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THESIS

A PERFORMANCE ANALYSIS OF MANAGEMENT INFORMATION DUE TO DATA TRAFFIC PROVISIONING IN A SONET/SDH COMMUNICATIONS NETWORK

by

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June 2005

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An evaluation of the performance of a SONET management system was conducted to better understand its management capabilities due to network disruptions in the presence of a traffic load. This study analyzed the Cisco Transport Manager (CTM) which manages a testbed of four Cisco ONS15454 optical systems. The network was injected with HTTP and FTP traffic generated by the Spirent Smartbits system installed with TeraMetrics Gigabit Ethernet modules and load calibration configured by the Spirent Avalanche software. To simulate real-world situations, power disruptions were applied to the network while collecting CTM traffic using Ethereal. Using queuing analysis, the arrival rates and service times were computed for various CTM traffic components and a utilization for 2500 network elements (NE) extrapolated. Self-similarity analysis was performed and the log-variance was plotted to extract the Hurst values. Finally, the results and findings were compared with prior research for loading and no-loading cases. The results of this study are useful in determining the maximum number of network elements manageable in a disruptive environment. Final analysis on the effects of link utilization on the queue size showed that the CTM is able to manage more NEs when the network is disrupted. Unfortunately, managing more NEs increases the queue size even though the utilization was found to be 0.83 for 5450 NEs. Consequently, in order to maintain a moderate queue size, the maximum number of NEs manageable was found to be 2495. This value is close to CISCO's specification of a CTM server managing a maximum of 2500 NEs.

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LIST OF SYMBOLS, ACRONYMS AND/OR ABBREVIATIONS

ANSI	American National Standards Institute
CTC	Cisco Transport Client
CTM	Cisco Transport Manager
DS-1/2/3	Data Signal Level 1/2/3
EML	Element Management layer
EMS	Element Management System
FTP	File Transfer Protocol
GIOP	General Inter–Orb Protocol
H	Hurst Parameter
HTTP	Hyper Text Transfer Protocol
IETF	Internet Engineering Task Force
IP	Internet Protocol
ITU	International Telecommunications Union
LRD	Long-Range Dependence
M/M/1	Queuing System with Poisson Arrival and One Exponential Server
NE	Network Element
NML	Network Management Layer
OC-12	Optical Connect Speed of 622.080Mbps
ONS15454	Optical Network System 15454
POS	Packet Over SONET
SDCC	Section Data Communications Channel
SDH	Synchronous Digital Hierarchy

SLA	Service Level Agreement
SONET	Synchronous Optical Network
TCP	Transport Control Protocol
T_a	Interarrival Time
T_s	Service Time
TE	Traffic Engineering
TMN	Telecommunications Management Network
WDM	Wavelength Division Multiplexing
λ	Mean Arrival Rate
ρ	Link Utilization

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EXECUTIVE SUMMARY

In today's network-centric warfare, the success of point-to-point communications hinges upon the survivability of the operations network. As networks grow and more services are introduced, managing the entire network becomes a daunting task. Deploying a super network management system or a manager of managers may be a solution but without the necessary tools to analyze and predict performances, it could result in precious time and revenue wasted as these advanced network management tools are very expensive.

This study investigated the performance of the Cisco Transport Manager (CTM version 4.6) in managing a Synchronous Optical Network (SONET) operating under external factors of network loading and power disruptions. Using empirical statistical methods, the effect of power disruptions on the SONET management traffic is analyzed. As SONET systems are configured in a ring topology, traffic could be routed by another path when one of the optical systems is down.

The CTM was deployed in an IP network and configured to manage four units of Cisco optical transport systems, known as ONS15454, which are installed in the Advanced Network Laboratory of the Naval Postgraduate School.

The optical systems are managed via its 192-kbps Section Data Communication Channel (SDCC) which is provisioned in the fiber links. Although Cisco has specified that the CTM is able to manage a maximum of 2500 NEs, the performance may differ under different network conditions. Prior studies, [11] and [12], have shown that the maximum numbers of NEs manageable are 1027 for a no-traffic loading network, and 1552 for a fully loaded network. The latter result is interesting as it was expected that the number of NEs manageable should drop due to higher intensity of network traffic.

The load traffic of this thesis was generated by the Spirent Smartbits 6000 hardware data generator which generates HTTP and FTP packets configured using Spirent Smartbits Avalanche software. The duration of the traffic was configured to run for ten days. The CTM management traffic was collected using an open source packet sniffer called Ethereal which collects the data packets arriving and leaving the CTM server. In particular, the management traffic of interest were Socks, SNMPv2 and related TCP data packets which are collectively referred to as CTM Ethernet traffic.

The analysis was performed using statistical methods by modeling the interarrival times and packet sizes as random variables based on the CTM data traffic collected. Queuing theory was applied to compute the arrival rates and service times which enable the utilization to be derived and subsequently extrapolated to estimate the utilization of 2500 NEs. Self-similarity analysis was also performed to extract the Hurst values of the CTM traffic. Finally, the maximum number of NEs was deduced using the Norros model which defines the relationship between utilization and queue size.

From the traffic analysis, it was observed that the Socks and SNMPv2 traffic decreases when the SONET network is loaded and disrupted by NE power failures. Though lower, the total Ethernet traffic was about 20% higher compared to the case when the network was loaded but not disrupted. While the decrease in Socks and SNMPv2 was due to the NE offline, the increase in Ethernet traffic was deduced to be generated by the CTM server due to polling of the NEs.

Further analysis on the interarrival time statistics revealed that the means are higher compared to no-disruption case. The higher mean interarrival times suggests that the arrival rate is lower which is consistent with the fact that the distribution graphs exhibit a faster decay rate compared to the no-disruption case. The statistical analysis on the packet size statistics revealed that the distribution varies only slightly when compared to the no-disruption case. Despite the minute differences, the Ethernet packet mean packet size was lower due to averaging over more packets collected for the loading/disruption case. Interestingly enough, Socks and SNMPv2 packet size means were lower too, although the number of packets were lower compared to the loading case.

The self-similarity analysis revealed that Socks traffic for the loading/disruption case was less self-similar compared to loading case, while more self-similar compared to no-loading case. The SNMPv2 traffic Hurst value drops below 0.5 which indicated that it

does not possess an exponential distribution due to disruption. The combined Socks and SNMPv2 had a Hurst value which fell in between the loading and no-loading cases, suggesting the dominant effect of Socks traffic over SNMPv within the SDCC channel. Nevertheless, the CTM Ethernet traffic was less self-similar compared to both loading and no loading cases.

Final analysis on the effects of link utilization on the queue size showed that the CTM is able to manage more NEs when the network is disrupted. Unfortunately, managing more NEs increases the queue size even though the utilization was found to be 0.83 for 5450 NEs. Consequently, in order to maintain a queue size of 1, for a utilization of 0.38, the maximum number of NEs manageable was found to be 2495. This value is close to CISCO's specification of CTM server managing a maximum of 2500 NEs.

Study of network loading coupled with power disruptions is an important research area which will be useful for high-speed computer networks administrators. The results and findings of this thesis will benefit the SONET network administrators by increasing their awareness of the limitations of SONET network management systems. Further, this research provides the ability to optimize the deployment of SONET optical systems in order to tackle network problems associated with network loading and power disruptions.

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I. INTRODUCTION

A. MOTIVATION

Systems adhering to the SONET/SDH standards have been widely deployed as the fiber optics transport backbone of many telecommunications service providers' networks. SONET was first introduced by Bellcore (now Tecordia) in the mid 1980's as the optical transport technology to support high capacity transport and has become the de-facto standard in the industry [1]. SONET is a very reliable transport system and until this date no suitable technology is able to replace it. The next generation SONET is built on Wavelength-Division Multiplexing (WDM) technology which provides much higher capacity [2]. This has occurred in tandem with the emerging field of Traffic Engineering (TE) which has become an important research area in optimizing and protecting next-generation optical networks [3].

SONET stands for Synchronous Optical Network which is defined by the American National Standards Institute (ANSI) for synchronous digital networks using optical media in the North America [4]. Its international equivalent is Synchronous Digital Hierarchy (SDH) which is the European standard defined by the ITU. In a typical deployment of the SONET system, a dedicated control channel known as the Section Data Communications Channel (SDCC) is provisioned as part of overhead in all the fiber links. This enables the SONET management system to communicate with the network elements which are deployed geographically apart.

In real-world situations, disruptions or network outages due to power failures and fiber disconnections are often unavoidable. Although there has been research on the measurement and modeling of computer networks with self-similar nature – specifically in the areas of router and web traffic [5], Internet traffic [6], wireless traffic [7], and Ethernet traffic [8] – the effects of network loading coupled with power disruptions have not been fully investigated. Furthermore, highly self-similar traffic could cause queuing delays, increase packet drop rates and prolonged periods of congestion [9]. As such, network loading coupled with power disruptions is an important research area useful for high-speed computer networks administrators.

Although SONET has the advantage of re-routing traffic via the next available optical path, it is not known whether the utilization rate of SDCC channel would be increased. Furthermore, it is known that current SONET management systems in the market employ several management protocols to manage their network elements [10], and these different types of management traffic behave differently within the network. It is important to understand whether disruption would affect the number of network elements manageable or cause bottlenecks within the network, due to an increase in management traffic. More importantly, it is imperative to investigate whether the management server is able to handle the possible increase in management traffic due to network disruptions.

Very often, the SONET network is designed based on the vendors' specification of the maximum number of network elements manageable. Over years of operation, network sizes expand and more nodes are added. Even though the total number of network elements is kept well within the maximum stated by the vendor, we do not know to what extent introducing more nodes would affect the utilization of the SDCC link. Furthermore, we do not know how disruptions within the network would affect the SDCC and whether it would cause the SDCC link utilization to increase or decrease.

B. THESIS OBJECTIVE

Armed with these questions in mind, it is important to investigate the performance of the SONET management system, to analyze the effects of disruptions using statistical means, and to derive the optimal number of network elements manageable with real-world factors taken into consideration. This is an important research area as the results and findings of this study would be useful and valuable, not only to the industry as well as the military in deploying SONET systems, but also to facilitate the understanding of the underlying intricacies of the network management paradigm in the fast-paced IT world.

For the purpose of this study, a Cisco SONET system was used as a platform to study the performance and effectiveness of a network management tool in managing the optical systems. Under this study, the network elements are the Cisco ONS15454 optical transport systems while the element management system is the Cisco Transport Manager (version 4.6). The CTM's server management performance was investigated by simulating network disruption within the fiber network under the conditions of injected data traffic within the network. Data analysis was performed on the data packets collected at the CTM server and statistical analysis was performed to determine the number of manageable NEs under loading of network with simulated disruption.

C. PRIOR WORK

In recent research by Lim [11], traffic analysis was carried out on the management traffic between the CTM server and ONS15454 without loading or disruption. It was found that the number of manageable NEs was 1027. A later study by Ng [12] carried out on the same network, with actual traffic loading of the fiber network, determined that the number of manageable NEs to be 1552.

D. THESIS ORGANIZATION

This chapter has presented the motivation of this study and the thesis objectives. Prior related work was also discussed. The next chapter introduces the Cisco SONET system overview and the network management system. Chapter III discusses the laboratory setup of the equipment for the data collection of the CTM management traffic. Chapter IV presents the statistical techniques employed in the analysis of the data collected. Chapter V discusses the results and findings from the statistical analysis. Last but not least, Chapter VI summarizes the research work with proposals for future work.

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II. SONET NETWORK MANAGEMENT SYSTEM OVERVIEW

A. CHAPTER OVERVIEW

This chapter presents the Cisco ONS15454 system overview, discussing the features of the ONS15454 optical system as a multiservice transport platform. The network management tools of Cisco Transport Client (CTC), Cisco Transport Manager Client and Server are also described. In addition, a brief discussion on the Simple Network Management Protocol (SNMP) is presented.

B. INTRODUCTION

As optical networks become very large, an efficient network management system is needed to manage resources. Telecommunications network management is an important area in the telecommunication industry as operators are concerned with revenue, service assurance, maintaining Service Level Agreements (SLA), and keeping operations costs low. Understanding the market concern, CISCO has introduced the CISCO Transport Manager (CTM), the industry's most advanced optical network management system [13]. In compliance with the Telecommunications Management Network (TMN) framework [14], the CTM sits within the Network Management Layer (NML) and the Element Management Layer (EML). Essentially, it is a Network Element (NE) manager, which incorporates industry standard interfaces for managing the optical devices, and provides management functions, operations, provisioning and maintenance of the entire optical network.

C. CISCO ONS15454 SYSTEM OVERVIEW

The Cisco ONS15454 is a SONET optical network system which provides a multiservice provisioning platform. It supports Time Division Multiplex standards for interfaces such as DS-1, DS-3, and EC-1, and data interfaces for Ethernet and Gigabit Ethernet [13]. The optical transport interface supports OC-3 to OC-192 with integrated dense WDM (DWDM).

Within the Advanced Network Laboratory of Naval Postgraduate School, four ONS15454 optical systems are installed in a ring configuration simulating the locations of Pacific Grove, Carmel, Salinas and Monterey, as depicted in Figure 1. Note that the dotted circle represents the SDCC link which supports the transfer of the management information. The Monterey optical system is connected to the IP network where the Cisco Transport Controller (CTC) Client, the Cisco Transport Manager (CTM) server and the CTM Client are located. The CTC Client is installed and configured to run on a Windows 2003 server. The CTM Client is installed on a Windows XP machine while the CTM Server is installed on Solaris server. Both the CTM Client and Server used in this laboratory setup are version 4.6. The following sections describe the respective software in detail.

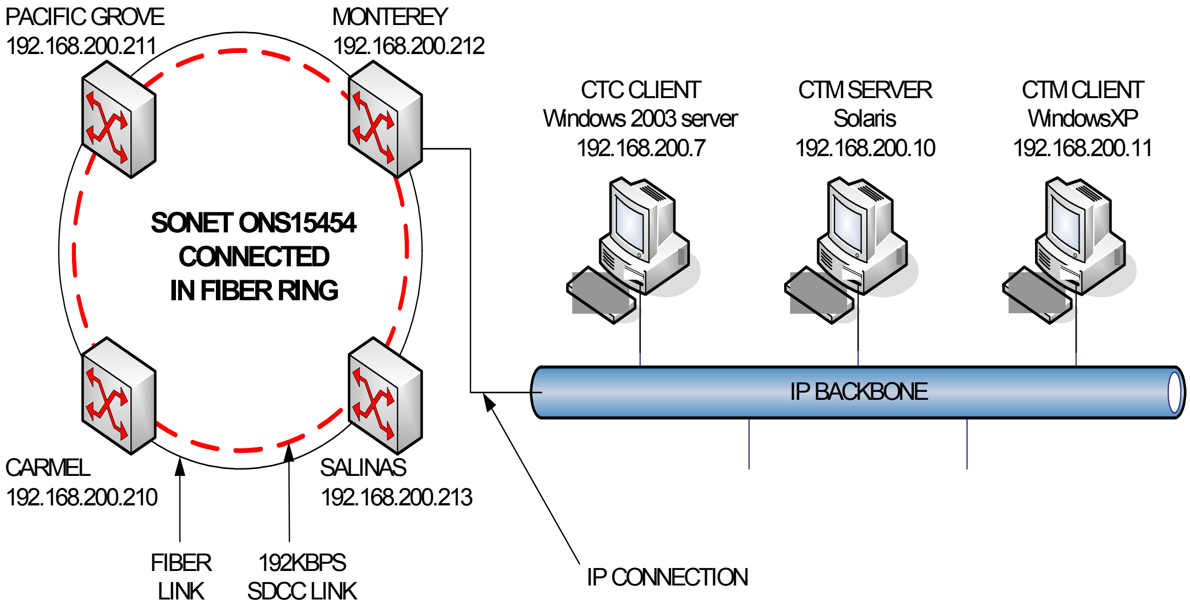
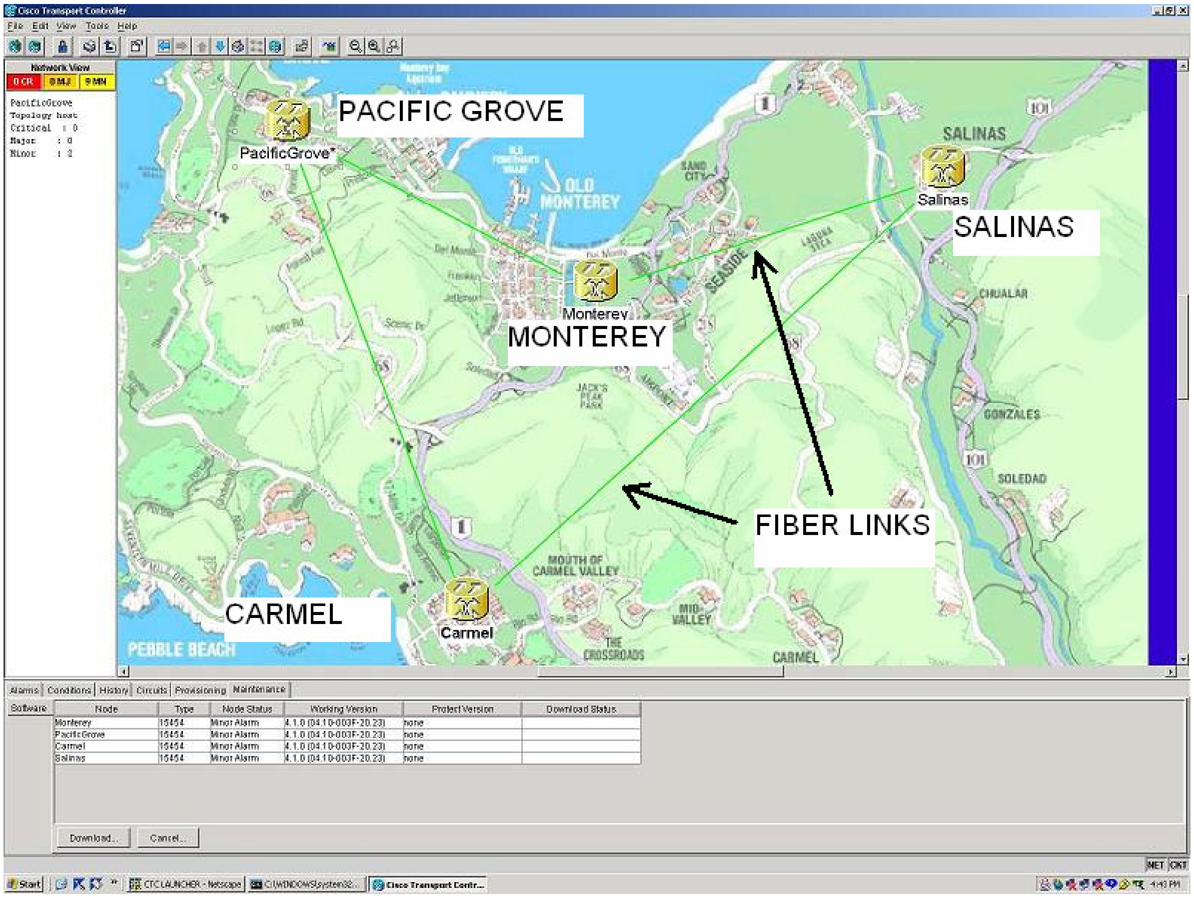


Figure 1. CISCO ONS15454 and SONET Network Management System Setup (After Ref. [11].)

