM	RT	2
				BE	3

(a) (b)

Figure 4.2: Architecture of 3LIHON. (a) detect packet type (DPT) subsystem implemented using OC detection [7], (b) OpMiGua and 3LIHON traffic class

Two traffic types in OpMiGua are extended in to three. In this way, QoS differentiation are further refined compared with OpMiGua.

●**Guaranteed Service Type (GST):**

Never allow any information loss inside the network, has the highest priority, inherit the property of GST in OpMiGua network.

●**Statistically Multiplexed Real Time (SM/RT):**

Resembling a packet switched service with contention for bandwidth and possible packet loss inside the nodes. It ensures no delay (or very limited delay) inside de nodes. It represents the higher requirement traffic types in OpMiGua SM traffic. However, here SM/RT traffics are given higher priority instead of equal priority in OpMiGua.

●**Statistically Multiplexed best effort (SM/BE):**

Resembling a packet switched service with very small overall packet loss but no guaranteed delay inside the nodes. It represents the lower requirement traffic types in OpMiGua SM traffic. However, here SM/BE traffics are given Lowest priority in 3LIHON.

The simulation [7] shows that when the total traffic load is less than 0.7, the higher the GST load, the lower the packet loss probability (PLP). The future traffic profile is expected to have 70%-80% video traffic, which can be transported as GST traffic. So the total GST traffic occupies approximate 50% of the total traffic load, and can be improved to 70% total traffic load with adding extra SM/RT traffic. This result is in accordance with the performance described in the H1 technical guide [25].

4.4 QoS Method in OpMiGua

In OpMiGua Hybrid Network, multiple schemes varies from physical design to algorithms are applied to ensure the QoS and improve the utilization. Electronic buffers are introduced in the original design of the OpMiGua node, for the use of storing and scheduling the SM packets. Many reservation techniques are studied, in order to match the SM packets to proper gaps and hence improve the link utilization. Some other schemes, i.e. Packet segmentation algorithm, redundancy schemes are proposed to improve the OpMiGua performance.

4.4.1 Electronic Buffer

For the efficient utilization of buffer, the idea of sharing buffering for SM packets is used in OpMiGua network. Sharing the buffer limit the size of switching matrix as well as the number of buffer interfaces. For electronic buffering, reducing the number of interfaces also helps reduce the number of optical to electronic (OE) and electronic to optical (EO) interfaces. The electronic buffer stores SM packets and re-insert those packets in to the gaps. Both of simple storage/insert and complex QoS management can be realized because of the electronic buffer utilization.

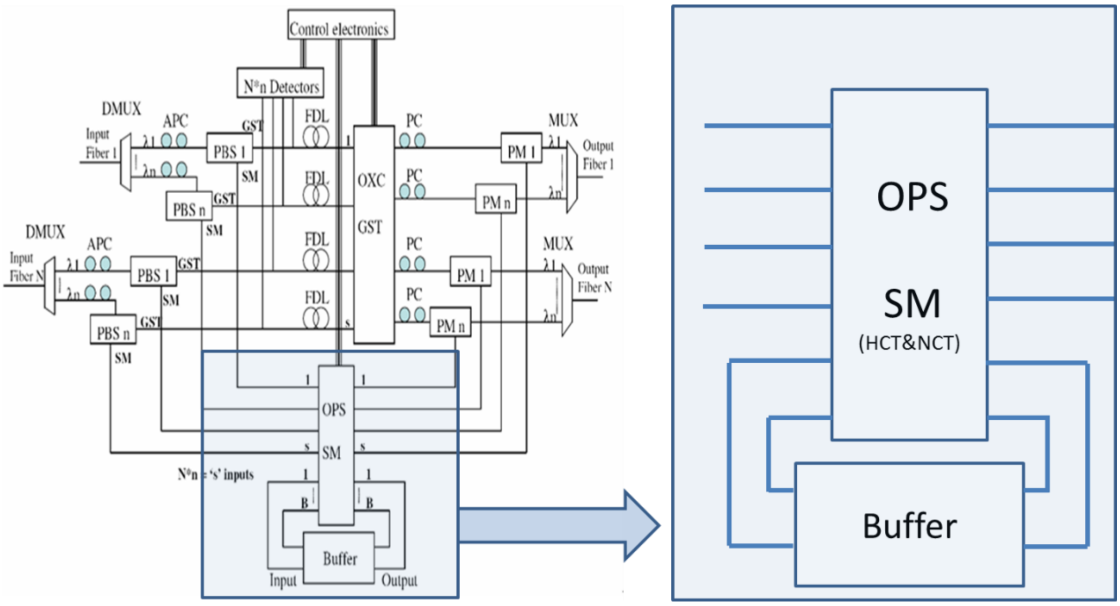


Figure 4.3: Electronic buffer in OpMiGua node

Without QoS differentiation among SM traffic, storing packets into the buffer follows the rule of FIFO. However, electronic buffer enables the use of the round robin gap-filling scheduler [22]. Round robin increases the probability of finding the proper SM packet to be scheduled into the gaps. Increasing the queue number also help increase the gap-filling probability.

QoS class differentiation of SM packets is proposed by Bjornstad, S. *et al*.[8]. SM packets are classified into high-class transport (HCT) with low PLR (10^-6) and normal class transport (NCT) with moderate PLR (10^-3). Delay and delay variance of HCT are minimized. The idea of differentiate QoS classes into HCT and NCT is similar to 3LIHON. 3LIHON realize the classification in a physical way, node architecture was changed. The differentiation in the electronic buffer realized the classification by algorithm.

4.4.2 Reservation Techniques

Kimsas A. *et al*. [12] specifically discusses about the reservation techniques used in OpMiGua node: Time Window Techniques and Preemptive Techniques. Each of these two methods has own advantages with respect to network layer efficiency and implementation.

Time Window Techniques:

Time-window technique is used to predict and avoid simultaneous transmission of GST and SM packets on the same wavelength and is a proactive scheme. Simple Time-Window (STW) and Length Aware Time-Window (LATW) are two techniques. STW does not consider the length of SM or GST packets when scheduling the SM packets. STW set up a time window, which is the length of the longest SM packet. Gaps cannot be utilized if GST packet is detected in the time window range, even if the gap is enough to schedule a SM packet. This has been named as reservation induced blocking (RIB) [8]. LATW is suggested to reduce the RIB. The time to GST arrival is continuously updated so that the scheduler is able to search the proper SM packet to be scheduled into gaps.

FDL is the key element introduced to fulfill a better performance of LATW scheme. The length of FDL equals the length of longest SM packet. GST packets pass through FDL with a constant time. In OpMiGua, the FDL delays GST packets for approximate 12 us. This time is utilized by the control logic to update and schedule the proper SM packets. Electronic buffer further decreases the PLP by buffering the unscheduled SM packets [22].

Preemptive Techniques:

Preemptive technique avoids simultaneous transmission by interrupting SM transmission after a conflict is detected and is a reactive approach. Preemptive technique does not rely on a time-window, but always attempts to transmit SM packet if the shared wavelength is currently available. The transmission of SM packet will be immediately terminated when GST packets are sensed on the input. Hence, preemptive technique introduces preemption induced blocking (PIB), though not suffering from RIB.

The combined (COMB) scheme uses elements from the STW and PRE techniques. It uses two time windows. One is the same length as Δ in STW, and the other one ∂, which is smaller than Δ. The SM packet will be transmitted when the wavelength is available and no GST packet is sensed in the smaller time window. This scheme shrinks the range of collision SM packet from $[0, \Delta]$ to $[\partial, \Delta]$. The SM packet which is shorter than ∂ will not meet collision.

4.4.3 Other Proposed Methods

Other than the schemes from the physical perspective, algorithm may also be applied to improve performance. Two ideas are proposed for improving performance in OpMiGua hybrid network: (a) redundancy scheme [26], and (b) rate-adaptive segmentation [23].

Redundancy scheme is a novel bufferless network approach where the performance of the SM class is satisfied by applying packet-level forward error correction (FEC) [26]. It introduces two implementation strategies: RedSM transmitting redundancy packets as SM traffic and RedGST transmitting redundancy packets as low-priority GST traffic. The study digs into the data packet loss ratio (DPLR) with respect to the redundancy ratio, as well as the other elements. The study shows that in moderate load and high multiplexing gain, redundancy scheme is attractive alternative to networking approaches employing buffers.

Rate-adaptive segmentation is one of the newest proposals for the OpMiGua network [23]. In previous architecture and ideas, the length does not change for a single packet. Since there existing small gaps and gaps that cannot fit the head SM packets in the buffer, segmenting packets to fit those gaps improve the bandwidth utilization. The scheme avoids unnecessary segmentation because of variable segment size and adapts to the average length of available bandwidth gaps. Simulation result [23] shows the scheme has a very attractive performance in improving bandwidth utilization.

Chapter 5
Experiment Setup

5.1 Introduction

The experiment purpose is to test the performance of FUSION ETHERNET H1 node. As described in Chapter 4, internet applications have QoS requirements to deliver services. Experiment of this project focuses on three performance aspects: latency, packet loss, packet delay variance. Many tests have been done by TransPacket and NTNU [10] [11] [12] [13]. The experiment is a further discovery of H1 node performance and try to locate H1 node into practical internet environment with real data collected from industry [29] [30]. Hence, the experiment result is closer to reality and provides more pragmatic solution for further improvement.

5.2 Equipment Materials

Two H1 nodes were utilized in this experiment. H1 nodes and Spirent TestCenter locate in UNINETT lab. The physical connections among H1 nodes and Spirent TestCenter are realized with the cooperation from UNINETT Technicians. Experiments were conducted remotely in NTNU campus with the help of Putty and Remote Desktop Connection. Figure 5.1 is the physical connection of experiment equipment.