1. Cisco Transport Client (CTC)

The Cisco Transport Client (CTC) is a Windows web-based Java program installed on a Windows 2003 server [15]. It is used to monitor the health status and alarms of the ONS15454 nodes. It also provides provisioning capabilities for configuration of the ONS15454 expansion cards to provision the fiber links and the Ethernet connections as depicted in Figure 2. It communicates with the CTM Server continuously to monitor the health status and to update the network provisioning configurations.



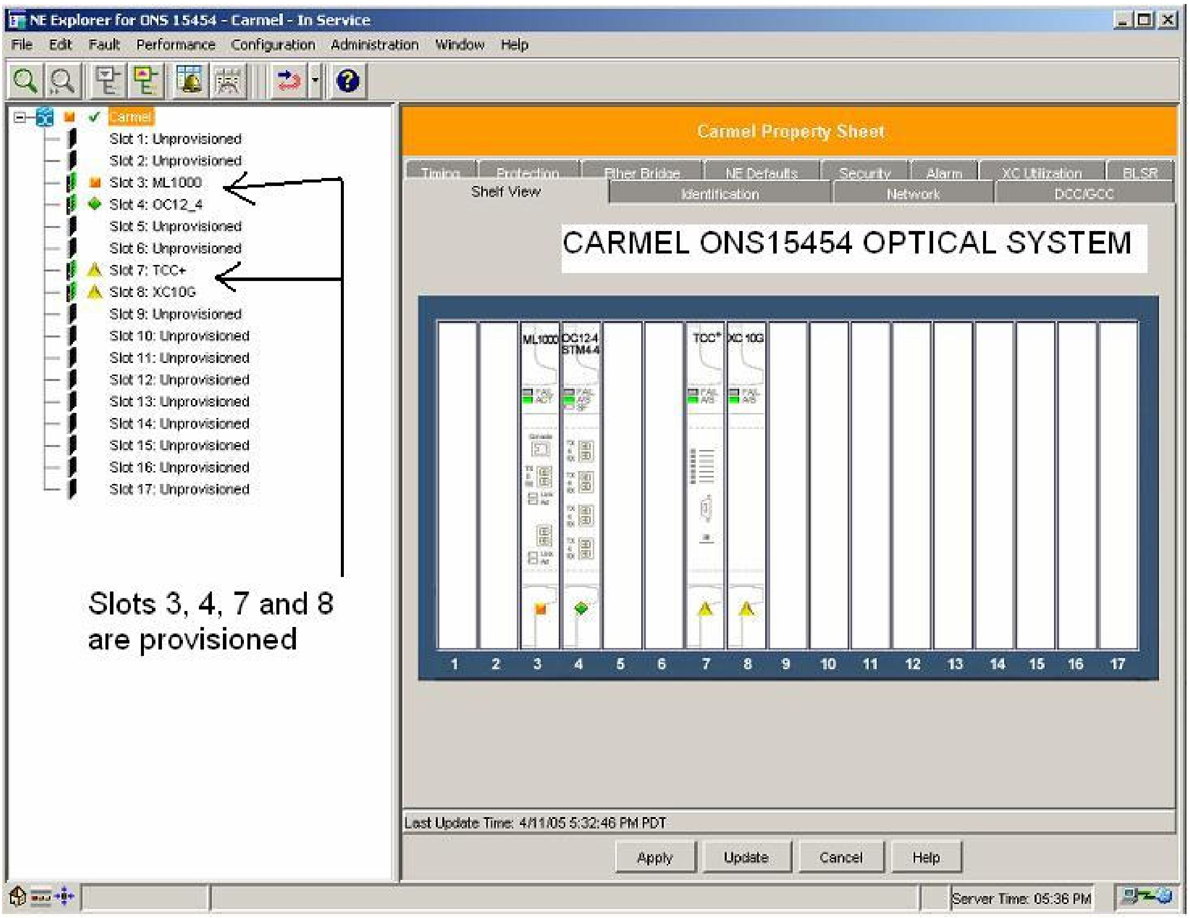
```
PacificGrove
Topology host
Critical  : 0
Major     : 0
Minor     : 2
```

Node	Type	Node Status	Working Version	Protect Version	Download Status
Monterey	15454	Minor Alarm	4.1.0 (04.10-003F-20.23)	none	
PacificGrove	15454	Minor Alarm	4.1.0 (04.10-003F-20.23)	none	
Carmel	15454	Minor Alarm	4.1.0 (04.10-003F-20.23)	none	
Salinas	15454	Minor Alarm	4.1.0 (04.10-003F-20.23)	none	

Figure 2. CTC management interface

2. Cisco Transport Manager Client (CTM Client)

The CTM Client is a Windows Java-based program installed on a Windows XP machine [15]. It is used to communicate with the CTM server for all activities related to user access and administration, network configuration and management services configuration. Figure 3 shows the CTM Client management interface for the Carmel optical system. The figure shows that Slot 3, 7 and 8 of the optical system are provisioned for Ethernet interface, OC12 circuit and two control channels, respectively.



Slots 3, 4, 7 and 8 are provisioned

Figure 3. CTM Client management interface

3. Cisco Transport Manager Server (CTM Server)

The CTM server is the Element Management System (EMS) for the ONS15454 fiber network [15]. It manages all fiber optic network elements and stores the configurations within its Oracle 8i database system which is installed on the same Solaris machine as the CTM. The CTM server issues commands and downloads configuration and performance information from every ONS15454 connected to the network.

4. The Section Data Communications Channel (SDCC)

The SDCC forms the heart of the SONET/SDH management transport functions. Essentially, the SDCC is a dedicated 192-kbps channel which is included in the SONET/SDH overhead and conveys the management information between the optical systems and the network management system [3]. The SDCC conveys all management traffic which are Socks and SNMPv2. The SDCC link is illustrated as the dotted line within the SONET ring in Figure 1.

D. SIMPLE NETWORK MANAGEMENT PROTOCOL (SNMP)

SNMP is a distributed network management protocol used to manage network elements which are connected within an IP network. Currently, there are three versions defined by the IETF [16]. The first version, SNMPv1, supports server commands “Get,” “GetNext” and “Set,” and agent commands “Get-Response” and “Trap.” SNMPv1 is inefficient as it retrieves the management information “entry-by-entry” and is thus time consuming and bandwidth inefficient. The second version, SNMPv2, implements two additional commands, “GetBulk” and “Inform”, as well as enhances the protocol operations. The “GetBulk” command is used to efficiently retrieve the entire record of management information from the network elements. Lastly, SNMPv3 adds security and allows remote configuration capabilities in addition to the previous versions.

Currently, the CTM server supports SNMPv2 for managing the ONS15454 optical switches which are connected within the IP network.

E. SUMMARY

In this chapter, the Cisco SONET optical transport system overview has been presented. A brief introduction of the SNMP protocol was also discussed. The next chapter describes the laboratory setup and the configuration details of Cisco SONET system.

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III. LABORATORY SETUP AND PROCEDURES

A. CHAPTER OVERVIEW

This chapter presents the laboratory setup of the Cisco SONET system describing the configurations of the Cisco ONS15454 optical system and the Cisco Transport Manager. The procedures for configuring the Spirent SmartBits 6000 traffic generator and for load calibration of the Spirent Avalanche software are also explained. The process of applying disruptions to the SONET network is described. Finally, the CTM data traffic collection procedure is presented.

B. DEFINING THE TEST SCENARIO

The objective of this study was to investigate the performance of the SONET management system under loading with network disruption. In order to simulate real world conditions, the SONET network was loaded with HTTP and FTP traffic to simulate users accessing web servers and establishing FTP sessions for data transfer. For disruptions within the network, one or more ONS15454 optical systems were switched off and turned back on a couple of times each day. This manual switching process was repeated over a 10-day data collection period. The entire process would be sufficient to simulate network loading with network outages manually induced on a worst case basis.

C. CONFIGURATION OF LABORATORY EQUIPMENT

The following describes the configurations of the respective laboratory components, the traffic generation and data collection processes.

1. Laboratory Setup of Equipment

The ONS15454 optical systems and CTM management system were installed and set up by Lim [11]. The ONS15454 nodes are connected in a ring with one of the switches connected to the IP network, as shown in Figure 4. Each ONS15454 is installed with a ML1000 card which provides Gigabit Ethernet connection to the LAN. Only one IP connection is necessary as the ONS15454 optical systems are interconnected by the

SDCC channel which is provisioned in the fiber links. The SDCC channel acts as the control channel and bridges to the IP network so that the CTM server can communicate with the optical systems via this channel. Another reason that the network was set up in this manner was to simulate the different geographical locations at which these optical switches are installed.

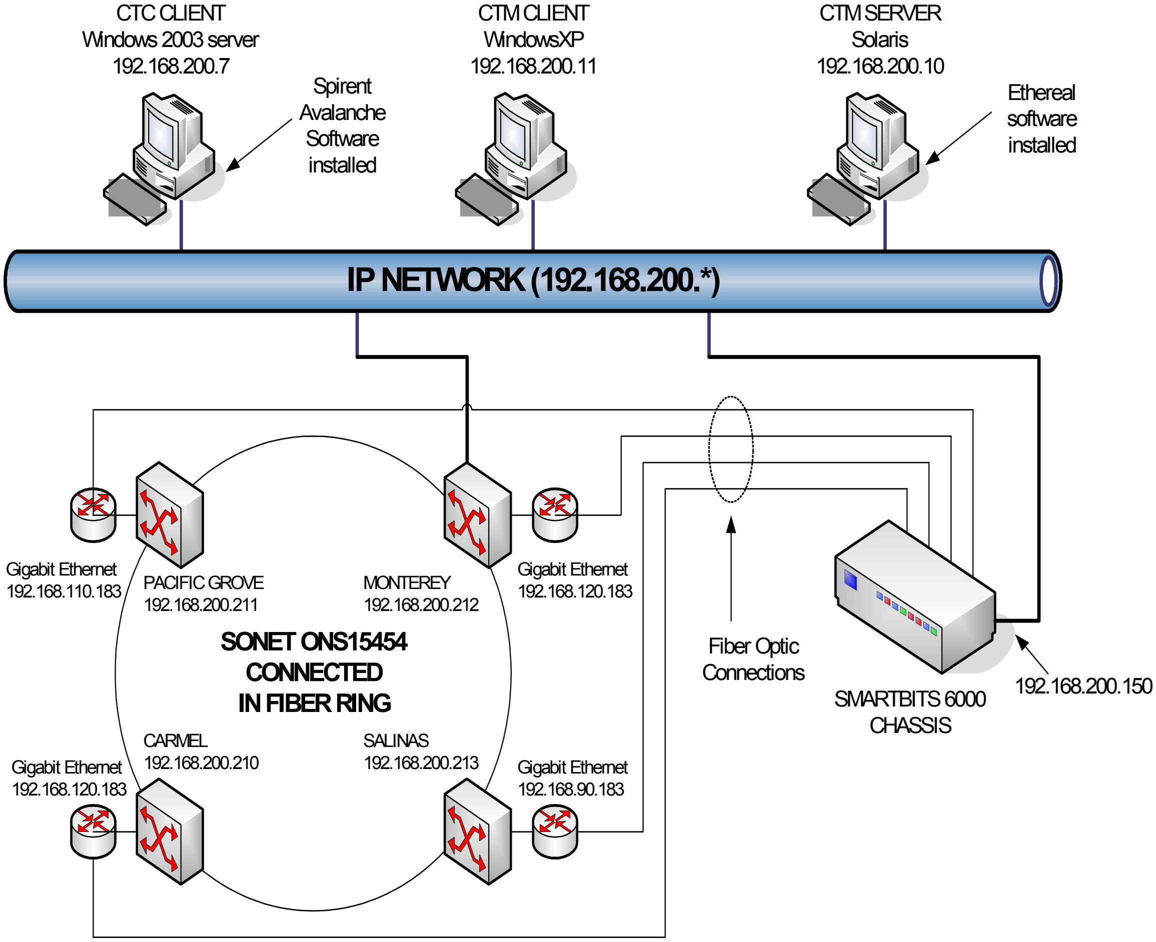


Figure 4. Laboratory Setup of the Cisco SONET system and Spirent traffic generator (After Ref. [12].)

The SmartBits 6000 chassis developed by Spirent Communications was connected to the IP network. It was installed with two TeraMetrics Gigabit Ethernet modules which provide the optical interfaces for connection to the ML1000 Gigabit interface cards on the ONS15454 chassis.

2. Configuring the ML1000 Interfaces

The ML1000 interface card supports Gigabit Ethernet access to allow bridging the LAN network to the optical transport network. Each ONS15454 was installed with this card which was connected to the TeraMetrics Gigabit Ethernet interfaces on the Spirent SmartBits 6000 chassis for data traffic to be injected into the SONET network. The IP addresses of the POS and Gigabit Ethernet interfaces of every ONS15454 card were configured by Ng [12] based on the configurations depicted in Table 1.

ONS15454 Card	Gigabit Ethernet Interface	POS0	POS1
Salinas	192.168.90.183	192.168.1.153	192.168.2.163
Monterey	192.168.100.183	192.168.1.163	192.168.2.163
Pacific Grove	192.168.110.183	192.168.1.173	192.168.2.173
Carmel	192.168.120.183	192.168.1.183	192.168.2.183

Table 1. IP addresses of the ONS15454 Packet-Over-SONET and Gigabit Ethernet interfaces (From Ref. [12].)

3. Configuring the Spirent Smartbits Traffic Generator

In order to inject real traffic into the optical network, a hardware and software setup using the Spirent Communications systems were required as shown in Figure 5. The Spirent SmartBits 6000 chassis was installed with two TeraMetrics LAN-3321A Gigabit Ethernet interface cards [17]. The SmartBits 6000 chassis and the TeraMetrics cards were configured using the SmartBits Avalanche software via the IP connection as shown in Figure 4.

4. Configuring the SmartBits 6000 Chassis

The TeraMetrics modules were configured with the settings shown in Table 2. Note that the TeraMetrics modules have to be configured in the same subnet with the Gigabit Ethernet interface cards of the ONS15454 optical systems.