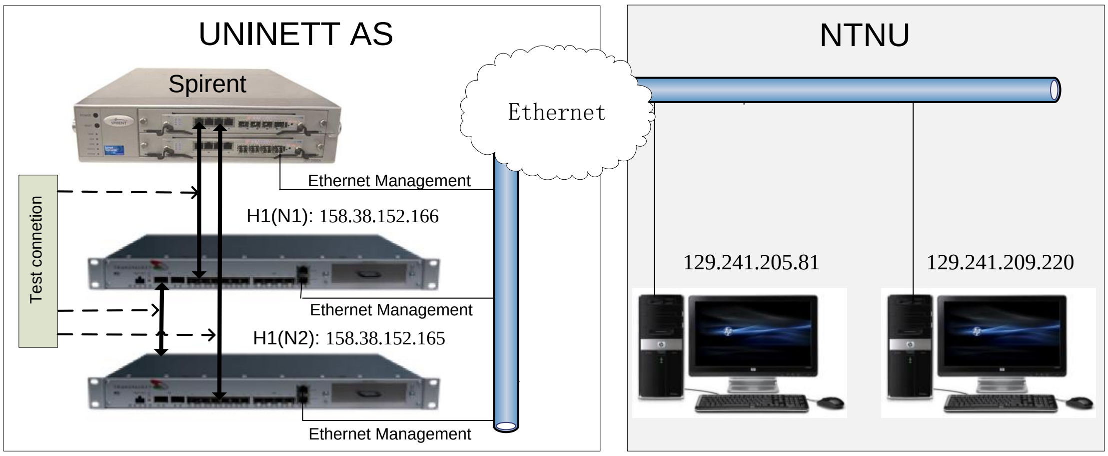


Figure 5.1 Experiment connection

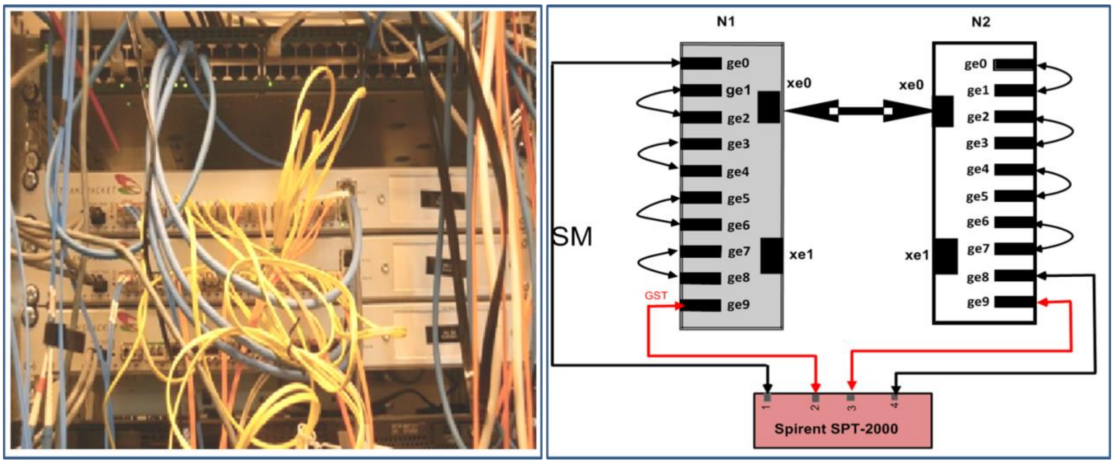
Two computers with constant IP addresses are able to connect to the H1 nodes through Ethernet. Each H1 node has Ethernet management port for node configuration. Putty is used to remotely configure H1 node following the H1 quick start guide [31]. With the assigned username and password, access to Spirent TestCenter is allowed by Remote Desktop Connection. Among the Spirent ports, port1- 4 are reserved for the experiment.

Details of equipment and quantities are listed in the Table 5-1.

Table 5-1: Equipment used in experiment

Equipment	Number	Note
PC	2	IP address for PCs to log on the H1 node PC1: 129.241.209.220 PC2: 129.241.205.81
TransPacket FUSION ETHERNET H1	2	Located in UNINETT AS Trondheim, With two Ethernet management ports for this experiment H1(N1): 158.38.152.166 H1(N2): 158.38.152.165
Spirent TestCenter	1	Located in UNINETT AS Trondheim, With two accounts to log on Spirent TestCenter remotely
Other auxiliary equipment	TransPacket XFP module TransPacket SFP module Cables	
Software	Putty: H1 control and configuration Remote Desktop Connection: Spirent TestCenter remote operation	

With the equipment, details of ports connection and node configuration are illustrated in Figure 5.2.



(a) (b)

Figure 5.2: Physical and logical connection (a) Physical connection of H1 nodes in UNINETT, (b) logical connection of H1 nodes and Spirent TestCenter

Figure 5.2 (a) is a photo taken from UNINETT lab. There are three H1 nodes in the figure, but just two (except the lowest one) of them were used in this study. Figure 5.2 (b) explains the physical connection of H1 nodes and Spirent TestCenter. 10GE interfaces xe0 of N1 and N2 were connected and serve as trunk interfaces. N1 ge0 and N2 ge8 were connected to Spirent port 1 and 4 respectively as SM access interface. N1 ge9 and N2 ge9 were connected to Spirent port 2 and 3 respectively as GST access interface. Since there was only one port of each node could be used as GST interface and ge9 had been configured as GST interface, interface xe1 of both nodes were not utilized. The rest GE interfaces of N1 and N2 were neighbor-connected as shown in the figure.

According to physical connection and experiment requirement, 10 VLANs were configured in both of the H1 nodes for traffic transmission. An access interface could be member of a single VLAN. A trunk interface could be member of one or more VLAN's. Here, GE interfaces ge0-9 were located in 10 VLANs as access interfaces. 10GE interface xe0 were shared by 10 VLANs as trunk interface. The configurations in two H1 nodes were exactly the same so that the connection could be set up and traffics would be forwarded to the right interface. The detail configurations of H1 nodes are attached in Appendix A-H1 node configuration.

VLAN setting is detailed described in Table 5-2 as well.

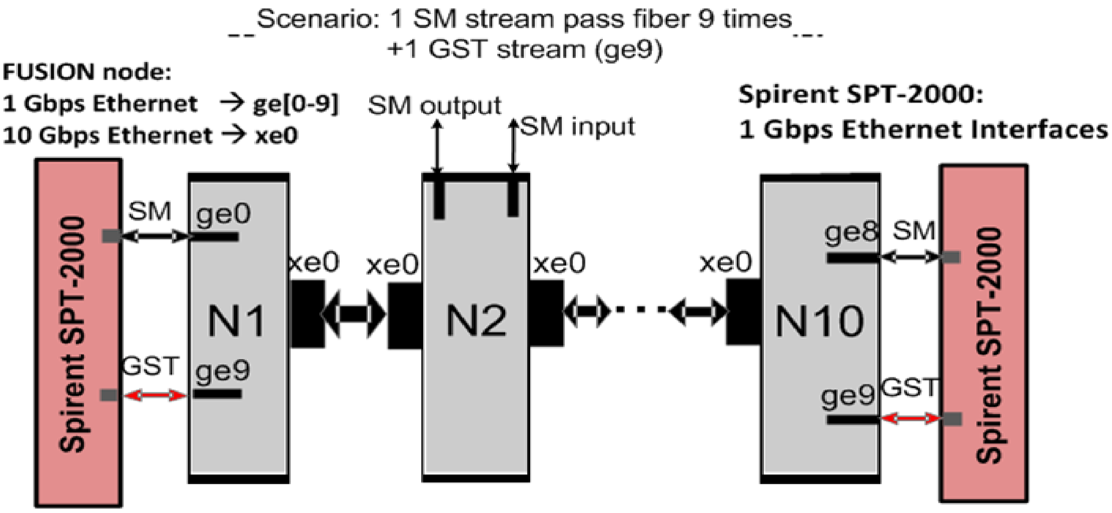
Table 5-2: VLANs connection setup

Category	***VLAN category***	***Interfaces***	***Note***
VLANs	SM vlans	N1:ge0-ge8,xe0 N2:ge0-ge8,xe0 ge0-8: as access interface for SM xe0: as trunk interface	Vlan0: Tag:100 xe0, trunk ge0, access, sm ⋮ Vlan8: Tag:108 xe0, trunk ge8, access, sm
	GST vlans	N1:ge9,xe0 N2:ge9,xe0 ge9: as access interface for GST xe0: as trunk interface	Vlan9: Tag:109 xe0, trunk ge9, access, gst
Connections	Spirent 1,2,3,4 (two devices are assigned to each port)	Connection1: SM: Spirent port1/device 1→Spirent port4/device 1 GST: Spirent port2/device 1→Spirent port3/device 1 Connection 2: SM: Spirent port4/device 2→Spirent port1/device 2 GST: Spirent port3/device 2→Spirent port2/device 2	

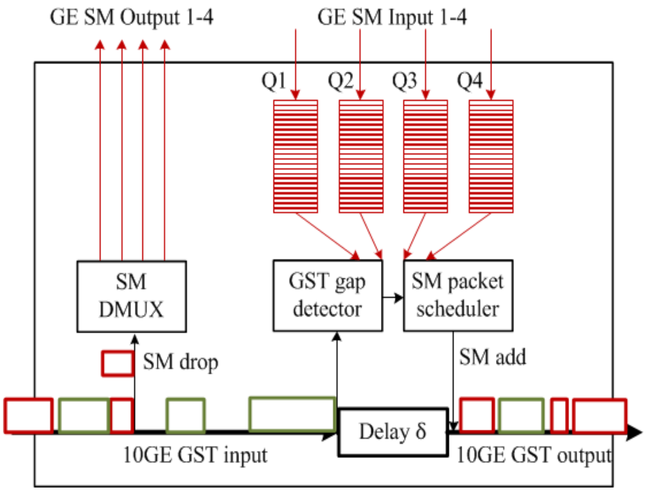
5.3 Experiment Scenario

The experiment was conducted based on the physical connection in Figure 5.2 and configuration in Table 5-2.