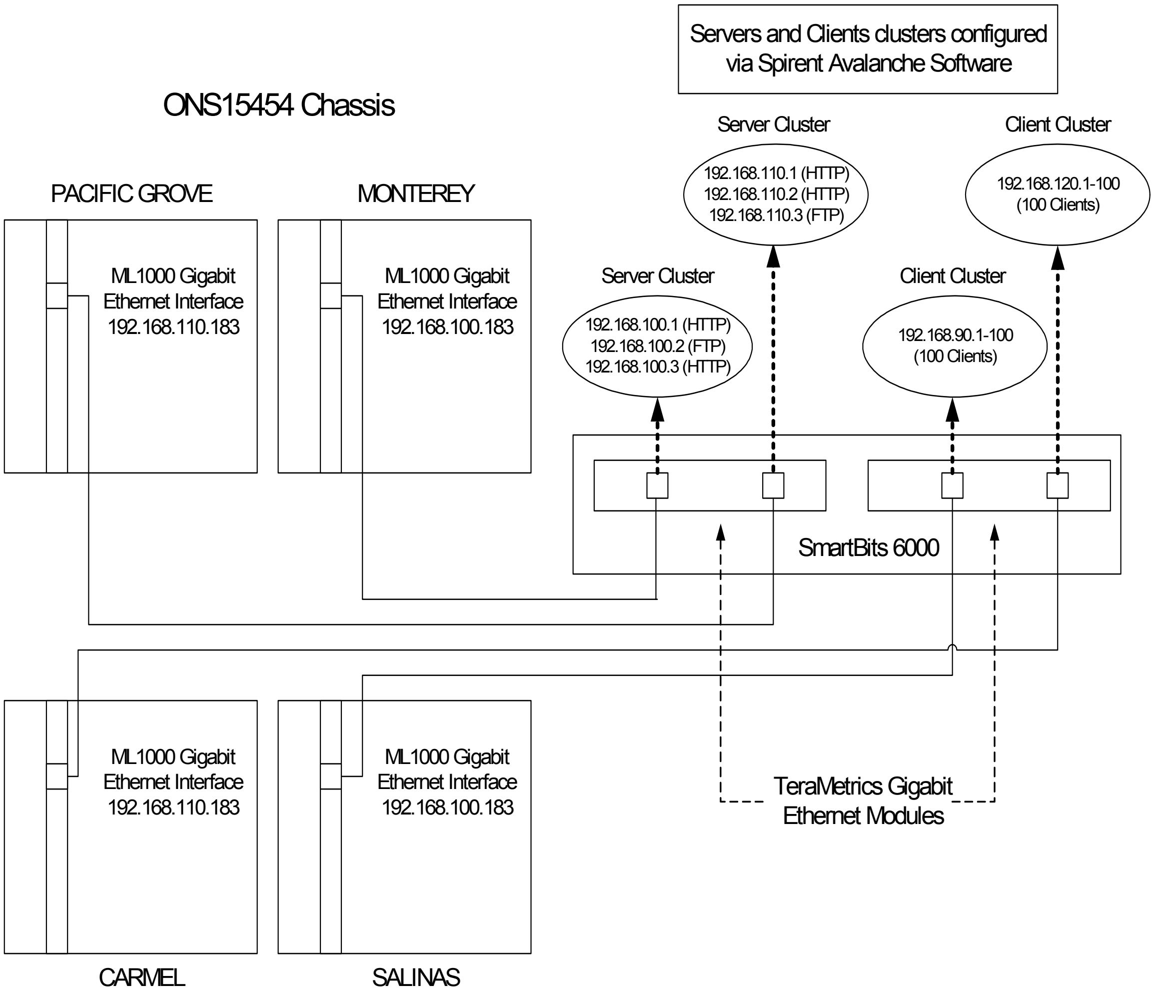


Figure 5. Connections between SmartBits 6000 and ONS15454 chassis, and configuration of servers/clients clusters of the TeraMetrics Gigabit Ethernet modules

5. Load Calibration using the SmartBits Avalanche Software

The SmartBits Avalanche software [18] was used to configure the following items:

a. Number of servers and clients

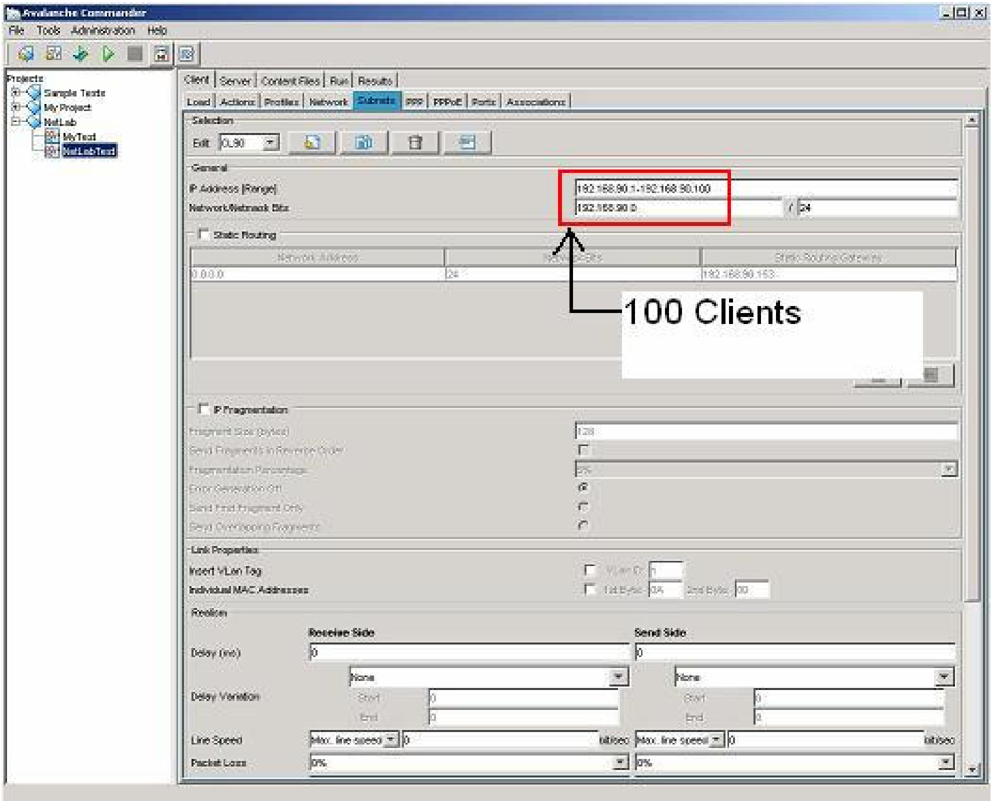
b. Types of servers (HTTP, FTP, SMTP, etc.)

c. Length of data traffic injection

Each TeraMetrics module features two fiber interface ports which are connected to the ML1000 cards on the ONS15454 chassis. One of the TeraMetrics fiber interface ports is configured as a server-LAN while the other is a client-LAN. The second TeraMetrics interface card is configured in a similar manner. Table 2 shows the configuration of the TeraMetrics modules and the connection to which ONS15454 chassis. Figure 6 shows the configuration of 100 clients and Figure 7 shows the association of the client-LANs with the respective TeraMetrics modules.

TeraMetric Module IP address	**Designated as**	**Types of servers/ clients**	**IP addresses configured in Spirent Avalanche Software**	**Connected to which ONS15454**
192.168.200.153:0 Card 1, port 0	Server-LAN	HTTP and FTP servers	192.168.100.1 (HTTP) 192.168.100.2 (FTP) 192.168.100.3 (HTTP)	Monterey
192.168.200.153:1 Card 1, port 1	Server-LAN	HTTP and FTP servers	192.168.110.1 (HTTP) 192.168.110.2 (HTTP) 192.168.110.3 (FTP)	Pacific Grove
192.168.200.154:0 Card 2, port 0	Client-LAN	100 Clients	192.168.90.1-100 100 Clients	Salinas
192.168.200.154:1 Card 2, port 1	Client-LAN	100 Clients	192.168.120.1-100 100 Clients	Carmel

Table 2. Configuration of the TeraMetrics modules the connections

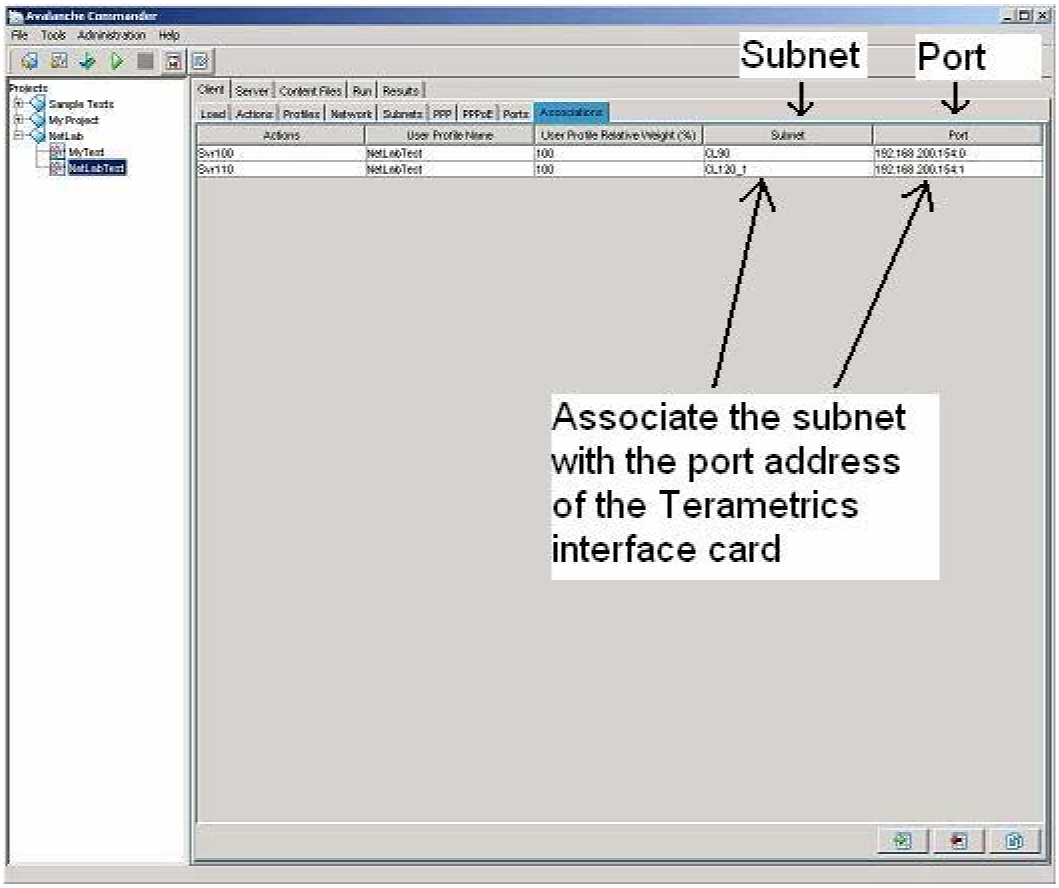


Edit CL90

IP Address (Range) 192.168.90.1-192.168.90.100

Network/Netmask Bits 192.168.90.0 / 24

Figure 6. Snapshot of configuration of the client subnets



Actions	User Profile Name	User Profile Relative Weight (%)	Subnet	Port
Svr100	NetLabTest	100	CL90	192.168.200.154.0
Svr110	NetLabTest	100	CL120_1	192.168.200.154.1

Subnet

Port

Associate the subnet with the port address of the Terametrics interface card

Figure 7. Snapshot of association of client-LANs with the TeraMetrics modules

6. Load Calibration

Once the TeraMetric modules were configured, the data traffic load calibration was configured using the model shown in Figure 8. Using the Spirent Avalanche software, four phases of the loading process were configured. Phase I is the ramping up of the data traffic to a height of *X* number of connections. Phase II is known as stepping whereby the number of connections is increased by steps of *X* from *X* to 4*X*. Phase III is known as the sustaining stage whereby the maximum number of connections are held for a period of time. Finally at Phase IV, the ramp down process, the number of connections are brought to zero.

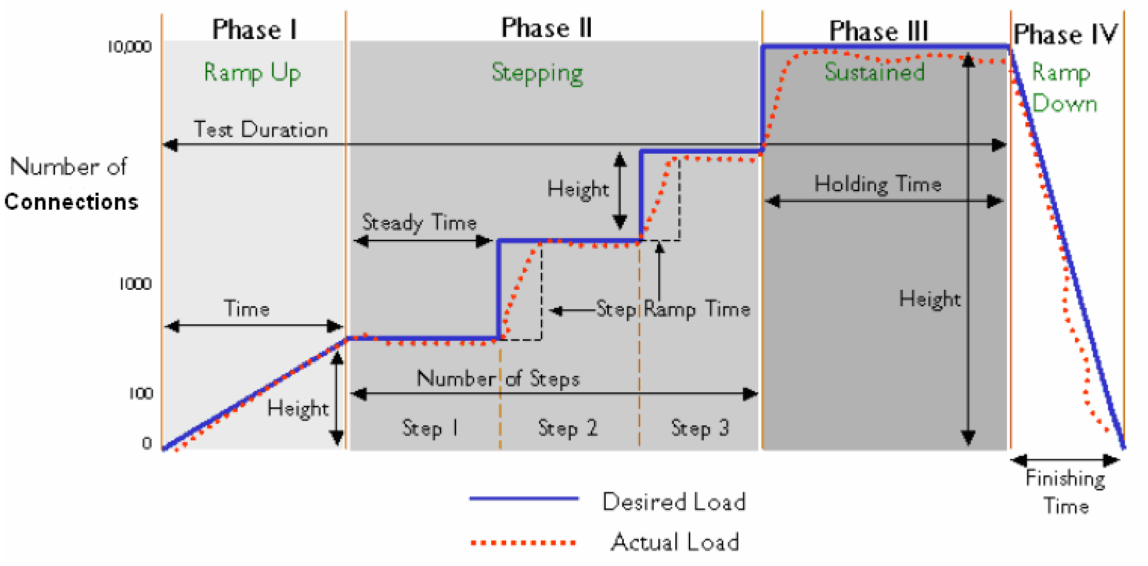


Figure 8. Diagram of the data traffic generation test phases (From Ref. [13].)

Based on the requirement of 10-day data collection period, the settings in Table 3 were configured in the "Load" submenu of the Spirent Avalanche software.

Phases	Settings	Values	Units
Phase 1: Ramp up	Time	300	Seconds
	Height	50	Connections
Phase 2: Stepping	Step ramp time	300	Seconds
	Step steady time	215,625	Seconds
	Step height	50	Connections
	Number of steps	3	
Phase 3: Holding	Holding time	215,625	Seconds
	Holding height	200	
Phase 4: Ramp down	Minimum finishing time	300	Seconds
Total time	300 + 300 × 3 + (215625) × 3 + 215625 + 300 = 864,000 seconds or 10 days		

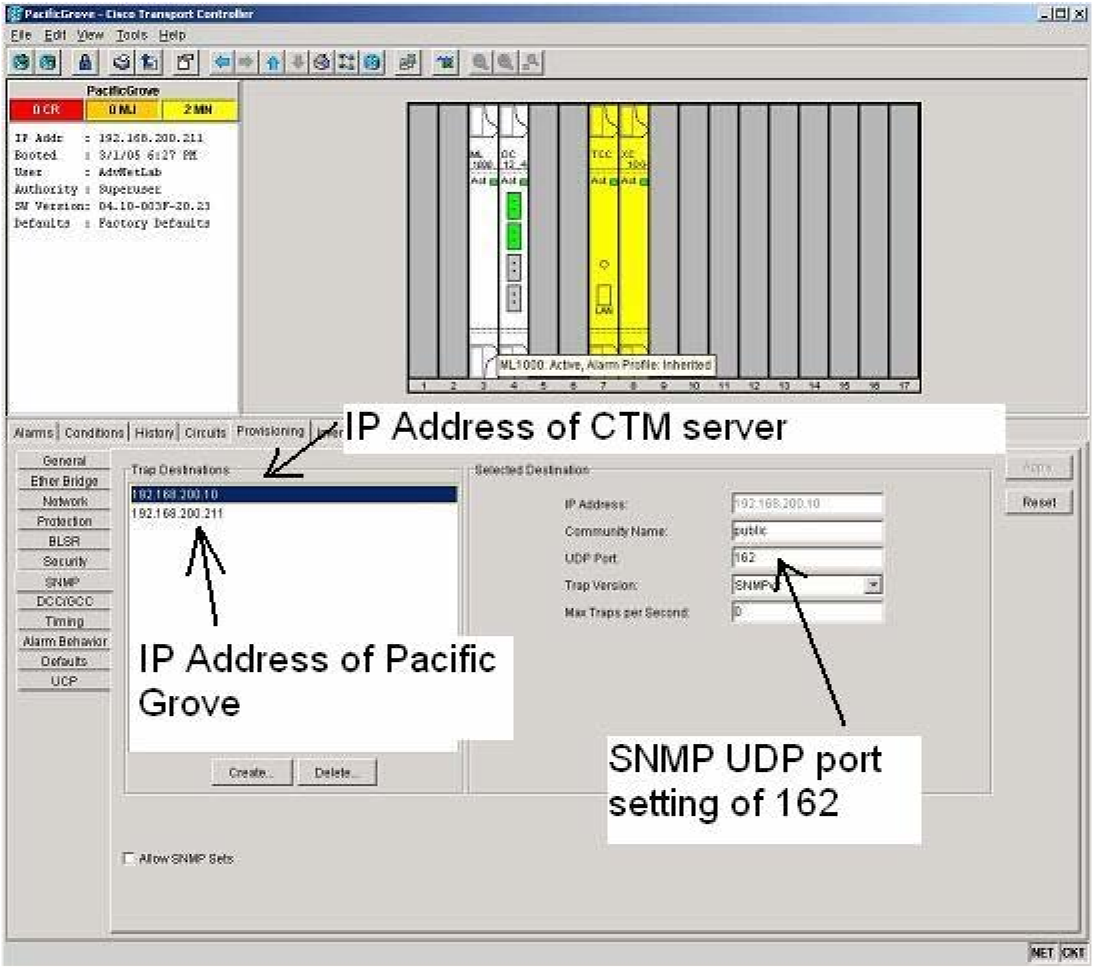
Table 3. Load calibration settings of the Spirent Avalanche software

7. Configuring the SONET Network Management System

In order to ensure that the CTM management traffic is flowing through the SDCC link, the following additional steps have to be taken.