In order to accurately measure the GST traffic performance, the GST traffic was added at N1 interface ge9 and received on N3 ge9. The packet length was uniformly distributed between 64 and 1518 bytes. The average GST load on the GE interface L_{GE}^{GST} was set to 0.95 by fixing the inter-packet length. The GST performance was measured for different network loads by changing the load L_{GE}^{SM} of one added SM stream up until network congestion. The one added SM stream passed through the fiber line 9 times, which was equivalent to add 9 streams. The measurements were conducted up to a total load L^{T}_{10GE} = 0.99 on the 10 Gbps Ethernet (10GE) lightpath.



(a)



(b)

Figure 5.3: Sketch of physical connections and packet processing. (a) equivalent physical connection with current set up, (b) packet processing detail of node from N2 to N9 [14]

Currently, two H1 nodes were used in the experiment. However, the physical connection set up was equivalent to that shown in Figure 5.3 (a). In each middle node from N2 to N9, SM packets were extracted and re-added in to the gaps between GST packets. The detail process of each node from N2 to N9 is indicated in Figure 5.3 (b). The extraction and re-insertion brought processing delay of SM packets in each node. The packet delay parameters monitored by Spirent was useful to acquire the SM packet mean processing time (SMPMPT) in each node. Meanwhile, when traffic load reached a certain high lever, packet loss might occur due to blocking.

The experiment setup parameters are listed in Table 5-3.

Table 5-3: Experiment parameter list

Component/Quantity	***Parameter***	***Value***	***Unit***
Normalized system load	A	0.18≤A≤0.99	Erlang
GST share of system load	S	9.6≤S≤51	[%]
SM/GST packet legnth	δ	[64-1518]	[Bytes]
Experiment legth per load	t	5000	Second

The Table 5-4 illustrates the experiments with respect to traffic load and load sharing. The design of experiment realized the system load coverage from 0.185 to 0.9905.

Table 5-4: list of experiment and load sharing

Experiment Number	SM rate (Gbps)	GST rate (Gbps)	Normalized system load (Erlang)	GST relative load (%)	SM relative load (%)
1	0.100	0.95	0.1850	51.35	48.65
2	0.200		0.2750	34.55	65.45
3	0.300		0.3650	26.03	73.97
4	0.400		0.4550	20.88	79.12
5	0.500		0.5450	17.43	82.57
6	0.600		0.6350	14.96	85.04
7	0.700		0.7250	13.10	86.90
8	0.800		0.8150	11.66	88.34
9	0.900		0.9050	10.50	89.50
10	0.950		0.9500	10.00	90.00
11	0.960		0.9590	9.91	90.09
12	0.970		0.9680	9.81	90.19
13	0.972		0.9698	9.80	90.20
14	0.975		0.9725	9.77	90.23
15	0.978		0.9752	9.74	90.26
16	0.980		0.9770	9.72	90.28
17	0.985		0.9815	9.68	90.32
18	0.990		0.9860	9.63	90.37
19	0.995		0.9905	9.59	90.41

The data collected from Spirent TestCenter will be further used to analyze the system performance corresponding to latency, packet loss rate, packet delay variation in Chapter 6.

Chapter 6
Result Presentation and Analysis

In this chapter, the experiment results are illustrated and analyzed. Meanwhile, the results are compared with the QoS parameters from chapter 4. ITU recommendation lists service classes QoS from different perspectives: PTD, PLR and PDV. With analysis of each aspect, mathematical model is derived for each performance aspect. Meanwhile, a trial of finding which parameter restricts the overall performance is conducted.

6.1 Result Presentation and Analysis

In this part, the experiment results are presented from three aspects as we expected: 1) Packet Transfer Delay, 2) Packet Loss Rate, and 3) Packet Delay Variation. Based on the observation, mathematical models are found out for each parameter. A system model is useful to evaluate the system performance before deployment, so that a comprehensive design can be deployed to provide a better service.

6.1.1 Packet Transfer Delay

In this experiment scenario, end-to-end delay results were acquired from Spirent TestCenter. Based on the results, each component of delay parameters was analyzed, e.g. processing delay, buffering time. The exploration of these parameters helped us deeply to discover H1 node performance and find out potential improvement solutions.

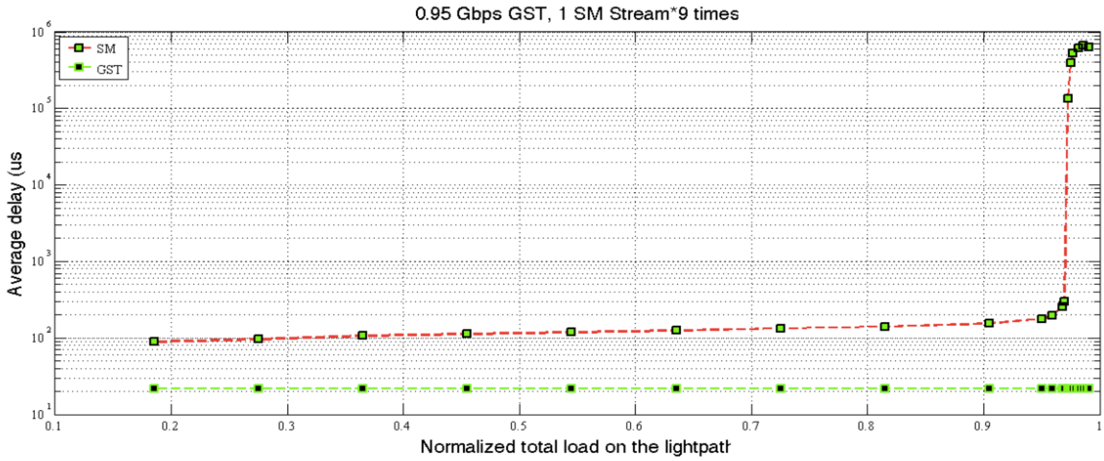


Figure 6.1: Average delay of SM and GST packet

Figure 6.1 illustrates the average latency result for the experiment scenario. From the figure, we observed that average SM packet latency kept the 10^2 us level until the normalized total load reached 0.97. The data collected from Spirent indicated that 0.97 was the threshold for average latency. After that, it increased sharply to an intolerable level. However, average delay of GST traffic kept the same level during the whole experiments. It proved that GST traffic was not influenced by the total load on the lightpath. The observed results match with the design principle that GST traffic is given the absolutely priority in network.

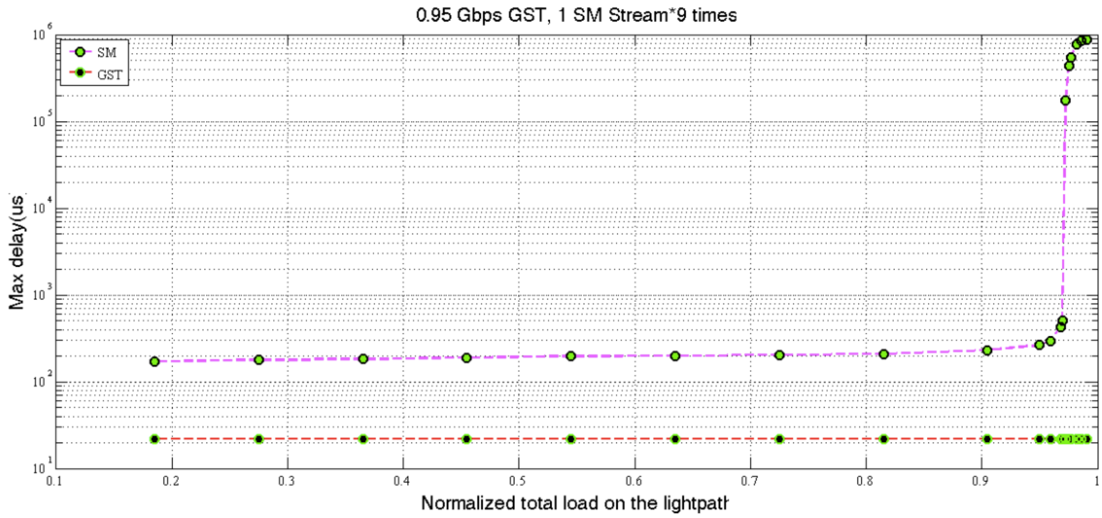


Figure 6.2: Maximum delay of SM and GST packet

Figure 6.2 is the plot of maximum SM packet delay with the same trend shown in Figure 6.1. The maximum SM packet delay indicates the peak of packet delay. The peak delay data is useful for time critical applications which tend to use SM traffic as the traffic type. A lightpath load threshold may be found out from Figure 6.2. Keeping the lightpath load below threshold can ensure the quality of such applications.

The node processing delay of the SM packets added on one GE interface, passed through 10GE light path and dropped at the other end's GE interface was measured to a reference value of 2.37 us [14]. From Figure 5.3 in Chapter 5, it is shown that SM packets are added in N1 and dropped in N10, the total number of processing time (add+drop) is 9. Hence, total processing delay is 2.37*9 = 21.33 us. Delay cause by Spirent is 0.093*2 = 0.186 us [14]. Since the packets didn't pass through fiber line, the propagation delay was zero in the experiment. The rest time was the delay in the buffers of 9 intermediate nodes. For each node, the buffer delay according to normalized traffic is illustrated in Figure 6.3.