Using the CTC client, each ONS15454 was configured with SNMP destination address of 192.168.200.10 and port number 162 so that SNMP traps could be sent to the CTM server. Port 163 is used for CTM server communicating with ONS15454. Figure 9 shows a snapshot of the SNMP trap setting for Pacific Grove. The IP address of the CTM server is entered with the UDP port number set to 162.

Next, the CTM Client is initiated to ensure that the management services and processes are configured. As depicted in the CTM Client "NEService" submenu window of Figure 10, the ONS15454 "green arrow" is up signifying that the management services are running on the CTM server. This is the management information conveyed in the SDCC link.



IP Addr : 192.168.200.211
Booted : 3/1/05 6:27 PM
User : AdvNetLab
Authority : Superuser
SW Version: 04.10-003F-20.23
Defaults : Factory Defaults

Trap Destinations:
192.168.200.10
192.168.200.211

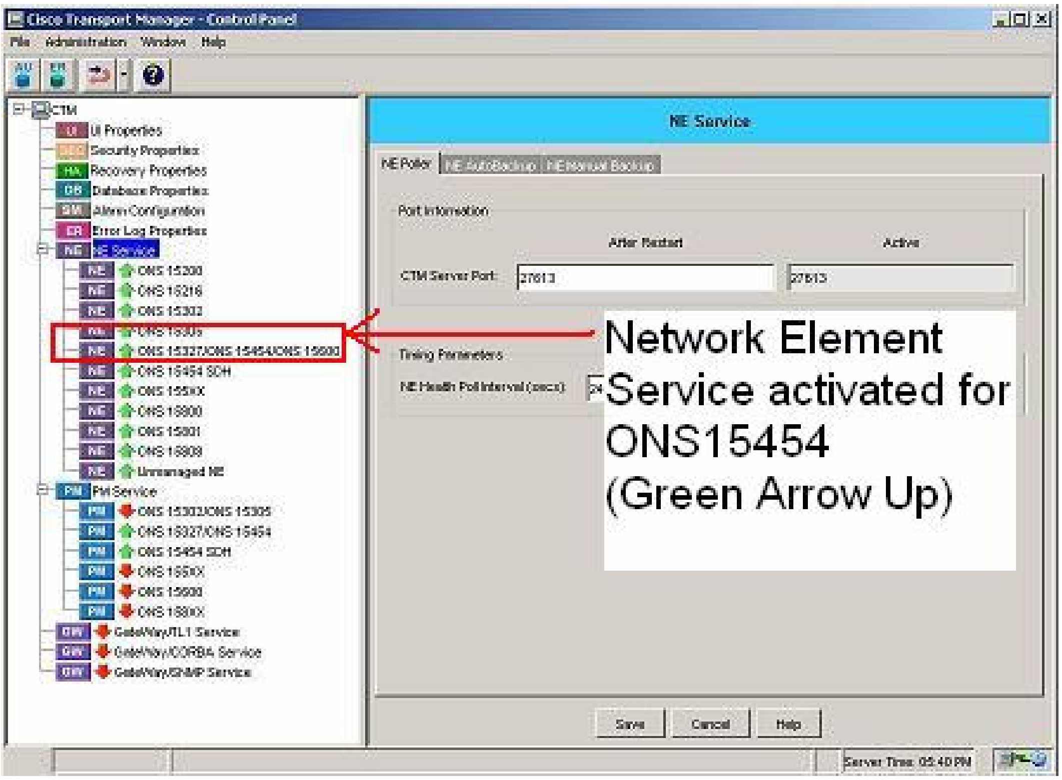
IP Address: 192.168.200.10
Community Name: public
UDP Port: 162
Trap Version: SNMPv
Max Traps per Second: 0

IP Address of CTM server

IP Address of Pacific Grove

SNMP UDP port setting of 162

Figure 9. Snapshot SNMP traps settings in the CTC Client interface

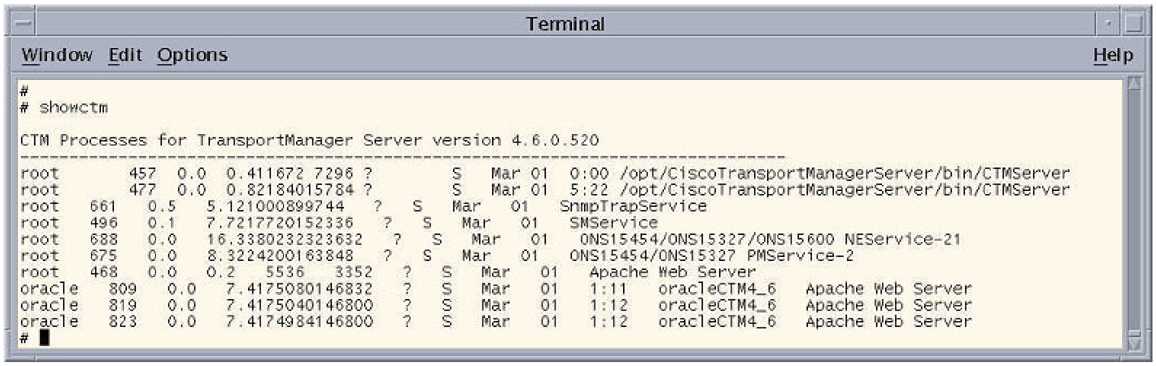


CTM Server Port: 27613 27613

Network Element Service activated for ONS15454 (Green Arrow Up)

Figure 10. Snapshot of management services and processes settings in the CTM Client interface

Lastly, on the Solaris machine where the CTM server is running, the command "showctm" is executed to display the management processes which have been configured to run. Figure 11 shows the snapshot from the Solaris machine which displays the processes of "SnmpTrapService," "SMService," and "NEService" running on the CTM server.



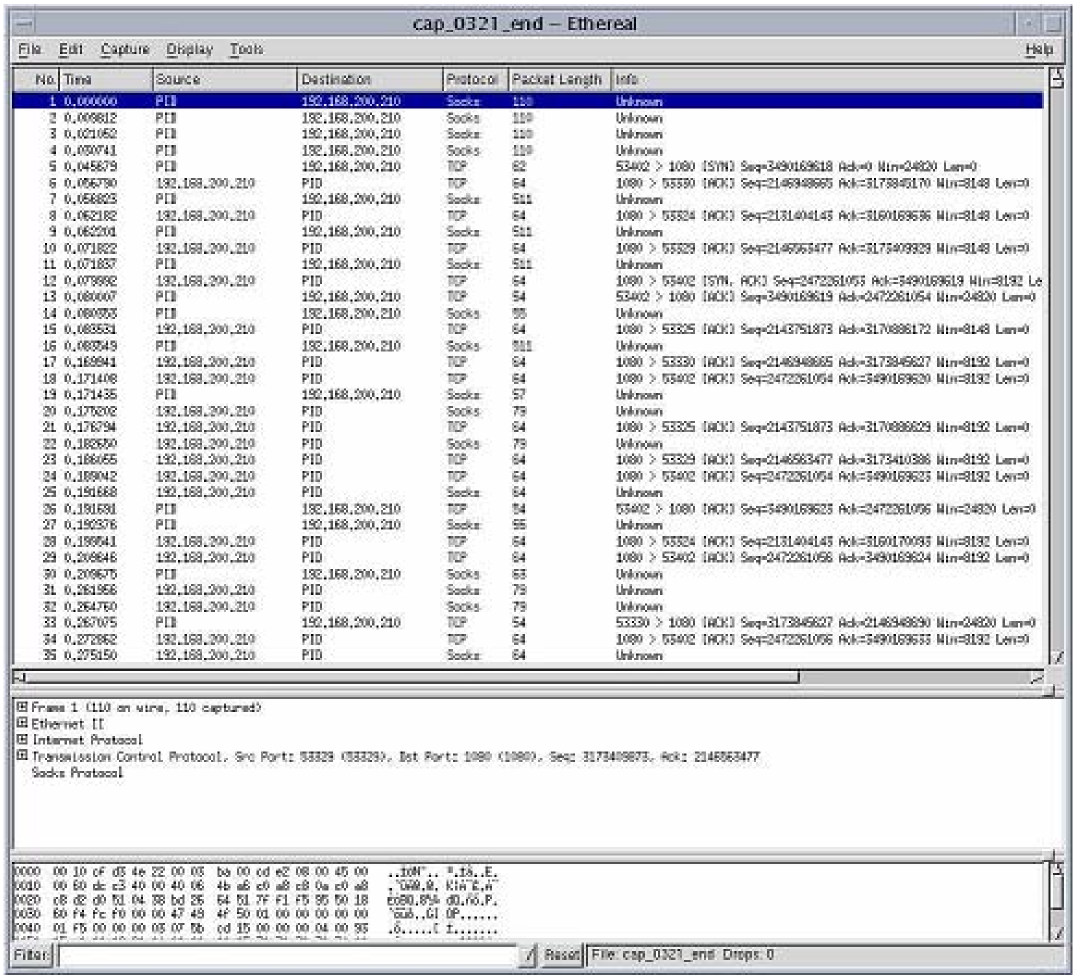
```
#
# showctm

CTM Processes for TransportManager Server version 4.6.0.520
--------------------------------------------------------------------------------
root        457  0.0  0.411672 7296 ?        S   Mar 01  0:00 /opt/CiscoTransportManagerServer/bin/CTMServer
root        477  0.0  0.82184015784 ?        S   Mar 01  5:22 /opt/CiscoTransportManagerServer/bin/CTMServer
root   661   0.5   5.121000899744   ?   S   Mar   01   SnmpTrapService
root   496   0.1   7.7217720152336   ?   S   Mar   01   SMService
root   688   0.0   16.3380232323632   ?   S   Mar   01   ONS15454/ONS15327/ONS15600 NEService-21
root   675   0.0   8.3224200163848   ?   S   Mar   01   ONS15454/ONS15327 PMService-2
root   468   0.0   0.2   5536   3352   ?   S   Mar   01   Apache Web Server
oracle   809   0.0   7.4175080146832   ?   S   Mar   01   1:11   oracleCTM4_6   Apache Web Server
oracle   819   0.0   7.4175040146800   ?   S   Mar   01   1:12   oracleCTM4_6   Apache Web Server
oracle   823   0.0   7.4174984146800   ?   S   Mar   01   1:12   oracleCTM4_6   Apache Web Server
# █
```

Figure 11. Snapshot of CTM management processes

8. Configuring Ethereal

After the SONET network and the Spirent traffic generator have been set up, the data packets of the CTM server are ready to be collected. An open source data packet sniffer known as Ethereal is installed on the Solaris server to collect the CTM management traffic. Figure 12 shows a snapshot of the Ethereal application running on the CTM server. It captures all incoming and outgoing packets at the CTM server and records the arrival times and packet lengths of all the packets.



```
No. Time      Source           Destination      Protocol Packet Length Info
  1 0.000000  PID              192.168.200.210  Socks    110           Unknown
  2 0.009812  PID              192.168.200.210  Socks    110           Unknown
  3 0.021052  PID              192.168.200.210  Socks    110           Unknown
  4 0.030741  PID              192.168.200.210  Socks    110           Unknown
  5 0.045879  PID              192.168.200.210  TCP      62            53402 > 1080 [SYN] Seq=3490169618 Ack=0 Win=24820 Len=0
  6 0.056790  192.168.200.210  PID              TCP      64            1080 > 53330 [ACK] Seq=2146948665 Ack=3173845170 Win=8148 Len=0
  7 0.058823  PID              192.168.200.210  Socks    511           Unknown
  8 0.062182  192.168.200.210  PID              TCP      64            1080 > 53324 [ACK] Seq=2131404145 Ack=3160169636 Win=8148 Len=0
  9 0.062201  PID              192.168.200.210  Socks    511           Unknown
 10 0.071822  192.168.200.210  PID              TCP      64            1080 > 53329 [ACK] Seq=2146563477 Ack=3173409929 Win=8148 Len=0
 11 0.071837  PID              192.168.200.210  Socks    511           Unknown
 12 0.079892  192.168.200.210  PID              TCP      64            1080 > 53402 [SYN, ACK] Seq=2472261053 Ack=3490169619 Win=8192 Le
 13 0.080007  PID              192.168.200.210  TCP      54            53402 > 1080 [ACK] Seq=3490169619 Ack=2472261054 Win=24820 Len=0
 14 0.080953  PID              192.168.200.210  Socks    55            Unknown
 15 0.083531  192.168.200.210  PID              TCP      64            1080 > 53325 [ACK] Seq=2143751873 Ack=3170886172 Win=8148 Len=0
 16 0.083549  PID              192.168.200.210  Socks    511           Unknown
 17 0.169941  192.168.200.210  PID              TCP      64            1080 > 53330 [ACK] Seq=2146948665 Ack=3173845627 Win=8192 Len=0
 18 0.171408  192.168.200.210  PID              TCP      64            1080 > 53402 [ACK] Seq=2472261054 Ack=3490169620 Win=8192 Len=0
 19 0.171435  PID              192.168.200.210  Socks    57            Unknown
 20 0.175202  192.168.200.210  PID              Socks    79            Unknown
 21 0.176794  192.168.200.210  PID              TCP      64            1080 > 53325 [ACK] Seq=2143751873 Ack=3170886629 Win=8192 Len=0
 22 0.182650  192.168.200.210  PID              Socks    79            Unknown
 23 0.186055  192.168.200.210  PID              TCP      64            1080 > 53329 [ACK] Seq=2146563477 Ack=3173410386 Win=8192 Len=0
 24 0.189042  192.168.200.210  PID              TCP      64            1080 > 53402 [ACK] Seq=2472261054 Ack=3490169625 Win=8192 Len=0
 25 0.191668  192.168.200.210  PID              Socks    64            Unknown
 26 0.191681  PID              192.168.200.210  TCP      54            53402 > 1080 [ACK] Seq=3490169625 Ack=2472261056 Win=24820 Len=0
 27 0.192376  PID              192.168.200.210  Socks    55            Unknown
 28 0.198541  192.168.200.210  PID              TCP      64            1080 > 53324 [ACK] Seq=2131404145 Ack=3160170093 Win=8192 Len=0
 29 0.208846  192.168.200.210  PID              TCP      64            1080 > 53402 [ACK] Seq=2472261056 Ack=3490169624 Win=8192 Len=0
 30 0.209675  PID              192.168.200.210  Socks    63            Unknown
 31 0.261956  192.168.200.210  PID              Socks    79            Unknown
 32 0.264760  192.168.200.210  PID              Socks    79            Unknown
 33 0.267075  PID              192.168.200.210  TCP      54            53330 > 1080 [ACK] Seq=3173845627 Ack=2146948690 Win=24820 Len=0
 34 0.272862  192.168.200.210  PID              TCP      64            1080 > 53402 [ACK] Seq=2472261056 Ack=3490169633 Win=8192 Len=0
 35 0.275150  192.168.200.210  PID              Socks    64            Unknown
```

```
⊞ Frame 1 (110 on wire, 110 captured)
⊞ Ethernet II
⊞ Internet Protocol
⊞ Transmission Control Protocol, Src Port: 53329 (53329), Dst Port: 1080 (1080), Seq: 3173409873, Ack: 2146563477
  Socks Protocol
```

```
0000  00 10 cf d3 4e 22 00 03  ba 00 cd e2 08 00 45 00
0010  00 60 dc c3 40 00 40 06  4b a6 c0 a8 c8 0a c0 a8
0020  c8 d2 d0 51 04 38 bd 26  64 51 7f f1 f5 95 50 18
0030  60 f4 fc f0 00 00 47 45  4f 50 01 00 00 00 00 00
0040  01 f5 00 00 00 03 07 5b  cd 15 00 00 00 04 00 95
```

Figure 12. Snapshot of Ethereal application running on the Solaris machine

9. Power Disruption Simulation

The Ethereal application is executed to commence with the CTM data traffic collection process which is immediately followed by initiating the traffic generation from the Spirent Avalanche application. Figure 13 shows the routing of traffic from Carmel to

Pacific Grove when Salinas is down. During the 10-day period, the ONS15454 designated as Salinas was switched off once a day for the first 5 days. Each time the ONS15454 was switched on, the average network recovery time was about 7 minutes. For the remaining 5 days, both Salinas and Carmel were switched off 2-3 times each day.

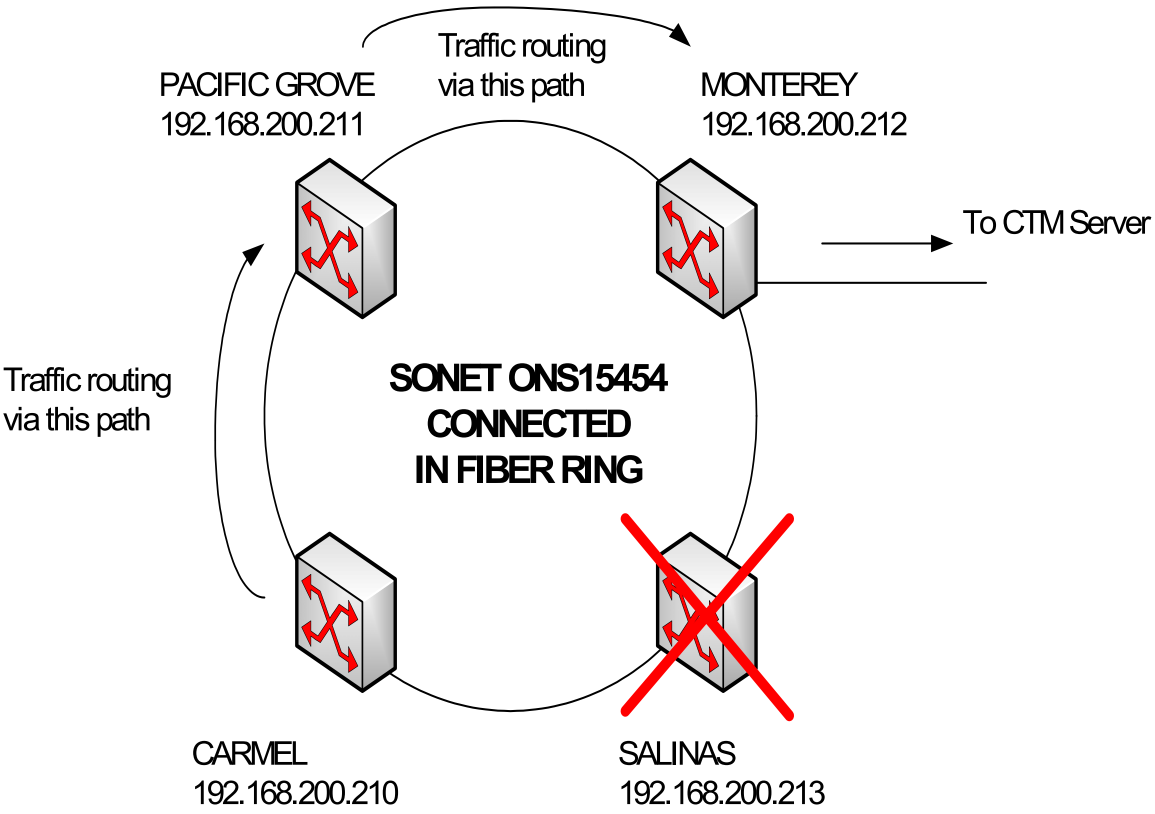


Figure 13. Power Disruption simulation of Salinas and traffic routing

During the process, the times at which the specific ONS15454 were switched off were recorded and the duration of the outage noted. Table 4 shows the complete log recorded in this study. Logging down the outage durations enables the network availability to be estimated.

From Table 4, by taking into consideration that the optical system takes about 7 minutes to synchronize the traffic flow, the network availability is estimated to be about 97.16%. Thus the network outage is about 2.84%.

Date	Time	Optical system switched off	Duration of power disruption (min)
Jan 26	1700	Test Started	
	1730	1730	1
Jan 27	0800	Salinas	1
Jan 28	1345	Salinas	1
Jan 29	0730	Salinas	1
Jan 30	0830	Salinas	1
Jan 31	0810	Salinas, Carmel	30
	1115	Salinas, Carmel	15
	1335	Salinas, Carmel	15
Feb 1	0820	Salinas, Carmel	30
	0920	Salinas, Carmel	20
	1105	Salinas, Carmel	30
	1715	Salinas, Carmel	30
Feb 2	0915	Salinas, Carmel	40
	1200	Salinas, Carmel	40
	1445	Salinas, Carmel	1
Feb 3	0915	Salinas, Carmel	1
	1105	Salinas, Carmel	1
	1405	Salinas, Carmel	1
Feb 4	0900	Salinas, Carmel	1
	1200	Salinas, Carmel	1
	1500	Salinas, Carmel	1

Table 4. Complete logging of optical system switched off over the 10-day period

D. SUMMARY

The laboratory setup and test procedures have been described in this chapter. The configurations and settings of the Cisco optical systems and network management systems are detailed. The procedures for configuring the Spirent SmartBits 6000 chassis and Avalanche software are described. In the next chapter, the relevant probability theory and the self-similarity concept are presented.

IV. PROBABILITY THEORY AND SELF SIMILARITY

A. CHAPTER OVERVIEW

This chapter presents the probabilistic theory of exponential and Poisson distribution which are important in the analysis of data traffic. Some basic queuing theory equations are also discussed which are fundamental to the analysis of the data packets. Lastly, the self-similarity concept is presented.

B. THE RANDOM VARIABLE AND PROBABILITY DISTRIBUTIONS

The random variable is a mapping of a set of elements to a sample space by a function [19]. For a random variable, *X*, the mean and variance of the random variable are defined as,

$$\mathrm{E}[X] = \overline{X} = \mu_X = \sum_{i=1}^{N} x_i P(x_i) \tag{4.1}$$

$$\mathrm{Var}[X] = \sigma_X^2 = \mathrm{E}[X^2] - (\mathrm{E}[X])^2 . \tag{4.2}$$

From the above statistical equations, an important quantity, known as the coefficient of variation, is defined as,

$$\frac{\sigma_X}{\mu_X} . \tag{4.3}$$

The coefficient of variation is a normalized measure of the degree of variability of the random variable.

In the field of queuing analysis, there are several probability distributions which are important. For the purpose of this study, the Poisson and exponential distributions will be discussed here [20].

Consider a discrete random variable, *X*, with an exponential distribution and characterized by the parameter $\mu > 0$, the mean and variance are given by, respectively,

$$\mathrm{E}[X] = \frac{1}{\mu} \tag{4.4}$$

$$\mathrm{Var}[X]=\frac{1}{\mu^2}. \tag{4.5}$$

The exponential distribution is often used to model the interarrival times between data packets, or the service time of the data packets. Notice that the coefficient of variation is equal to 1, which is a special case of the exponential distribution.

Consider a discrete random variable, *Y*, which is Poisson distributed and characterized by the parameter λ > 0, the mean and variance, respectively,

$$\mathrm{E}[Y]=\lambda \tag{4.6}$$

$$\mathrm{Var}[Y]=\lambda. \tag{4.7}$$

The Poisson distribution is important because the arrival rate of data packets is usually assumed to be Poisson distributed which forms the basis of developing the queuing theory equations. In a Poisson process, the probability of a packet arriving within an interval is independent of the arrival of the previous or next packet. If we model arrival process as Poisson, the following equations apply.

$$\Pr\{k \text{ items arrive in time interval } T\}=\frac{(\lambda T)^k}{k!}e^{-\lambda T} \tag{4.8}$$

$$\mathrm{E}\{\text{number of items arriving in time interval } T\}=\lambda T \tag{4.9}$$

$$\text{Mean arrival rate (items per unit time)}=\lambda. \tag{4.10}$$

Poisson arrivals are also considered random arrivals as the probability of an item arriving within a small interval is proportional to the interval length and independent of the time elapsed since the arrival of last item.

The Poisson process is also related to the exponential distribution. By considering interarrival times of T_a, the following relationships are defined,

$$\Pr[T_a<t]=1-e^{-\lambda t} \tag{4.11}$$

$$\mathrm{E}[T_a]=\frac{1}{\lambda}. \tag{4.12}$$

Hence, the arrival rate is the inverse of the mean interarrival time.

C. QUEUING THEORY EQUATIONS

Most process models are described by the Kendall's notation [21], *X/Y/N*, where *X* refers to the interarrival time distribution, *Y* the service time distribution, and *N* the number of server in the system. In this study, the M/M/1 model is assumed. M/M/1 is the model notation for a single-server with Poisson arrivals or exponential inter-arrival times, and exponential service times. From Equation (4.18), the arrival rate is given by,

$$\lambda = \frac{1}{\mathrm{E}[T_a]} = \frac{1}{\text{Mean Interarrival Times}}. \tag{4.13}$$

As the mean service time is related to the mean packet length and link rate, the mean service time is defined as [6]

$$T_S = \frac{\text{Mean Packet Length (bytes)} \times 8}{\text{Link rate (kbits/s)}}. \tag{4.14}$$

Consequently, combining Equations (4.20) and (4.21) gives the utilization of the link

$$\rho = \lambda T_S. \tag{4.15}$$

D. SELF-SIMILARITY IN COMPUTER NETWORKS

Self-similarity is a phenomenon described for a particular process which appears the same when viewed at different magnification of time scales. Such processes have characteristics which are very different from conventional telephone traffic, which is usually modeled as Poisson process. The paper by Leland *et al.* [8] demonstrated that Ethernet traffic is actually self-similar and that a Poisson process used to describe Ethernet traffic may not be a sufficient model.

Self-similar processes tend to exhibit persistence in clustering which suggests that clustering occurs at different time scales [20] and burstiness of traffic would occur over long periods. This is in contrast with the Poisson process where clustering usually occurs in the shorter term and smoothes out over the long term. This would suggest that a Poisson arrival will flatten out over the long term. Thus buffers of data would build up shortly and be cleared over time. For the self-similar process, this is not the case as burstiness tends to prolong over long periods of time.

The concept of self-similarity is often associated with long-range dependence (LRD) [6]. Long-range dependence signifies the persistence of self-similar processes which exhibit clustering and bursty characteristics at all time scales.

1. Modeling Self-Similarity, Long-Range Dependence and Heavy-Tailed Distributions

In order to estimate the self-similar nature of the data traffic, the Hurst parameter [20] is used. It is a measure of the persistent nature of the self-similarity phenomenon and a measure of the long-range dependence of the process. A value of $H = 0.5$ represents an absence of long-range dependence and is usually associated with Poisson processes. Values of H closer to 1 indicate a greater degree of persistence.

There are several approaches in which the Hurst parameter is estimated, such as the “R/S plots” [5]. In this study, the “Variance-Time Plot” method will be used [20]. The process x is said to be self-similar if the aggregated time series $x^{(m)}$ obeys the following,

$$\mathrm{Var}(x^{(m)}) \sim \frac{\mathrm{Var}(x)}{m^{\beta}} \tag{4.16}$$

where the self-similarity Hurst parameter is given by,

$$H = 1 - \frac{\beta}{2}. \tag{4.17}$$

Taking the log of both sides, Equation (4.16) can be written as,

$$\log[\mathrm{Var}(x^{(m)})] \sim \log[\mathrm{Var}(x)] - \beta \log(m). \tag{4.18}$$

Thus, by plotting $\log[\mathrm{Var}(x^{(m)})]$ against $\log(m)$, the result would be a straight line of slope $-\beta$. Subsequently, the Hurst parameter can be deduced from Equation (4.18).

A self-similar process is often referred to as possessing long-range dependence (LRD). LRD refers to processes which have autocovariance that decay very slowly or there exist finite samples at larger values of the distribution. LRD has the following property [20],

$$C(k) \sim |k|^{-\beta} \quad \text{as } k \to \infty, \qquad 0 < \beta < 1, \tag{4.19}$$

where $C(k)$ denotes the autocovariance function for the stationary process and k the aggregate time series for $k \geq 0$.

Note that if β is between 0 and 1, this means that H is between 0.5 to 1. Thus processes which exhibit LRD are also self-similar. Although larger β would lead to lower H, i.e., less self-similar, in this study, the terms self-similarity and LRD are used interchangeably.

A process is considered to possess a "heavy-tailed" distribution if large values of the random variable exist with non-zero probabilities [6].

2. Performance Implications, Norros Model

Proposed by Norros [22], for a given self-similar process of Hurst parameter H, the buffer requirement q is related to the utilization ρ given by,

$$q = \frac{\rho^{1/2(1-H)}}{(1-\rho)^{H/(1-H)}}. \tag{4.20}$$

Using this equation, the utilization graph (q versus ρ) could be plotted to assess whether the buffer requirements would escalate at lower utilization rates due to high degree of long-range dependence (H closer to 1). This analysis will be useful in estimating the buffer required for a particular network at the desired utilization rate or vice versa.

E. SUMMARY

This chapter has presented the probability theory and the self-similarity concepts which are essential tools required in analyzing data traffic. In the next chapter, the traffic analysis of the CTM traffic are analyzed and, using the concepts presented in this chapter, the statistical analysis is detailed.

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V. TRAFFIC ANALYSIS, PERFORMANCE MODELING AND ESTIMATION

A. CHAPTER OVERVIEW

This chapter presents the traffic analysis of the collected SONET management traffic. A close analysis is performed on the data packets collected from Ethereal which is followed by statistical analysis to determine the mean interarrival times and packet size of the different types of management traffic. Next the computations of the Hurst parameters are presented which leads to the estimation of link utilization for the different types of management traffic. Finally, comparisons with the previous research are presented.

B. TRAFFIC ANALYSIS OF SONET MANAGEMENT TRAFFIC

The SONET management traffic was collected using Ethereal during the ten-day period from 28 January to 6 February 2005. The duration of the ten-day data collection period was chosen to make it consistent with the prior research [11, 12]. Over the ten-day collection period, the total number of packets collected and the respective breakdown of the types of SONET management traffic are presented in Table 5.

	This Study	**Previous work**	
	Case 1	**Case 2**	**Case 3**
Types of traffic	**Data collected from 28 January to 6 February 2005**	**Data collected from Ng (From Ref. [12].)**	**Data collected from Lim (From Ref. [11].)**
CTM Socks	86730	94916	203278
CTM SNMPv2	3714	4332	7364
CTM Socks and SNMPv2	90444	99248	210642
CTM Ethernet	238659	206694	471103
Others	212904	98138	193333
Total (CTM Ethernet + Others	452563	304832	664436

Table 5. Breakdown of the number of data packets collected for the CTM traffic and comparison with previous works

From the data packets collected, only the Socks, SNMP and the related TCP packets related were used in this analysis. There were plenty of packets from the General

Inter-Orb Protocol (GIOP) communications which is not relevant to this study as they were routine database updates to-and-from the CTM server with the NEs, although they were part of the SONET management traffic. The Socks traffic was due to the NEs updating their status information with the CTM server, while the SNMPv2 traffic was due to the CTM server initiating "GetBulk" commands from the NEs. The total management traffic of Socks, SNMPv2 and the related TCP packets are collectively termed as "CTM Ethernet."

For the purpose of this traffic analysis discussion, Case 1 is used for this study for data collected under loading with network disruption conditions. Case 2 is used for data collected under loading, as referenced from [12]. Case 3 is referring to data collected under no-load conditions [11].

Looking at the number of packets collected from Case 1, considering that disruption was applied to the SONET network, it was found that the number of Socks and SNMPv2 were about 10% less than that collected when there was no disruption. Although the SONET network was continuously loaded by the SmartBits traffic generator, the management traffic appeared to drop by some extent. This drop is due to the network outages when the ONS15454 was turned off. It was noted that, on the average, the ONS15454 took about 7 minutes to synchronize the optical circuits after it is switched on. By taking into consideration of the outage time duration, the network availability was computed to be about 97.16%. Thus the network outage of 2.84% has caused the Socks and SNMPv2 packets to drop by 10%.

When considering the overall management traffic, the total amount of Ethernet packets was higher compared to Case 2. This could be due to CTM issuing more health status requests to the NEs that were offline but less Socks packets as the NEs were down. The increase in TCP communications was about 20% as noted from the table. Another possibility could be due to online NEs which are communicating more often with the CTM server when one of the NEs is down.

Comparing Case 1 with Case 3, the management traffic was significantly lower by more than 50%. The consequence of loading the network with applied disruption has reduced the number Socks and SNMPv2 traffic drastically. This is an interesting phenomenon as the main cause is due to the disruption. This is expected because there would be less Socks and SNMPv2 packets generated when the NEs were down.

C. STATISTICAL ANALYSIS AND COMPARISONS WITH PRIOR WORK

From the data collected, the random variables of interest are interarrival times and the packet sizes. As the total number of packets is very large, manual calculation of the statistics would be very tedious. Furthermore, in order to extract the Hurst parameter, the variances have to be computed for different aggregated time series (10, 32, 100, 320 and 1000 seconds). To simplify the process, two Mathcad script files were used to carry out the required operations. Both of these script files were developed by Lieutenant James Young from the EC4850 (Summer 2003) class. The first script file computes the mean and variances of interarrival times and packet sizes of the data collected. In addition, it also computes the variances for several aggregated time series data. The second script file computes the histogram distribution of the interarrival times and packet lengths and outputs to a Microsoft Excel file, which is then plotted to give the distribution of the data traffic.

1. Interarrival Times Distribution Graphs

Using the Mathcad script, the histogram data was generated, exported to Excel and plotted. Figures 15, 16, 17 and 18 shows the interarrival times distributions for the loading/disruption and loading/no disruption cases.