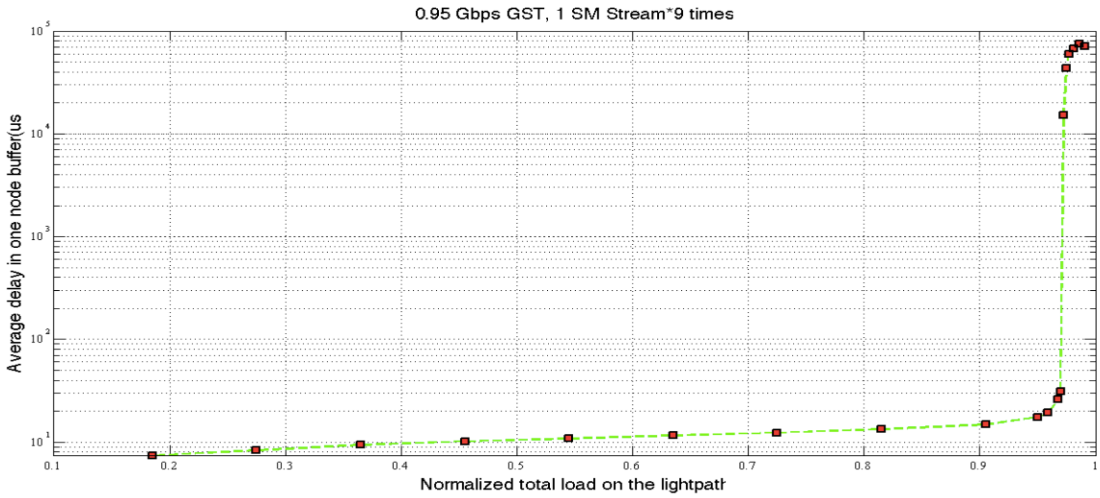


Figure 6.3: Average delay of SM packet in each node buffer

Figure 6.4 is a nonlinear regression model for the node buffering time. For the accuracy, regression model was separated into three parts according to load interval: [0,0.9], [0.9,0.97] and [0.97,1). For each interval, a most suitable regression model was discovered to match with the experiment result.

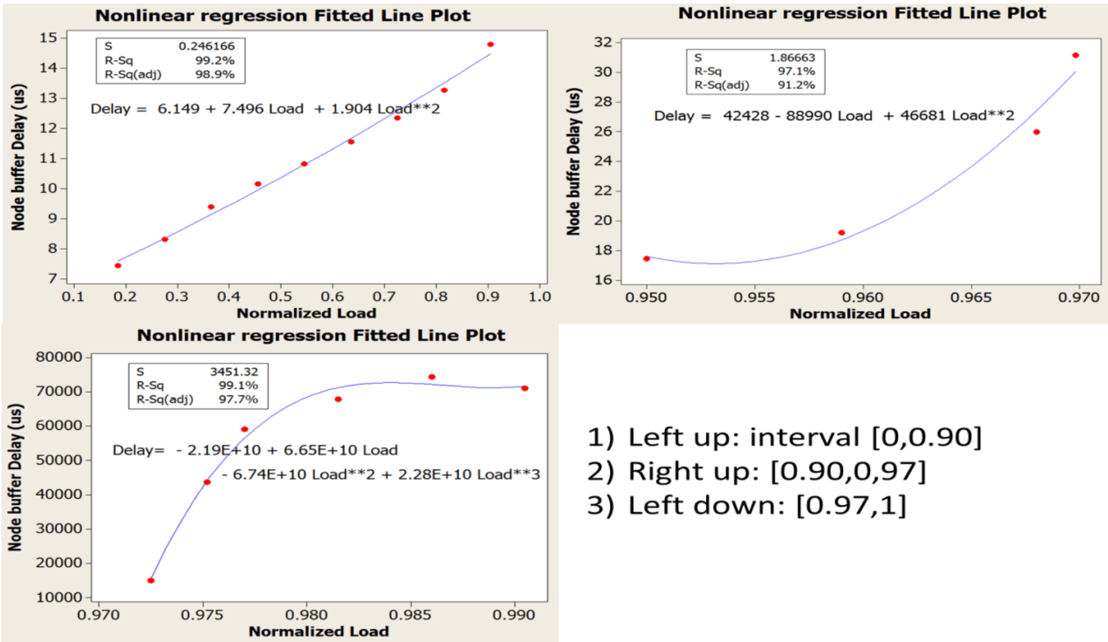


Figure 6.4: Nonlinear regression plot of Node buffer delay

Here the end equipment was neglect. Delay was mainly composed by three components shown in Table 6-1.

Table 6-1: Delay analysis

Delay type	Time(us)	Parameters
Processing delay/node	2.37	
Buffering delay/node	Delay(A) $= \begin{cases} 6.149 + 7.496 * A + 1.904 * A^2, \\ 0 < A < 0.9 \\ 42428 - 88990 * A + 46681 * A^2, \\ 0.9 < A < 0.97 \\ (-2.19E+10) + (6.65E+10) * A - \\ (6.74E+10) * A^2 + (2.28E+10) * A^3 \\ 0.97 < A < 1 \end{cases}$	A: Normalized system load
Propagation delay	Dist/[(C/η)]	Dist: Distance C: Speed of light (299.792 m/us) η: Refractive Index

Excluding end user equipment, the total delay of packet in the path can be estimated with the function below:

$$Delay_{total} = N * Delay_{process} + N * Delay_{buffer} + Delay_{propagation}$$

With this equation, an approximation of packet latency can be estimated in this deployment scenario. The estimation is quite important before physical equipment deployment. Knowing the system requirement and product performance helps better design the network.

6.1.2 Packet Loss Ratio

Packet loss appears when one or more data packets travelling across network fail to reach their destination. In H1 node, as analyzed in chapter 4, blocking is the main reason that cause packet loss. Different applications have different tolerability of PLR.

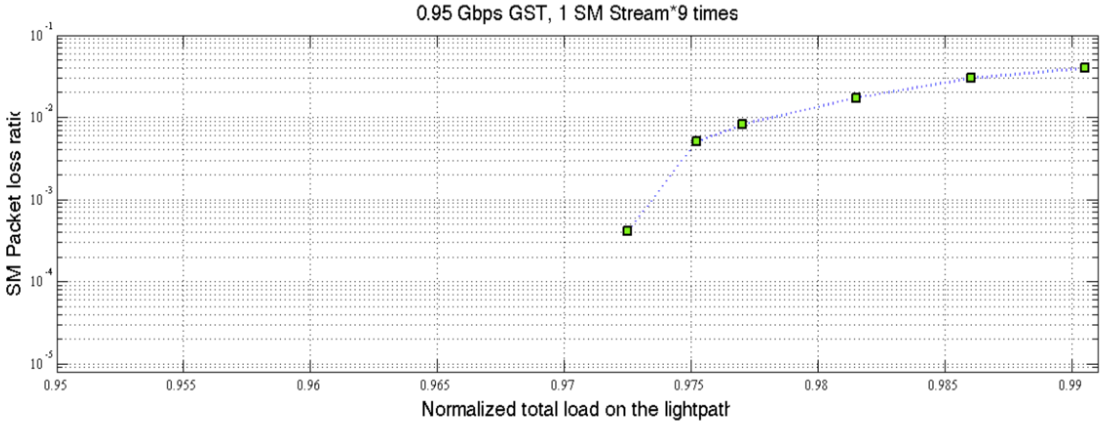


Figure 6.5: Average SM packet loss ratio

Figure 6.5 illustrates one of the most important factors in the experiment. In H1 node, GST packets pass through FDL, which give time to controller to calculate the gap length between GST packets. SM packet will be scheduled only if the gap is long enough to transmit the whole packet. Therefore, H1 node avoid losing packet because of Contention induced Blocking (CIB). Reservation induced Blocking (RIB) and Head-of-line blocking (HoL) are the two reasons cause packet loss in H1 node. In the experiment, the packet loss was observed after normalizing load 0.97. As known, 0.97 is the threshold of SM packets delay. The correlation between the two thresholds indicates that the long delay causes buffer overflow.

Based on the experiment, no packet loss was observed within load interval [0,0.97]. Meanwhile, a single model is found to match the loss ratio within load interval [0.97,1). Therefore, the PLR regression model was separated into two intervals: [0,0.97] and [0.97,1). The regression of interval [0.97,1) is indicated in Figure 6.6.

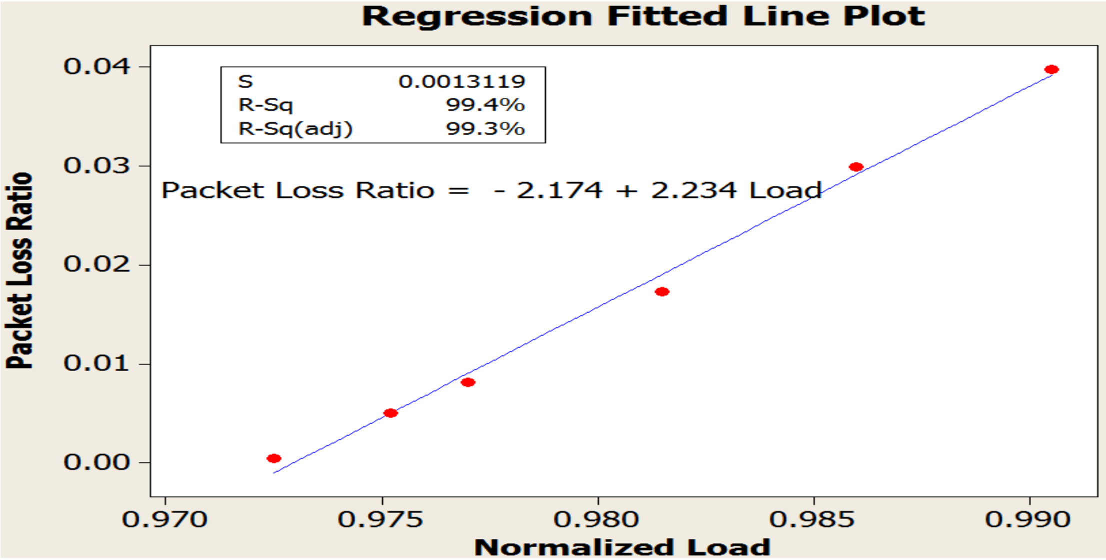


Figure 6.6: Nonlinear regression plot of PLR

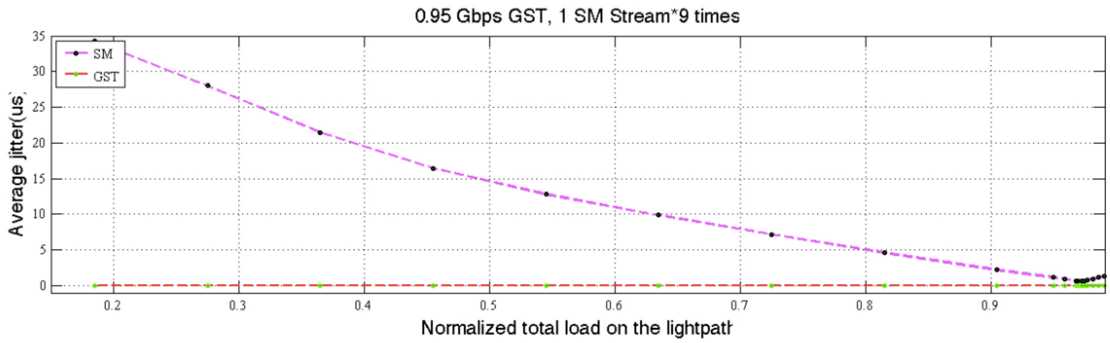
From the above analysis, we have the equation of PLR as below:

$$PLR_{avg} = \begin{cases} 0, & 0 < A < 0.97 \\ -2.174 + 2.234 * A, & 0.97 < A < 1 \end{cases}$$

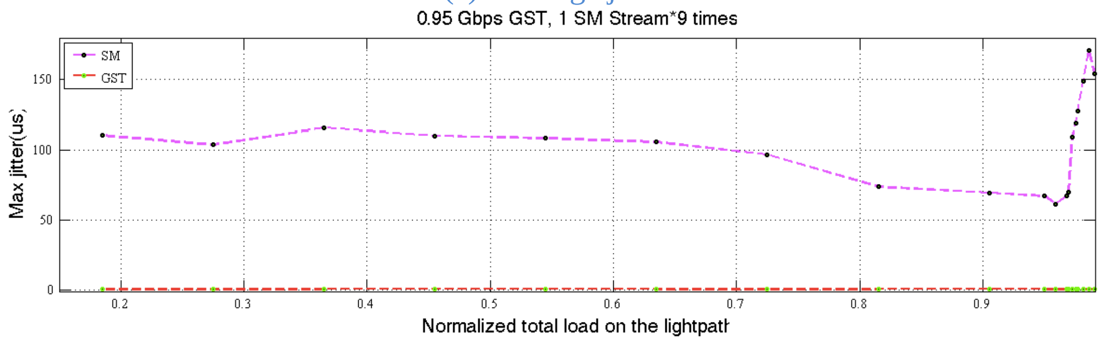
As mentioned in part 6.1.1, system load in 0.97 is a threshold for ensuring the quality of service. Therefore, in most occasions, only the first case, which is PLR = 0, may be considered.

6.1.3 Packet Delay Variation

PDV is the difference in end-to-end one-way delay between selected packets in a flow with any lost packets being ignored [32]. The performance of PDV represents system's capability of delivering service with stability and continuity. PDV influents service quality and PDV tolerability depends on the application. In H1 node, because of service classification, both of traffic load and SM traffic scheduling algorithm may influent PDV of SM packet. Average PDV and maximum PDV results were acquired from experiments for analysis, both of SM and GST traffic.



(a) Average jitter



(b) Maximum jitter

Figure 6.7: Plot of average and maximum jitter. (a) SM and GST packet average jitter, (b) SM and GST packet maximum jitter

Figure 6.7 (a) and (b) are the results of average PDV and maximum PDV respectively from the experiment. For GST traffic, PDV kept constant at a very low level regardless of normalized system load. Average PDV and Maximum PDV of SM traffic kept a decreasing trend until the threshold load 0.97. An obvious change occurred at system load 0.97, where both average and maximum PDV began to increase sharply.

In the design of end equipment, jitter buffer was introduced to reduce or eliminate delay jitter. Here in the experiment scenario, jitter decreased while traffic load increased. Each H1 node had an electronic buffer. When traffic load was small, the queue length in the buffer was short and SM packets passed through H1 node without long delay. Therefore, the delay jitter could not be mitigated by the electronic buffer. When load increased, packets stayed in the buffer for a longer time, and buffer's function as jitter mitigator was well utilized.

To find out the relation between jitter and buffer utilization, a mathematical model was derived. Buffer utilization is behaved as the average packet delay in each

H1 node. The longer of average packet delay in H1 node means the higher of buffer utilization.

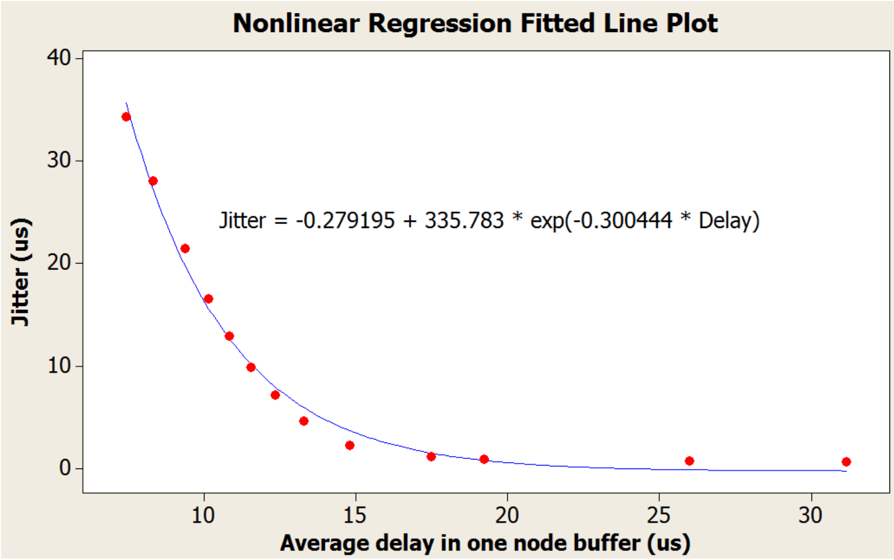


Figure 6.8: Jitter plot with respect to buffer utilization

As depicted in Figure 6.8, jitter is negative exponentially distributed with respect to average delay in node buffer. The model has proved the analysis above. Before node buffer overflows, it helps mitigate delay jitter.

Figure 6.9 is a regression model of SM packet average PDV. The regression model is separated into two parts based on system load interval: [0,0.97] and [0.97,1).

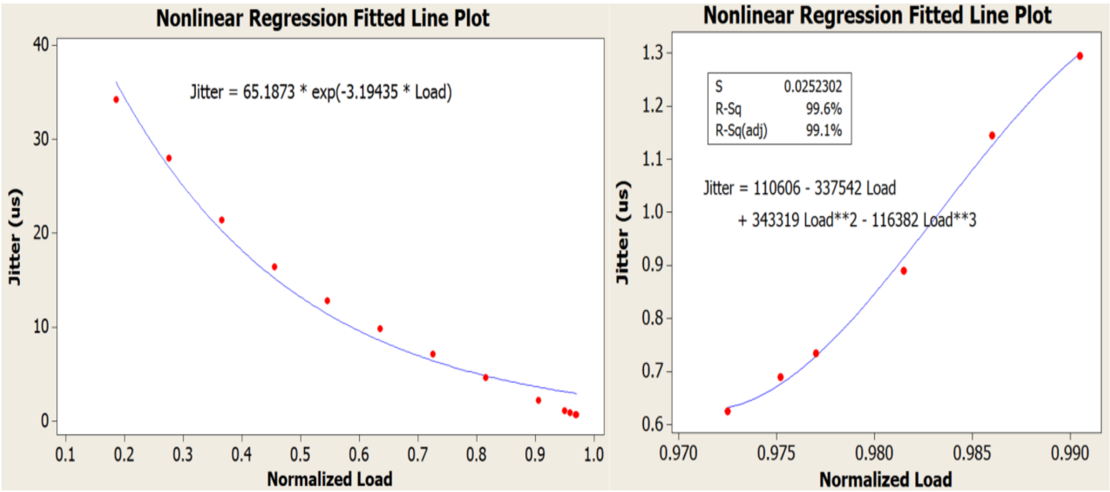


Figure 6.9: Nonlinear regression plot of PDV

From the regression above, an average PDV equation was acquired as below:

$$PDV_{avg} = \begin{cases} 65.1873 * \exp(-3.19435 * A), & 0 < A < 0.97 \\ 110606 - 337542 * A + 343319 * A^2 - 116382 * A^3, & 0.97 < A < 1 \end{cases}$$

With this equation, approximate PDV can be measured without experiment.

6.2 QoS Comparison with Result

In chapter 4, the QoS requirement of different service classes are described. The overall requirements are listed in Table 4-1 and Table 4-2. The requirements are mainly focused on three performances: IPTD, IPLR and IPDV. The results with respect to these three performances have been presented in part 6.1. A comparison between QoS requirement and experiment result is presented here.

6.2.1 Packet Time Delay

The first performance is PTD. As generalized in Table 4-2**,** the PTD was classified into three class levels:

Table 6-2: Service classes in PTD

Class No.	Upper delay bound	Class type
1	100 ms	Control Traffic
2	100 or 400 ms	Interactive and daily application
3	1 s	General data transfer

This classification covers all the service classes listed in ITU recommendation [27]. Because upper bound delay is used in recommendation, maximum packet delay from the experiment was used correspondingly in the comparison. The H1 nodes in experiment have no physical distance so that the maximum packet delay does not include propagation delay. A comparison is indicated in the Figure 6.10.