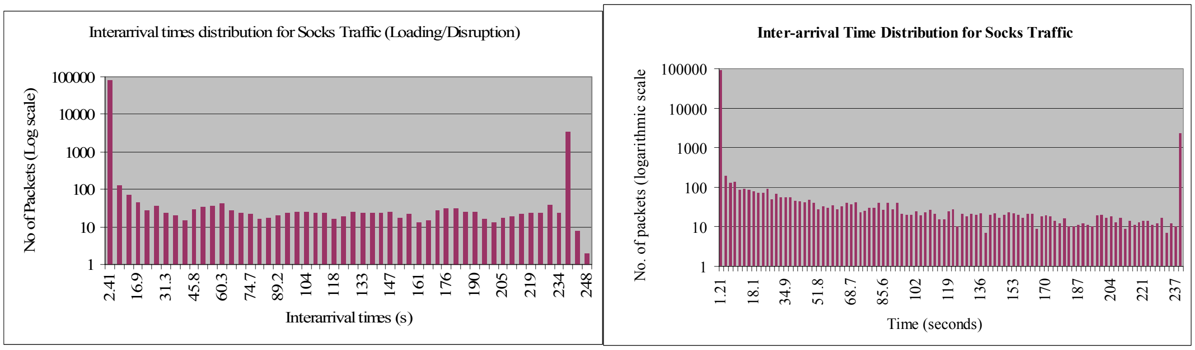

Figure 14. Distribution of Socks traffic interarrival times, loading/disruption (left), loading (Right, from Ref. [12].)

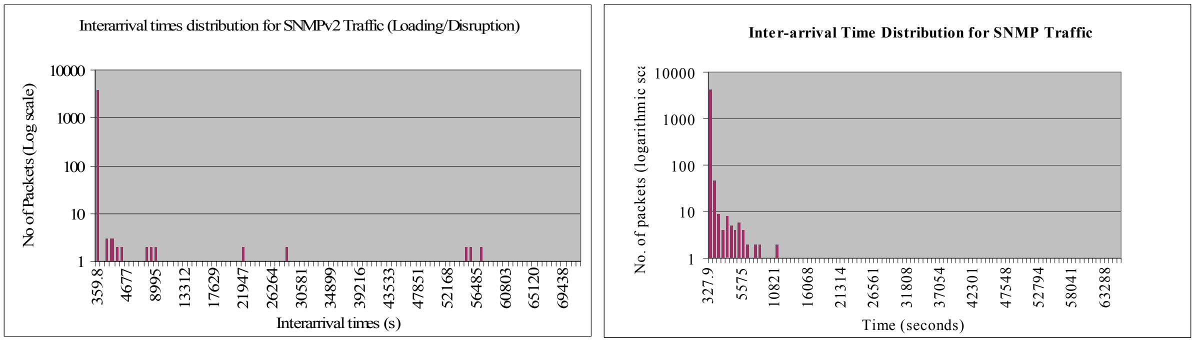

Figure 15. Distribution of SNMPv2 traffic interarrival times, loading/disruption (left), loading (Right, from Ref. [12].)

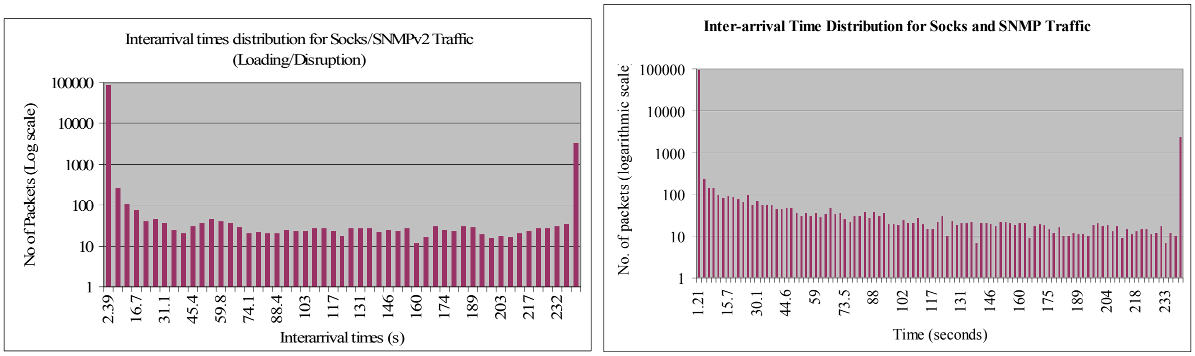

Figure 16. Distribution of combined Socks/SNMPv2 traffic interarrival times, loading/disruption (left), loading (Right, from Ref. [12].)

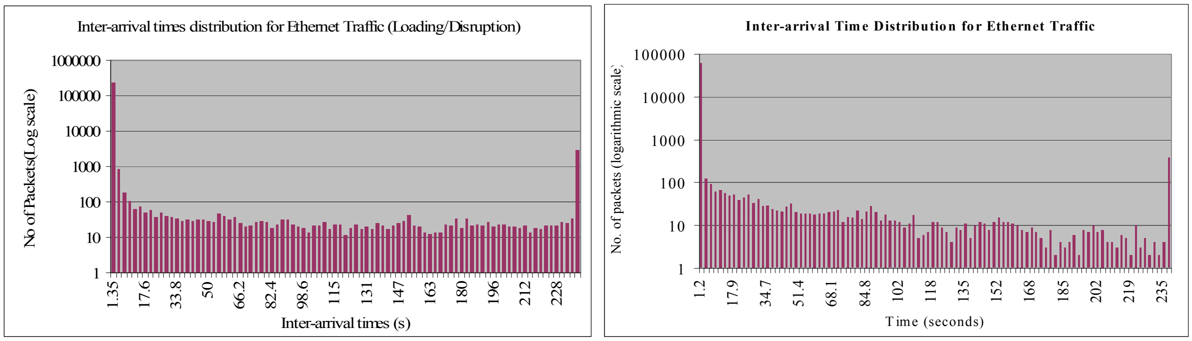

Figure 17. Distribution of Ethernet traffic interarrival times, loading/disruption (left), loading (Right, from Ref. [12].)

Figure 14 shows that the Socks traffic exhibits a "heavy-tailed" distribution. It is observed that Socks traffic with loading and disruption decays slightly faster than the loading case for small values of interarrival times. This suggests that the arrival rate is slightly smaller in the case when the network is loaded and disrupted. Although the loading/disruption case decays slightly faster, it is still "heavy-tailed." This suggests that the Socks traffic has prolonged burstiness. For the no disruption case, though, the tail is slightly larger compared to the loading/disruption case.

In Figure 15, the loading/disruption SNMPv2 traffic exhibit a slight degree of "heavy-tailed" distribution as opposed to the loading/no-loading case which resembles an exponential distribution. Close examination on the loading/disruption case appears to decay faster than that of the loading/no disruption case for small interarrival times.

In Figure 16, similar observations were made. For the combined Socks and SNMPv2 traffic, it is observed that the Socks distribution dominates as depicted by the similarity between Figures 14 and 16 for the loading/disruption case. Furthermore, it is observed that the loading/disruption case has a slightly smaller tail compared to the loading/no-disruption case and decays slightly faster for small interarrival times.

Similar observations are made for the CTM Ethernet traffic as depicted in Figure 17. In general, the loading/disruption interarrival time distribution decays faster but has a larger tail compared to the no-disruption case.

2. Interarrival Times Statistics

Using the Mathcad script, the statistics of mean, variance and coefficient of variation, using Equation (4.3) are computed. Tables 6, 7 and 8 tabulate the values for the mean, variance and coefficient of variation, respectively. The respective values are compared with those of loading, loading without disruption and no loading.

Mean, E[T_a] (s)	**Loading/ Disruption**	**Loading (From Ref. [12].)**	**No loading (From Ref. [11].)**
CTM Socks	10.858	8.2	4.553
CTM SNMPv2	253.581	179.533	120.043
CTM Socks and SNMPv2	10.413	7.842	4.394
CTM Ethernet	3.93	3.213	1.965

Table 6. Comparison of means of interarrival times

Variance (s^2)	**Loading/ Disruption**	**Loading (From Ref. [12].)**	**No loading (From Ref. [11].)**
CTM Socks	2356	1630	772
CTM SNMPv2	1.10×10^7	4.54×10^6	6.27×10^5
CTM Socks and SNMPv2	2242	1560	746
CTM Ethernet	821	543	324

Table 7. Comparison of variances of interarrival times

	Loading/ Disruption	**Loading (From Ref. [12].)**	**No loading (From Ref. [11].)**
CTM Socks	4.471	4.927	6.103
CTM SNMPv2	13.062	11.863	6.597
CTM Socks and SNMPv2	4.547	5.041	6.215
CTM Ethernet	7.293	7.249	9.159

Table 8. Comparison of coefficient of variation of interarrival times

From Table 6, it is observed that the overall means for the loading/disruption case are higher compared to those of the loading and no-loading cases. This is expected as the average duration of the network outages adds to the mean interarrival times of the statistics. For Table 7, the variances obtained from loading/disruption case are higher in general. This is expected as the network outages introduce some degree of irregularities into the interarrival times. In Table 8, it is observed that the loading/disruption coefficients of variations of the different types of traffic are close to those of loading. This might suggest that the degree of variability does not change significantly when the network was subject to disruption. In contrast, when comparing the loading/disruption case to the no-loading case, the higher value for SNMPv2 suggests that the disruptive network has increased the variability of SNMPv2 traffic significantly.

3. Arrival Rates

After computing the mean interarrival times, the arrival rates for the respective traffic are computed using Equation (4.13). Table 8 shows the arrival rate comparisons for the current work (loading/disruption case) with previous research.

It is observed from Table 8 that all arrival rates of loading/disruption case are all lower than those of loading and no-loading cases. This is expected as network outages caused a reduction of traffic between the server and the NE that was down. As for the CTM Ethernet traffic, the drop in arrival rate is fairly small, suggesting that the network outage causes little disruption to the CTM Ethernet traffic.

Arrival rates, λ (s^{-1})	**Loading/ Disruption**	**Loading (From Ref. [12].)**	**No loading (From Ref. [11].)**
CTM Socks	0.092	0.122	0.220
CTM SNMPv2	0.00394	0.00557	0.008
CTM Socks and SNMPv2	0.096	0.128	0.228
CTM Ethernet	0.254	0.311	0.509

Table 9. Comparison of arrival rates

4. Packet Size Distribution

Using the Mathcad script, the histogram data is generated, exported to Excel and plotted. Figures 18, 19, 20 and 21 shows the packet size distributions for the loading/disruption, loading and no-disruption cases.

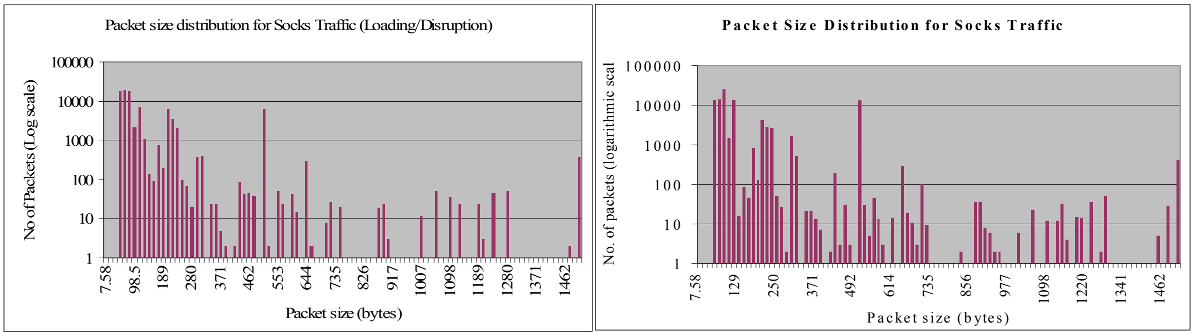

Figure 18. Distribution of Socks traffic packet sizes, loading/disruption (left), loading (Right, from Ref. [12].)

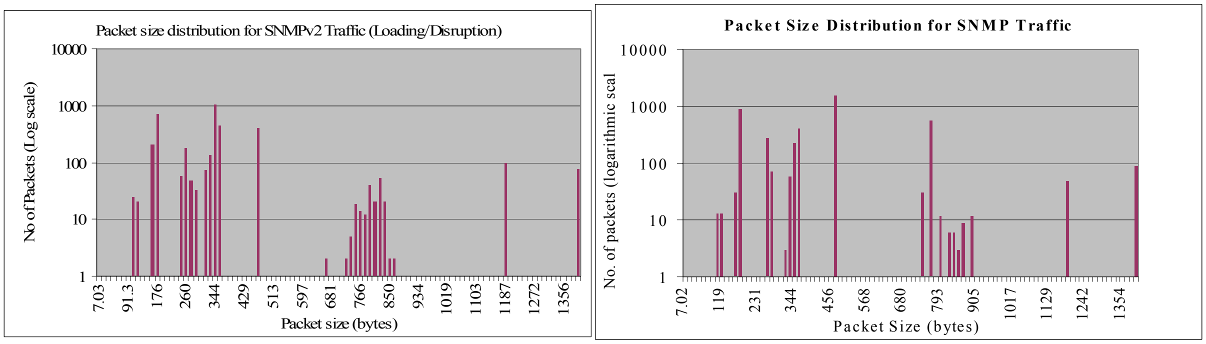

Figure 19. Distribution of SNMPv2 traffic packet sizes, loading/disruption (left), loading (Right, from Ref. [12].)

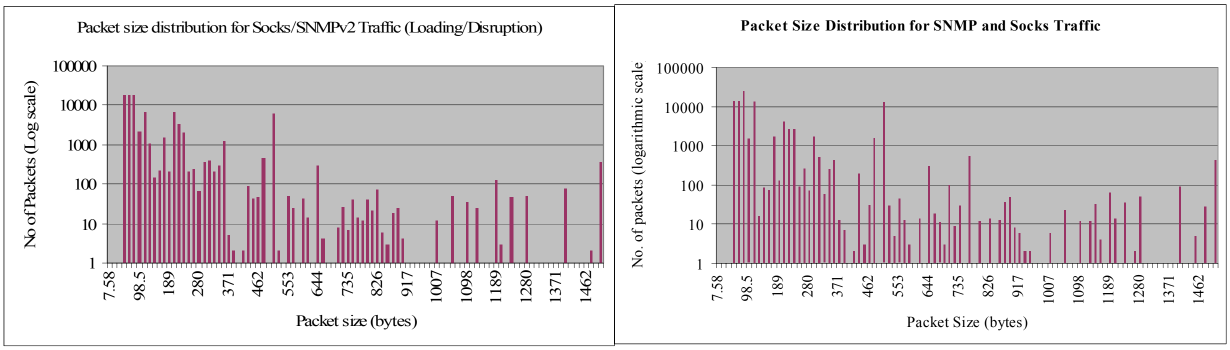

Figure 20. Distribution of Socks/SNMPv2 traffic packet sizes, loading/disruption (left), loading (Right, from Ref. [12].)

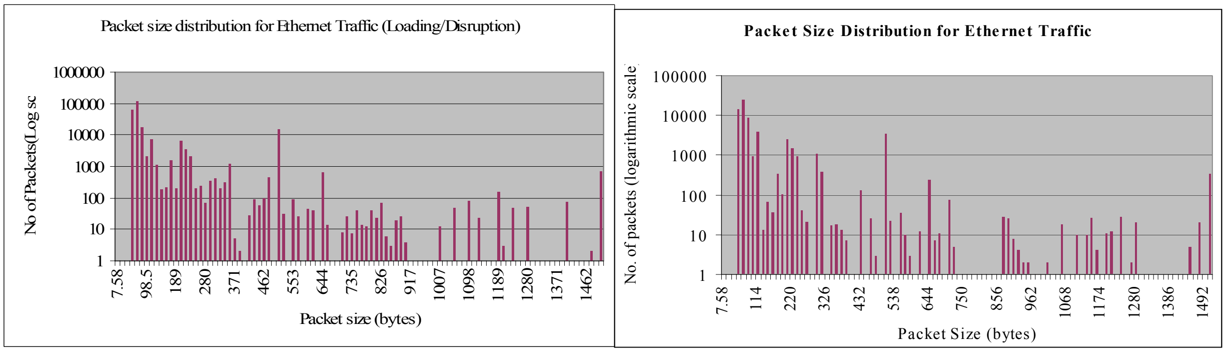

Figure 21. Distribution of Ethernet traffic packet sizes, loading/disruption (left), loading (Right, from Ref. [12].)

From Figure 18, it is observed that both loading/disruption and loading cases have similar distribution of Socks data packets. The loading/disruption case appears to have more packets in the region of 100-200 bytes. In Figure 19 of the SNMPv2 packet size distribution, it is observed that the distribution exhibits a heavy-tail as there exists finite samples at higher values. The loading/disruption case has higher number of packets in the regions of 260, 344 and 800 bytes.

In Figure 20 for the combined Socks and SNMPv2 traffic, it is observed that the loading/disruption case has a slightly heavier tailed compared to loading/no-disruption case. For Figure 21, the same observations hold for the CTM Ethernet traffic.

5. Packet Size Statistics

The mean, variance and coefficient of variation are computed and shown in Tables 10, 11 and 12, respectively.

Mean (bytes)	**Loading/ Disruption**	**Loading (From Ref. [12].)**	**No loading (From Ref. [11].)**
CTM Socks	143	172	145
CTM SNMPv2	376	441	455
CTM Socks and SNMPv2	152	184	156
CTM Ethernet	116	125	103

Table 10. Comparison of means of packet size

Variance (bytes^2)	**Loading/ Disruption**	**Loading (From Ref. [12].)**	**No loading (From Ref. [11].)**
CTM Socks	27690	35800	21537
CTM SNMPv2	62320	61200	2628
CTM Socks and SNMPv2	31260	40000	42122
CTM Ethernet	23370	27900	13118

Table 11. Comparison of variances of packet size

	Loading/ Disruption	**Loading (From Ref. [12].)**	**No loading (From Ref. [11].)**
CTM Socks	1.166	1.101	1.09
CTM SNMPv2	0.664	0.561	1.012
CTM Socks and SNMPv2	1.161	1.089	0.113
CTM Ethernet	1.321	1.334	0.996

Table 12. Comparison of coefficient of variances of packet size

From Table 10, it is observed that the mean packet size for the loading/disruption case is lower compared to both loading and no-loading cases except for the CTM Ethernet traffic. The mean packet size for loading/disruption case is lower than that of loading but higher than no-loading case. This phenomenon could be due to smaller packets been transacted between the server and the NEs or it could be as a result of more packets for the loading/disruption case compared to the loading case. As for Table 11, the loading/disruption case's variances are generally lower except for the SNMPv2 traffic which is close to that of the loading case.

For Table 10, it is observed that the coefficient of variances for the loading/disruption case is close to that of the loading case. This suggests that the network disruption did not alter the packet size distribution very much. But, when compared to the no-loading case, there is a significant difference for the SNMPv2 traffic as it is less than 1, although higher than the loading case's.

6. Service Times

From the mean packet size, the mean service times are computed using Equation (4.14). The values are shown in Table 13, along with the results from previous research. Note that during the computation, the link rates for Socks and SNMPv2 are 192 kbps, for the SDCC link, while that for the CTM Ethernet traffic is 100 Mbps.

Mean Service Times, T_s (ms)	**Loading/ Disruption**	**Loading (From Ref. [12].)**	**No loading (From Ref. [11].)**
CTM Socks	5.944	7.161	6.044
CTM SNMPv2	15.661	18.382	18.967
CTM Socks and SNMPv2	6.343	7.651	6.496
CTM Ethernet	9.257μs	10.021μs	8.214μs

Table 13. Comparison of Service Times

It is of interest to note that the service times for the Socks and SNMPv2 traffic are lower compared to the loading and no-loading cases. This is due to fewer packets sent in the network when one or two of the NEs were down. The CTM Ethernet traffic service time is lower than the loading case but higher than the no-loading case. This is because the CTM server takes slightly longer to process the packets due to the larger packet size compared to the no-loading case, while it takes a slightly shorter time to process due to the smaller packet size compared to the loading case.

7. Link Utilization

Using Equation (4.15), the link utilization for 4 NEs is computed as shown in Table 14. It is then extrapolated to determine the utilization for 2500 NEs presented in Table 15.

	Loading/ Disruption	**Loading (From Ref. [12].)**	**No loading (From Ref. [11].)**
CTM Socks	5.475×10^{-4}	8.736×10^{-4}	1.330×10^{-3}
CTM SNMPv2	6.176×10^{-5}	1.024×10^{-4}	1.580×10^{-4}
CTM Socks and SNMPv2	6.092×10^{-4}	9.793×10^{-4}	1.480×10^{-3}
CTM Ethernet	2.356×10^{-6}	3.117×10^{-6}	4.180×10^{-6}

Table 14. Comparison of link utilization for 4 NEs

	Loading/ Disruption	**Loading (From Ref. [12].)**	**No loading (From Ref. [11].)**
CTM Socks	0.342	0.546	0.830
CTM SNMPv2	0.039	0.064	0.099
CTM Socks and SNMPv2	0.381	0.612	0.926
CTM Ethernet	1.472×10^{-3}	1.948×10^{-3}	2.620×10^{-3}

Table 15. Comparison of link utilization for 2500 NEs

From the results shown in Table 15, it is observed that the effective network utilization for the combined CTM Socks and SNMPv2 traffic is lower compared to loading and no-loading cases. Intuitively, although the network utilization were expected to be lower due to disruption, the statistical analysis presented has shown that the results match the initial guess. Therefore, the net effect of loading coupled with network disruption has decreased the network utilization further due to a combination of lower arrival rate and lower service time (although lower than the loading case but higher than the no-loading case).

8. Log-Variance Versus Aggregated Interarrival Time and Packet Size Series Plots

Using the Mathcad script files, the variances for respective aggregated time series are generated and exported to Excel worksheets. The variance versus aggregate interarrival time and packet size series plots are plotted for the various CTM data traffic. Figures 22 to 29 show the variance plots for the various CTM data traffic. Note that the approximate variances values for the loading case are plotted along the same respective aggregates. The straight line is fitted to the loading/disruption plots in order to extract the gradient for the computation of the Hurst parameters.

From Figure 22, for the loading/disruption case of Socks traffic, it is observed that the log-variance values at higher aggregates of 1.5 to 3 (corresponding to 32 to 1000) are higher by about 0.5. Further, the variance is higher at smaller aggregated time-series values such that the curve has more of an exponential decay than a linear decay. This implies that there exists a higher degree of long-range dependence over the long term than over the short term.

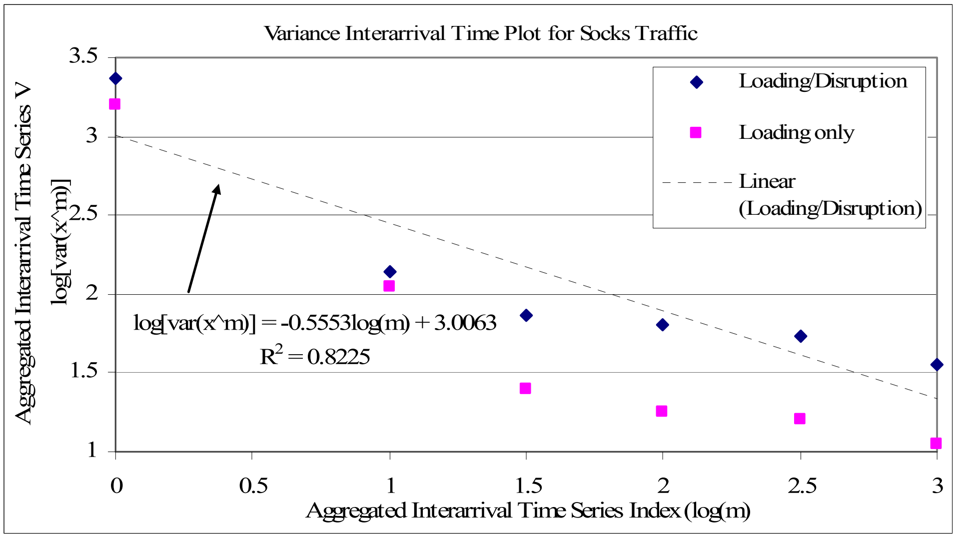

Figure 22. Graph of Variance-time plots for Socks traffic

From Figure 23, for the loading/disruption case of SNMPv2 traffic, it is observed that the log-variance values at aggregate values above 1.5 are higher compared to the loading case. At an aggregate value of 3, the difference is almost 1 which corresponds to a factor of 10.

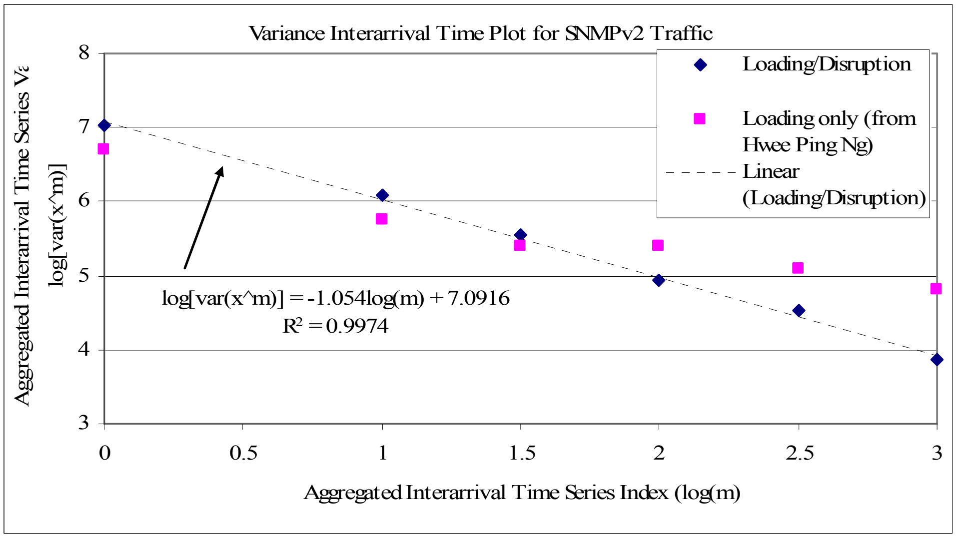

Figure 23. Graph of Variance-time plots for SNMPv2 traffic

From Figure 24, for the loading/disruption case of combined Socks/SNMPv2 traffic, it is observed that the log-variance values are higher compared to that of the loading case. Again, the curve exhibits more of an exponential decay implying that there may be higher long-term dependence over longer intervals.

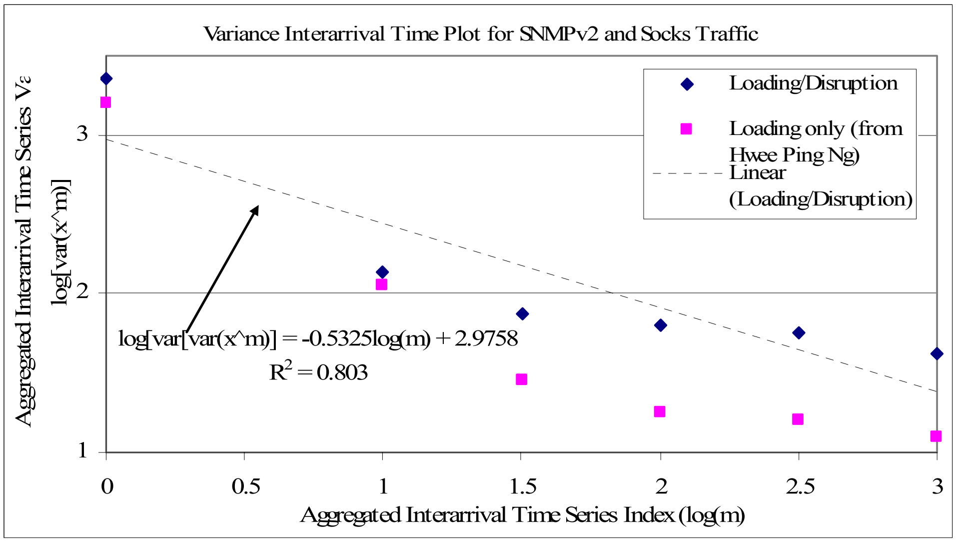

Figure 24. Graph of Variance-time plots for combined Socks/SNMPv2 traffic

From Figure 25, for the loading/disruption case of the CTM Ethernet traffic, it is observed that the log-variance value at aggregate 1 is higher by about 1 (or factor of 10).

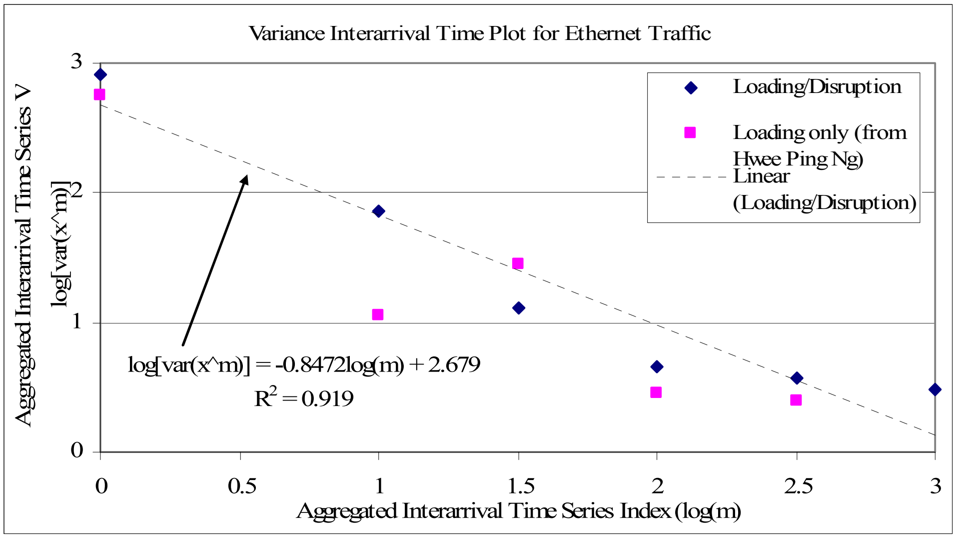

Figure 25. Graph of Variance-time plots for Ethernet traffic

From Figures 26 to 29, for the loading/disruption case of packet size, the log-variance values are very close to that of the loading case. This suggests that the packet size distribution varies slightly due to disruption. In Figure 29, it is observed that the log-variances values for the loading/disruption case are lower compared to the loading case. At a log aggregate time series of 1, the value is higher by about 0.7 (or a factor of 5).