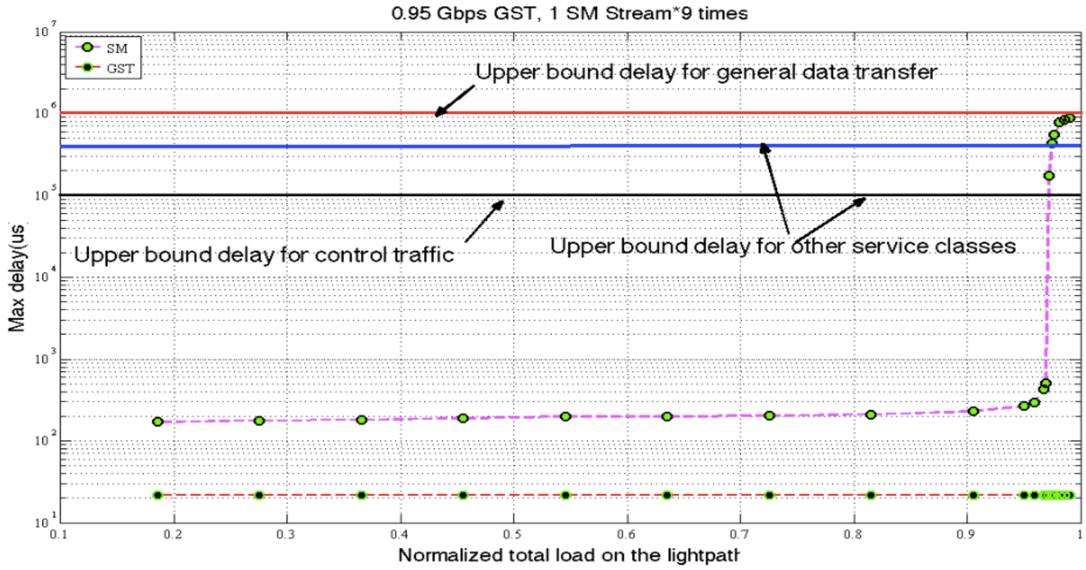


Figure 6.10: PTD comparison between experiment and QoS requirement

The comparison has revealed several information: 1) In a large scale of system load, the PTD performance of H1 node is far better than Upper bound requirement. 2) System load at 0.97 is the threshold for most of the services. In this scenario, when system load exceed 0.97, H1 node is not able to provide a satisfactory service with SM traffic. However, in real application, propagation delay should be taken into consideration.

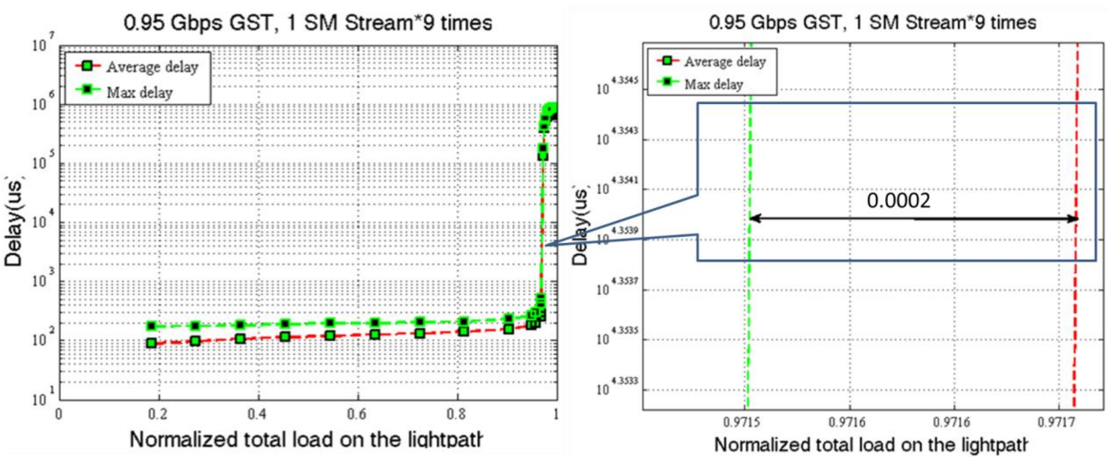


Figure 6.11: Threshold difference between average and maximum latency

Another comparison of the threshold between average delay and maximum delay is indicated in Figure 6.11. The difference between two thresholds is 0.02% of the normalized load. The difference is in negligible level. Therefore, once the detected maximum latency is out of the QoS upper bound, H1 node is not able to provide proper quality of service. The maximum delay is enough to represent as a comparator here.

6.2.2 Packet Loss Rate

The second performance compared is PLR. In Table 4-2, the PLR are classified into two class levels:

Table 6-3: Service class in PLR

Class No.	Upper loss bound	Class type
1	10^-5	Video streaming and music streaming
2	10^-3	The rest services

Figure 6.12 is a comparison between two upper loss bounds and experiment PLR result.

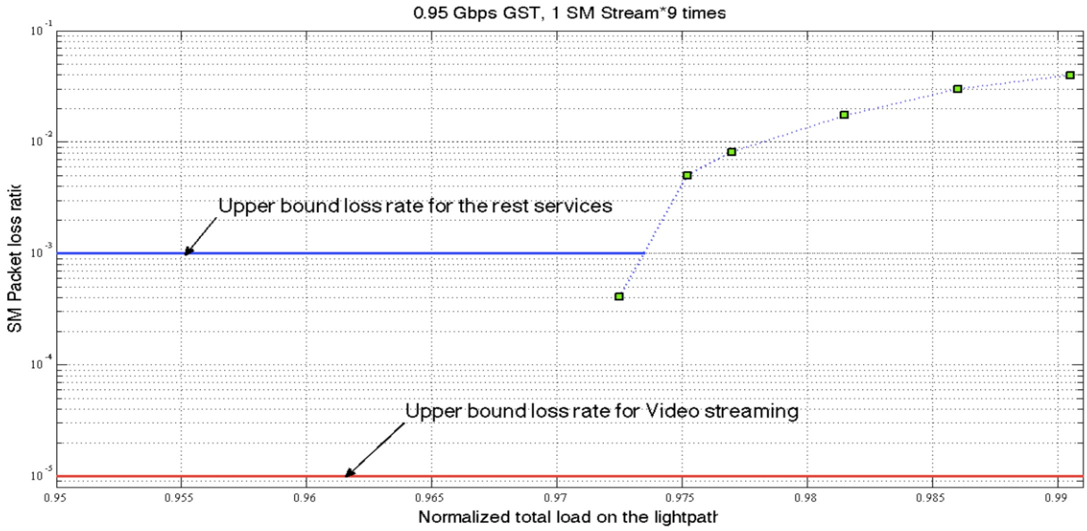


Figure 6.12: PLR comparison between experiment and QoS requirement

Video streaming and music streaming have very strict PLR requirement which is at 10^{-5} level*. In this experiment scenario, SM packet loss was not observed until the system load was 0.97. Therefore, with the system load under 0.97, all the applications can be properly served by H1 node. The rest services have an upper bound at 10^{-3} level, with a system load threshold around 0.973, which is not a significantly improvement of bandwidth utilization.

* Note: Y.1541 Amendment 3: 10^{-7} to 10^{-11} defined for 'Digital television transmission', use of Forwarding Error Correction may be unavoidable [7]

6.2.3 Packet Delay Variation

The last performance compared is PDV. In Table 4-2, only one upper bound jitter 50ms is specified. Therefore, in PDV comparison, only one service class exists.

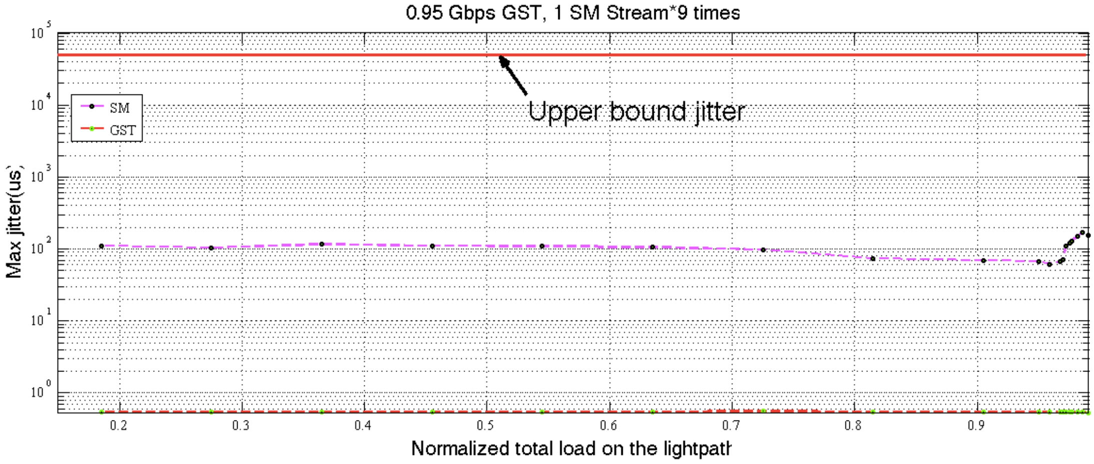


Figure 6.13: PDV comparison between experiment and QoS requirement

In Figure 6.13, the ITU recommended upper bound PDV is much bigger than the maximum PDV, even with system load over 0.97. Thus, among the three aspects: PTD, PLR, PDV, H1 node performs the best in PDV. PDV has no restriction on the bandwidth utilization of H1 node.

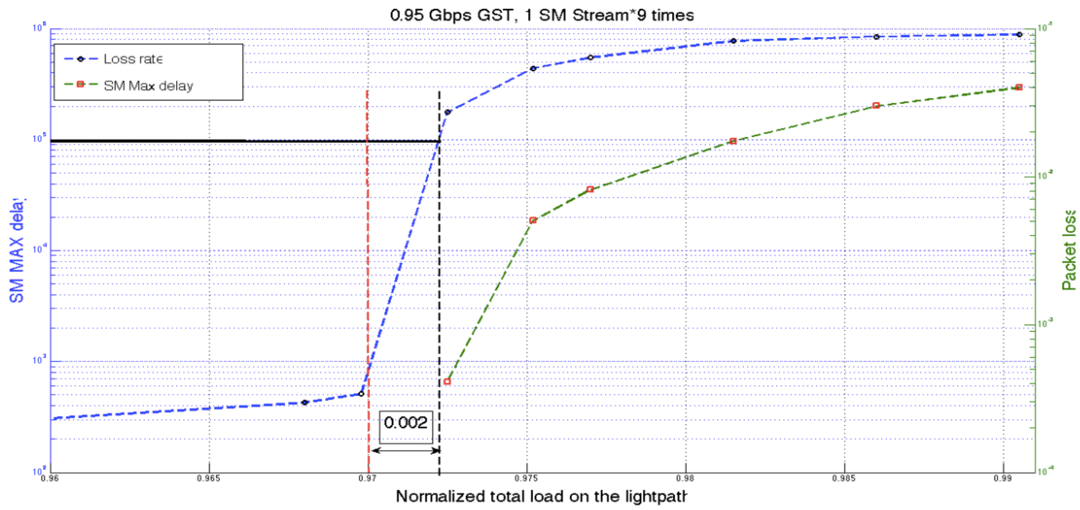


Figure 6.14: Threshold comparison between PTD and PLR

Between PTD and PLR, a comparison of the bound restriction is indicated in Figure 6.14. PTD performs slightly better than PLR, with 0.2% load utilization improvement.

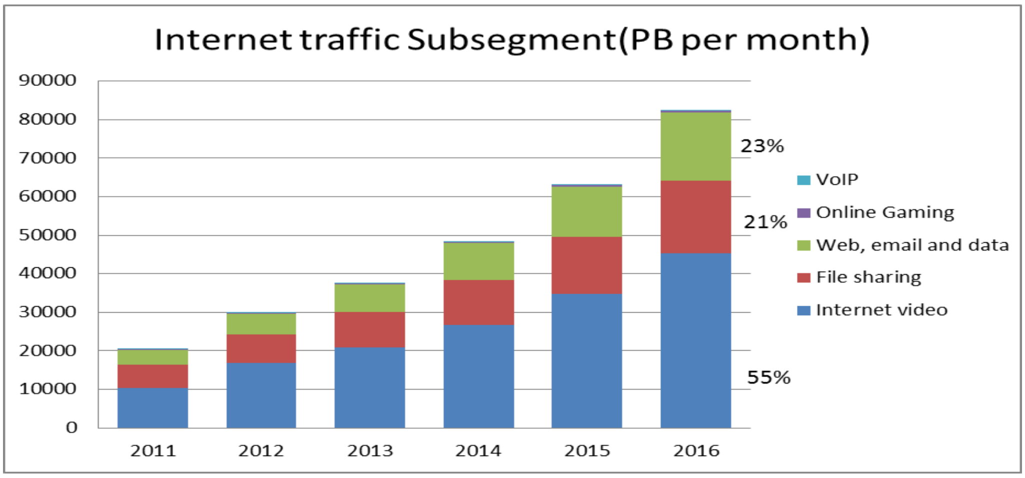


Figure 6.15: Histogram of Internet traffic

Figure 6.15 is an internet traffic histogram from cisco white paper [30]. From the current and forecast trend, internet video takes 55% of the whole traffic. Video streaming has the highest requirement of PLR and it consumes the highest proportion in internet traffic. Therefore, it is recommended to keep the system load under 0.97 to ensure the performance of H1 node.

Chapter 7
Discussion

The main goal of this thesis was to test and analyze the performance of TransPacket Ethernet Node H1. The evaluation is based on several performance aspects: packet delay, packet loss, packet delay variation.

For the accuracy of the experiment, a series of intensive experiments were conducted with respect to different traffic load. The time for each experiment was set long enough to lower the influence from transient time. The results show that H1 node has very attractive performance in providing the service.

The latency of GST traffic keeps constant at a low level of ca. 21 us. It is mainly caused by passing through FDL. The variation of normalized traffic load does not influent the PTD of GST traffic. GST PDV showed a same trend with PTD, which also keeps constant at a low level. No GST packet loss occurs in the experiment. Experiment results have proved the design principle of OpMiGua in differentiating services. GST traffic has the absolutely priority.

SM PTD keeps a low level and growth slowly until the traffic load reach the threshold around 0.97. SM also ensures a 100% packet delivery until the threshold of around 0.97 traffic load. When normalized traffic load pass the threshold, PTD increases rapidly into an intolerable level, as well as SM PLR. From the trend of PTD, we have found out that RIB is the main reason that causes packet loss in this scenario. Without proper gaps to schedule SM packets, SM packet PTD increases and causes buffer overflow.

SM packet average PDV shows a negative exponential distribution with respect to normalized system load. H1 node electronic buffer plays the function as a jitter buffer. When load increases, SM packet queue in H1 node buffer becomes longer. Within the buffer size, the higher utilization of buffer space, the better in mitigating the jitter.

A comparison was illustrated in part 6.2 of Chapter 6. From the three aspects tested, GST traffic qualifies every service class requirement. The overall performance of GST traffic is far better than recommended. As for SM traffic, PDV performs best among the three aspects. SM PDV satisfies the recommendation in the load range from 0 to 1. SM PTD and PLR qualify every service class requirement when the normalized traffic load is lower than 0.97. Once the load is over 0.97, traffic jam occurs and most of the services cannot be provided with a satisfactory quality. PTD may be regarded as the main restriction in H1 node, since packet loss is induced by long packet latency.

We derived mathematical regression model for each performance aspects: PTD, PLR and PDV. Our models may only be suitable for the scenario illustrated in Chapter 5, which is 9 GE interfaces for SM traffic and 1 GE interface for GST. With other different deployment, different regression model may exist.

Our results have demonstrated that H1 node is qualified for the ITU recommendation. We found out the load threshold of delivering the services with a certain quality. H1 node deployment may take the load threshold into consideration. It helps deploy a load sharing and robust network. As indicated above, different regression model of system performance may exist for other configurations. It is valuable to keep research on those models.

Chapter 8
Conclusion and Summary

TransPacket Ethernet H1 node product has been developed step by step. It started from the idea of OpMiGua, with the research of proper technologies. Then, many simulations based on the OpMiGua node design, with various performance improvement solutions are tested. After the birth of real H1 node product, some field trials have been tested to observe the performance [10]. However, to our knowledge, there is no comparison between H1 node performance and the detail QoS requirement respect to different traffic classes. Neither there are mathematical models to evaluate H1 node performance. This is the first work connecting H1 node performance and traffic QoS requirement. The work is specifically focused on comparing H1 node performance to ITU traffic classification recommendation.

Firstly, we studied the principle of hybrid network and deeply discovered the design of OpMiGua. The combination of OCS and OPS provides the possibility of QoS differentiation. Quality guaranteed service is realized by OCS and high bandwidth utilization is reached by OPS. The design combines two switching technologies and GST packets get the absolutely priority. Therefore, SM traffic performance becomes the key factor that affects the overall system performance. This brought the research of OPS QoS for SM packets.

Secondly, QoS classification and requirement from ITU are concretely studied. For each types of traffic class, it has PTD, PLR, PDV specifications. QoS improvement methods were then further discussed. The methods vary from contention-resolution to 3LIHON architecture. In OpMiGua, electronic buffer and reservation techniques are illustrated to ensure and improve the performance.

Thirdly, a series of rigorous and intensive experiments were conducted. The detailed experiment and configurations are illustrated in chapter 5. The experiment includes 10 GE ports and one xe port from each node. Among them, 9 GE ports are utilized for SM access interfaces and 1 GE port is used as GST access interface. The physical connection and 10 VLANs configuration of H1 node make it possible to reach a load from 0 to 100% on the fiber. Therefore, we could acquire node performance in a wide range of traffic load.

Spirent TestCenter was used in the experiment as packet generator and traffic monitor. In order to achieve accurate and credible result, each experiment was set for a long time to eliminate the influence from transient time. Results acquired from Spirent are used to calculate three performance factors:

1) Packet delay
2) Packet loss rate
3) Packet delay variation

Finally, the overall performance with the result acquired from experiment was analyzed. The mathematical models for each performance parameter were derived in the current configuration scenario. The models are useful to estimate the system performance before deploying H1 node. After that, a comparison was made between the experiment results with the ones in QoS specification. In our experiment scenario, H1's capability of delivering high quality service within a system load threshold was proved.

Chapter 9
Future Work

The findings gathered in this work are a part of work in system test. There are two ways to expend based on the research performed: further system test and system refinement.

Further system test:

a) Other application scenario:

In our experiment scenario, 9 GE interfaces for SM traffic and 1 GE interface for GST traffic were utilized. However, the scenario with 10GE interface xe interface for GST traffic and 10 GE (ge0-ge9) interfaces for SM traffic can be also tested. In the new scenario, GST traffic load can reach a higher level. It is interesting to observe the performance and derive a different mathematical model from the new scenario.

b) System dependability:

System dependability test is a further experiment to discover the performance of H1 node from the perspective of reliability. The former performance experiment was conducted when the system was working. However, in reality, system might be down because of failure, software or hardware. The availability of the service bases on the proportion of up time. Once the system met failure and unable to provide service, it decreases the overall performance dramatically. For that reason, system dependability is one of the crucial factors that must be taken into consideration when purchasing and deploying a system. To some extent, system dependability is given a higher position than performance in other aspects.

To acquire the reliability of the system, Markov model (state transition diagrams) could be used. It is important to find out the system's failure intensity and recovery time. Software failure may be just temporary failure and can be recovered back to work by simply restarting the system. Hardware failure may take longer operation time for the system to go back to work. Acquiring these parameters may help derive dependability of H1 node. With this figures, it is possible to design and optimize an overall network system that satisfy customer's requirement in dependability.

System refinement:

In Chapter 4 the QoS methods and the methods utilized in OpMiGua have been discussed. OpMiGua classifies the traffic into two classes. However, as shown in the ITU recommendations, services are divided into many classes. The different classes have QoS requirements over three levels. Bjornstad, S *et al* [8] and Stol, N *et al*.[7] proposed the three levels classification from different aspects including the current OpMiGua node architecture [8] and evolved the node architecture [7]. Simulations of the proposed solutions showed attractive results. Therefore, it is interesting to know the performance after their implementation.

Another aspect in system refinement is to update the current scheduling method. When GST traffic reach a high level, the bandwidth cannot be fully utilized even add more SM traffic. The total fiber load can reach 0.7 [25]. This is due to the inefficient usage of gaps between GST packets. In our scenario, RIB is also found to be the main obstacle for further improve the performance. It is the shortage of current scheduling technique in H1 node. A rate-adaptive segmentation algorithm [23] is newly proposed, but have not been implemented into the system. The result shows an improvement of the overall performance. Other scheduling algorithms may also be found to improve the utilization.

To conclude, H1 node strives to provide the best service in hybrid network and it satisfies the QoS requirement in our scenario. However, there are many aspects need to be evaluated and may be improved. Hybrid network is a wide area and will attract more attentions from academia and industry.

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Appendix A

H1 node configuration

H1: 158.38.152.165

VLAN: vlan0
802.1Q Tag: 100
  xe0, trunk
  ge0, access, sm
VLAN: vlan1
802.1Q Tag: 101
  xe0, trunk
  ge1, access, sm
VLAN: vlan2
802.1Q Tag: 102
  xe0, trunk
  ge2, access, sm
VLAN: vlan3
802.1Q Tag: 103
  xe0, trunk
  ge3, access, sm
VLAN: vlan4
802.1Q Tag: 104
  xe0, trunk
  ge4, access, sm
VLAN: vlan5
802.1Q Tag: 105
  xe0, trunk
  ge5, access, sm
VLAN: vlan6
802.1Q Tag: 106
  xe0, trunk
  ge6, access, sm
VLAN: vlan7
802.1Q Tag: 107
  xe0, trunk
  ge7, access, sm
VLAN: vlan8
802.1Q Tag: 108
  xe0, trunk
  ge8, access, sm
VLAN: vlan9
802.1Q Tag: 109
  xe0, trunk
  ge9, access, gst

H1: 158.38.152.166

VLAN: vlan0
802.1Q Tag: 100
  xe0, trunk
  ge0, access, sm
VLAN: vlan1
802.1Q Tag: 101
  xe0, trunk
  ge1, access, sm
VLAN: vlan2
802.1Q Tag: 102
  xe0, trunk
  ge2, access, sm
VLAN: vlan3
802.1Q Tag: 103
  xe0, trunk
  ge3, access, sm
VLAN: vlan4
802.1Q Tag: 104
  xe0, trunk
  ge4, access, sm
VLAN: vlan5
802.1Q Tag: 105
  xe0, trunk
  ge5, access, sm
VLAN: vlan6
802.1Q Tag: 106
  xe0, trunk
  ge6, access, sm
VLAN: vlan7
802.1Q Tag: 107
  xe0, trunk
  ge7, access, sm
VLAN: vlan8
802.1Q Tag: 108
  xe0, trunk
  ge8, access, sm
VLAN: vlan9
802.1Q Tag: 109
  xe0, trunk
  ge9, access, gst

Appendix B

Experiment data collection

SM traffic route 1							
Normalized Load	Average Latency (us)	Min Latency (us)	Max Latency (us)	Drop frame	Drop frame percent (%)	Average jitter(us)	Max Jitter(us)
1.850	88.43	26.94	169.79	0	0	34.31	112.29
2.750	96.32	26.92	176.74	0	0	28.07	104.59
3.650	106.13	26.97	181.88	0	0	21.46	115.89
4.550	112.87	27.13	189.82	0	0	16.52	111.63
5.450	118.92	27.70	193.71	0	0	12.87	108.97
6.350	125.48	28.39	197.63	0	0	9.87	106.24
7.250	132.56	32.04	202.65	0	0	7.17	101.29
8.150	140.89	43.21	210.30	0	0	4.60	75.97
9.050	154.65	98.88	230.75	0	0	2.22	72.44
9.500	178.64	100.63	265.76	0	0	1.13	73.32
9.590	194.25	126.27	296.49	0	0	0.92	68.46
9.680	255.64	131.59	436.41	0	0	0.71	70.27
9.698	302.20	42.79	517.19	0	0	0.67	77.50
9.725	263893.53	64.04	275094.00	621200	0.082	0.64	122.08
9.752	510466.77	64.85	544720.97	3202323	0.424	0.67	113.73
9.770	531840.05	133.49	548817.96	5747858	0.761	0.72	126.06
9.815	634046.05	52.38	819801.96	7097108	0.934	0.66	143.50
9.860	690070.71	42.89	828097.54	12833398	1.682	0.78	183.41
9.905	520712.51	51.56	767641.30	18194228	2.372	0.84	147.77

GST traffic route 1							
Normalized Load	Average Latency (us)	Min Latency (us)	Max Latency (us)	Drop frame	Drop frame percent (%)	Average Jitter(us)	Max Jitter(us)
1.850	21.47	20.80	21.59	0	0	0.05	0.54
2.750	21.47	20.80	21.59	0	0	0.05	0.54
3.650	21.47	20.80	21.59	0	0	0.05	0.54
4.550	21.47	20.81	21.59	0	0	0.05	0.54
5.450	21.47	20.80	21.59	0	0	0.05	0.54
6.350	21.47	20.79	21.59	0	0	0.05	0.53
7.250	21.47	20.80	21.59	0	0	0.05	0.55
8.150	21.47	20.80	21.59	0	0	0.05	0.54
9.050	21.47	20.80	21.59	0	0	0.05	0.54
9.500	21.47	20.80	21.59	0	0	0.05	0.54
9.590	21.47	20.79	21.59	0	0	0.05	0.54
9.680	21.47	20.80	21.59	0	0	0.05	0.54
9.698	21.47	20.80	21.60	0	0	0.05	0.55
9.725	21.47	20.81	21.60	0	0	0.05	0.54
9.752	21.47	20.80	21.60	0	0	0.05	0.54
9.770	21.47	20.80	21.59	0	0	0.05	0.54
9.815	21.47	20.81	21.60	0	0	0.05	0.54
9.860	21.47	20.80	21.59	0	0	0.05	0.55
9.905	21.47	20.80	21.59	0	0	0.05	0.53

SM traffic route 2							
Normalized Load	Average Latency (us)	Min Latency (us)	Max Latency (us)	Drop frame	Drop frame percent (%)	Average Jitter(us)	Max Jitter(us)
1.850	88.48	26.98	172.78	0	0	34.22	108.90
2.750	96.32	27.05	179.05	0	0	27.98	103.31
3.650	106.01	27.07	181.82	0	0	21.46	115.32
4.550	112.97	27.16	187.22	0	0	16.32	109.23
5.450	119.04	27.43	200.20	0	0	12.77	108.25
6.350	125.62	29.46	197.64	0	0	9.84	106.04
7.250	132.78	34.13	205.32	0	0	7.17	93.00
8.150	141.13	66.63	209.30	0	0	4.64	71.84
9.050	154.90	106.79	230.19	0	0	2.22	66.73
9.500	178.94	120.65	263.37	0	0	1.13	61.45
9.590	194.53	93.89	291.90	0	0	0.91	55.07
9.680	255.08	121.15	412.01	0	0	0.71	64.34
9.698	301.51	60.53	500.13	0	0	0.67	63.32
9.725	7079.23	91.04	76331.62	0	0	0.61	97.36
9.752	275305.43	94.15	328603.72	4376899	0.58	0.71	124.05
9.770	531840.05	133.49	548817.96	6532950	0.865	0.75	128.80
9.815	587186.76	102.23	728617.24	19221333	2.532	1.12	153.89
9.860	648856.17	127.79	860279.76	32828975	4.302	1.51	158.74
9.905	759206.93	108.20	998239.18	42806776	5.582	1.75	161.20

GST traffic route 2							
Normalized Load	Average Latency (us)	Min Latency (us)	Max Latency (us)	Drop frame	Drop frame percent (%)	Average jitter(us)	Max Jitter(us)
1.850	21.48	20.81	21.60	0	0	0.05	0.54
2.750	21.48	20.81	21.60	0	0	0.05	0.55
3.650	21.48	20.80	21.60	0	0	0.05	0.54
4.550	21.48	20.80	21.60	0	0	0.05	0.54
5.450	21.48	20.80	21.60	0	0	0.05	0.54
6.350	21.48	20.80	21.60	0	0	0.05	0.55
7.250	21.48	20.80	21.60	0	0	0.05	0.56
8.150	21.48	20.80	21.60	0	0	0.05	0.54
9.050	21.48	20.81	21.60	0	0	0.05	0.54
9.500	21.48	20.80	21.60	0	0	0.05	0.54
9.590	21.48	20.80	21.60	0	0	0.05	0.55
9.680	21.48	20.80	21.60	0	0	0.05	0.54
9.698	21.47	20.79	21.59	0	0	0.05	0.54
9.725	21.47	20.80	21.59	0	0	0.05	0.55
9.752	21.47	20.79	21.59	0	0	0.05	0.56
9.770	21.48	20.80	21.60	0	0	0.05	0.54
9.815	21.47	20.79	21.59	0	0	0.05	0.54
9.860	21.48	20.80	21.60	0	0	0.05	0.54
9.905	21.47	20.79	21.59	0	0	0.05	0.54