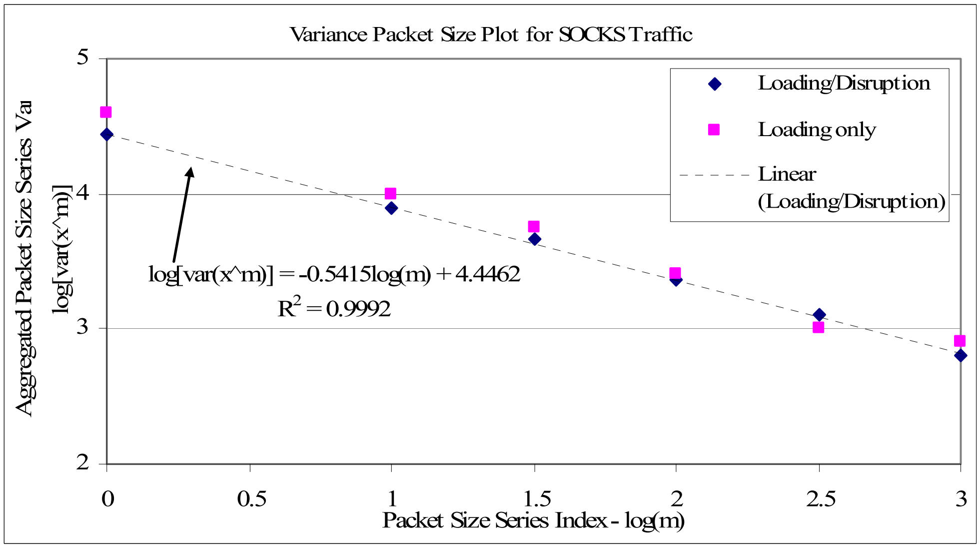

Figure 26. Graph of Variance-packet size plots for Socks traffic

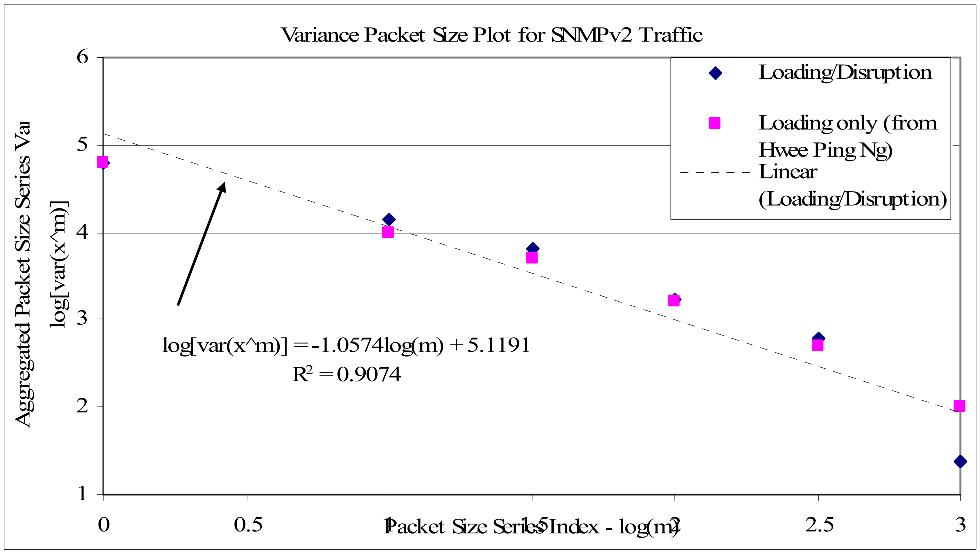

Figure 27. Graph of Variance-packet size plots for SNMPv2 traffic

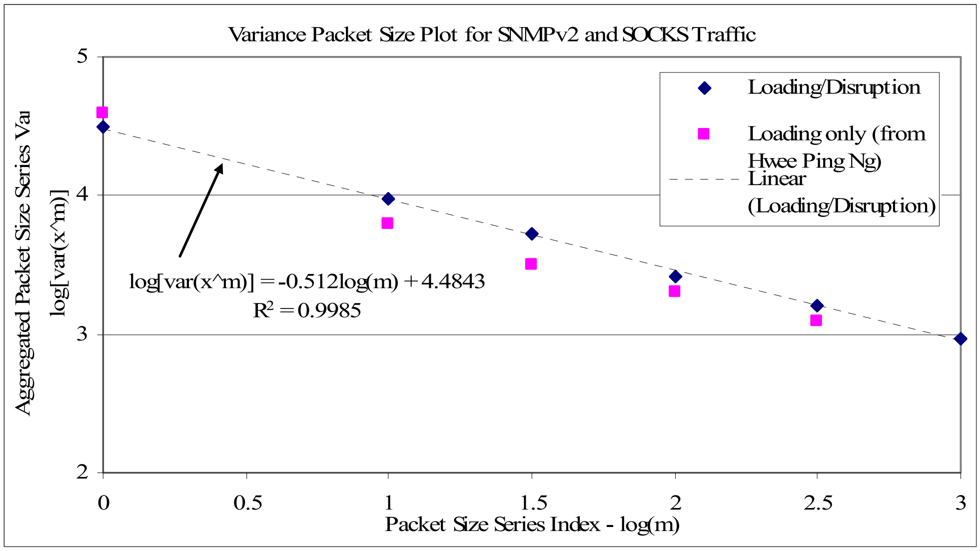

Figure 28. Graph of Variance-packet size plots for combined Socks/SNMPv2 traffic

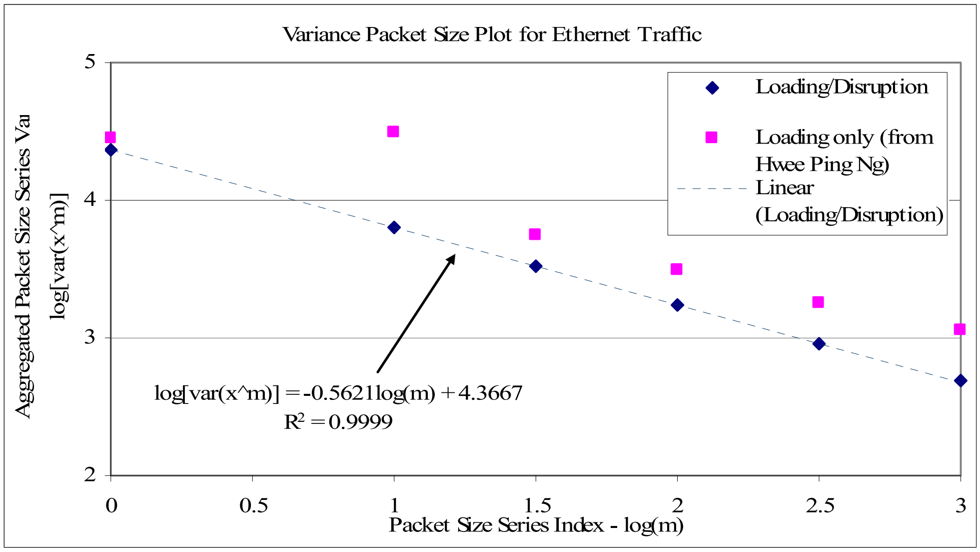

Figure 29. Graph of Variance-packet size plots for Ethernet traffic

9. Self-Similarity Analysis and Hurst Parameter

From Figures 22 to 29, the respective gradients of the straight-line fits were extracted for computation of Hurst parameters. Tables 16 and 17 present the Hurst parameter computed using Equation (4.17) after extracting the slope ($-\beta$) from the straight-line fit.

Interarrival Times	**Loading/ Disruption**	**Loading (From Ref. [12].)**	**No loading (From Ref. [11].)**
CTM Socks	0.7224	0.8073	0.5050
CTM SNMPv2	0.4730	0.8314	0.7024
CTM Socks and SNMPv2	0.7338	0.8124	0.5108
CTM Ethernet	0.5764	0.7334	0.6838

Table 16. Comparison of Hurst parameters of interarrival times

Packet Size	**Loading/ Disruption**	**Loading (From Ref. [12].)**	**No loading (From Ref. [11].)**
CTM Socks	0.7293	0.8256	0.5567
CTM SNMPv2	0.4713	0.7349	0.9066
CTM Socks and SNMPv2	0.7440	0.8248	0.6227
CTM Ethernet	0.7190	0.8430	0.8025

Table 17. Comparison of Hurst parameters of packet size

On the Hurst parameters for the interarrival times, the loading/disruption-case values are lower compared to loading-case values. This suggests that the management traffic has become less self-similar which is due to the network disruption. As noted above, there is some short-term bias in these values which may be closer to the non-disruption case over the long term. The loading/disruption-case Socks and the combined Socks/SNMPv2 traffic are more self-similar compared to the no-loading case, while the loading/disruption-case CTM Ethernet traffic is less self-similar compared to no-loading case. This is consistent with the earlier analysis of the interarrival times distribution graphs as the higher degree of the long-range dependence implies lower β , which means a higher H value by Equation (4.17). It is of interest to note that SNMPv2 has a Hurst value less than 0.5, which suggests that the SNMPv2 traffic is not self-similar.

Similar observations are made for the packet sizes. In general, the loading/disruption-case packet sizes deceases in its self-similarity compared to the loading case, while the SNMPv2 packet size is not self-similar. The loading/disruption-case Socks and the combined Socks/SNMPv2 packet sizes are more self-similar compared to no loading case, but the loading/disruption case Ethernet traffic is slightly less self-similar compared to no-loading case.

10. Effects of Self-Similarity on the Queue Size

To understand the effect of self-similarity on the queue size, the graphs for q versus ρ are plotted for different Hurst parameters using Equation (4.20) based on Norros' model. Figures 30 and 31 show the graphs for $q = 10$ and 100, respectively.

From Figure 30, it is observed that moving from a utilization rate of $\rho = 0.38$ to 0.67, the queue size increases by 10 fold. In Figure 31, going from $\rho = 0.67$ to 0.83 causes the queue size to increase further to 100. This is highly undesirable as more packets are building up at the queue of the CTM server. Too much queuing is undesirable. Hence, for safe operation, the number of NEs should not exceed 2495. Coincidentally, this figure corresponds to the specification that the CTM server can manage a maximum of 2500 NEs.

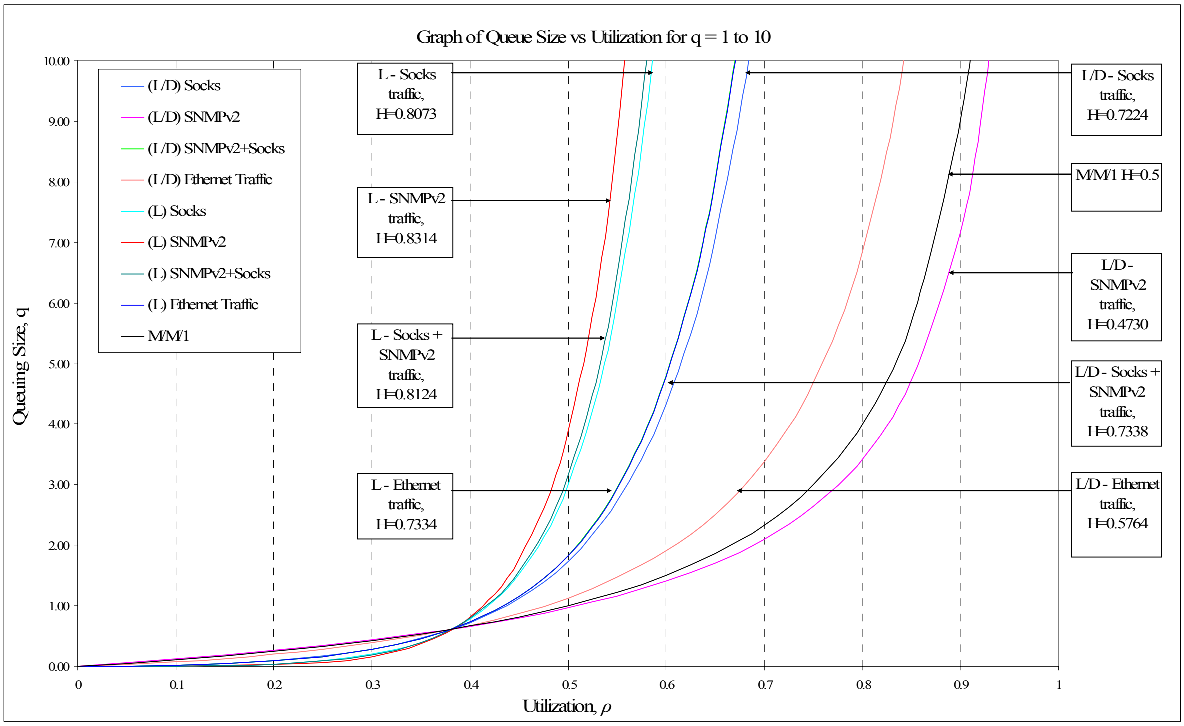

Figure 30. Graph of Queue Size vs Utilization for q = 1 to 10

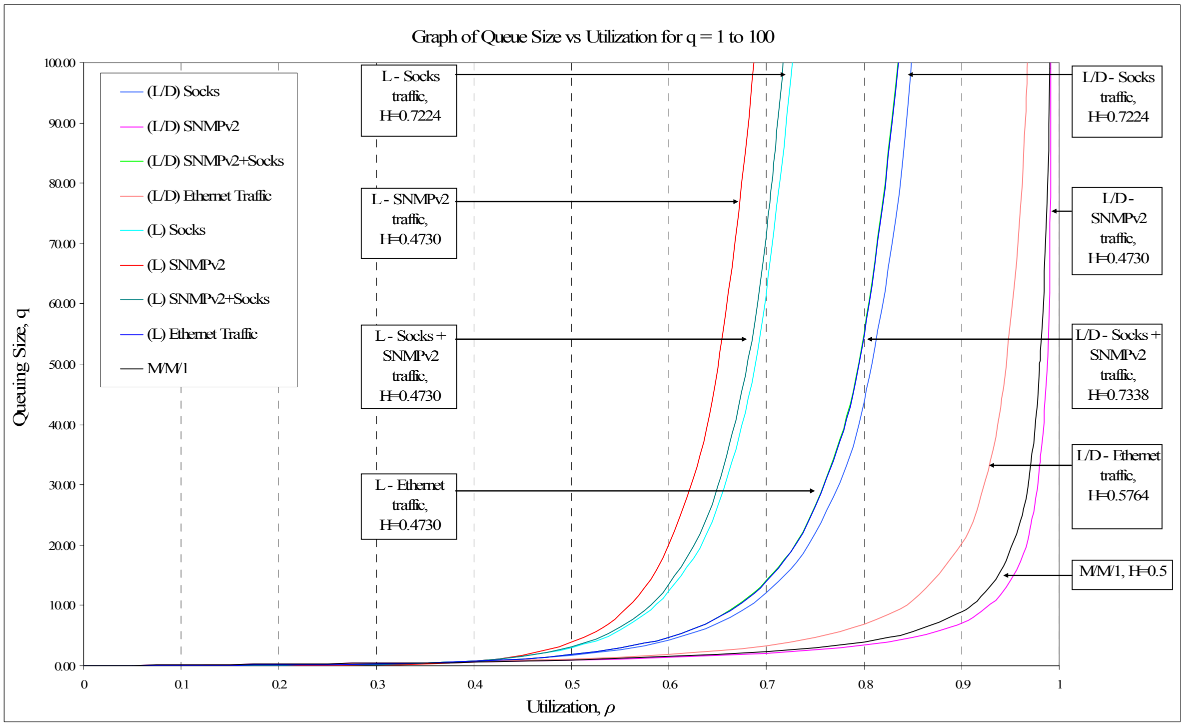

Figure 31. Graph of Queue Size vs Utilization for q = 1 to 100

11. Maximum Number of Manageable NEs

In the computation of the number of manageable NEs, only the CTM's combined Socks and SNMPv2 traffic are of interest as they occupy the 192-kbps SDCC link. It is noted that when $\rho = 0.38$, the queue sizes of all the data traffic are less than 1. In order to maintain a queue size of less than 1 at the CTM server, the utilization must not exceed 0.38; therefore the corresponding number of NEs for the respective CTM server traffic are computed as shown in Table 18.

	Loading/ Disruption	**Loading (From Ref. [12].)**	**No loading (From Ref. [11])**
CTM Socks	2776	1739	1142
CTM SNMPv2	24611	14843	9620
CTM Socks and SNMPv2	2495	1552	1027

Table 18. Comparison of number of NEs for $\rho = 0.38$

It is observed that the number of manageable NEs based on the CTM's combined Socks and SNMPv2 traffic is 2495 which is a 61% increase from the loading case. It should be noted, however, that this is a liberal estimate due to the bias of short-term aggregated time series on the Hurst parameter calculation. Prudent operation would suggest operating with fewer NEs on the network.

D. SUMMARY

In this chapter, the traffic and statistical analysis of the CTM management data packets collected has been presented. The statistics of the interarrival times and packet sizes were also computed and distribution graphs plotted. The log-variance vs. aggregated interarrival times and packet sizes graphs were plotted which allows the gradients of the straight-line fit to be extracted and the Hurst parameter computed. Finally, the effects of utilization on the queue size were discussed with the help of queue size plots. From the statistical analysis, much understanding was gained on the nature of the CTM traffic under loading and disruption conditions.

The next chapter concludes the analysis and the findings. Future possible research areas are also discussed.

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VI. CONCLUSION AND FUTURE RESEARCH AREAS

A. CHAPTER OVERVIEW

This chapter summarizes the traffic and statistical analysis of the SONET Network Management System CTM server data traffic and observations. From the findings of the analysis, several future research areas are proposed.

B. CONCLUSION

The analysis of the CTM management traffic has shown that the Socks and SNMPv2 traffic decreases when the SONET network is fully loaded and disruptive power failures are applied. Further, the total number of CTM Ethernet packets of the SONET management system is about 20% higher compared to the amount of data packets collected when the SONET network was fully loaded without any disruption. This is an interesting phenomenon as the server has initiated more TCP transactions but less Socks and SNMPv2 packets in the event of disruption within the SONET network. The increase in TCP packets is probably due to the CTM server polling for the health status of the NEs which are down. It may also be associated with TCP retransmissions due to timeout conditions. Nevertheless, the total Ethernet traffic is observed to be about 50% less compared to the case when the SONET network is not loaded. Hence, it is concluded that the nature of the CTM server traffic is such that more Ethernet traffic is generated when the NE is down, while less Socks and SNMPv2 packets are observed when the NE is down.

Further analysis of the data packets collected using statistical methods reveal more interesting facts about the CTM management traffic. The statistical means of the interarrival times of CTM's different management traffic (Socks, SNMPv2 and Ethernet), were all higher compared to the case when the network was not disrupted. The higher means are due to the time outages during which the offline NE is not communicating with the CTM server. The evaluation of the coefficient of variation for the interarrival times revealed that the CTM's different management traffic vary only slightly when a SONET network is disrupted, even though the graphs of the interarrival time distribution depicted that the loading/disruption exhibit slightly faster exponential decays. This, in turn, suggests that the arrival rate for the loading/disruption case is lower which means that mean interarrival times are higher. This is consistent with the higher mean interarrival times computed.

Although the SONET network was fully loaded and disruption injected into the network, the packet length distributions of the CTM management traffic (includes Socks, SNMPv2 and Ethernet) appeared to vary very little as depicted by the graphs. Again, this is consistent with the close coefficient of variation values between the loading/disruption and loading case. Nevertheless, the mean packet sizes of the CTM Ethernet traffic was lower for the loading/disruption case which is due to more TCP packets generated by the CTM server. Interesting enough, the Socks and SNMPv2 traffic mean packet sizes were lower even though there is less Socks and SNMPv2 traffic. Thus, it is concluded that the TCP packets generated by CTM server have a more dominant effect.

The self-similarity analysis revealed a more interesting nature about the CTM management traffic. The Socks traffic Hurst value of 0.7224 was found to be lower than the loading case of 0.8073, but higher than no-load case of 0.505. There is a bias due to the short-term aggregated time series which means that these estimates should be liberally considered. The lower Hurst value suggests that disruption with a loaded network has reduced the degree of self-similarity while still high enough due to network loading compared to no-load case. This suggests that the less bursty nature of the Socks traffic is a result of the offline NE(s) which is/are not sending Socks packets to the CTM server.

On the self-similarity analysis of the loading/disruption SNMPv2 traffic, the Hurst value of 0.4730 suggests the absence of self-similarity as it is less than 0.5. This is consistent as a Hurst value of 0.5 or less indicates the absence of long-range dependence which is apparent in the SNMPv2 interarrival time distribution graph. This also suggests that the SNMPv2 becomes less bursty over prolonged operation in an environment that is affected by severe network outages. This would mean that SNMPv2 operation could break down in the event of network outages which would result in CTM server not updated with the latest management information of the NEs. Thus it is concluded that the CTM SNMPv2 traffic does not operate well in a network environment with severe network outages.

The combined Socks and SNMPv2 traffic Hurst value was found to be lower than the loading case of 0.8124, but higher than no-load case of 0.5108. This is similar to the Socks traffic case which suggests that the Socks traffic has a more dominant self-similarity nature than SNMPv2. The Ethernet traffic's Hurst value of 0.5764 is less than both the loading and no-load values of 0.7334 and 0.6838, respectively. This indicates that the Ethernet traffic has become less self-similar due to network disruption. Similar observations were made on the packet-size Hurst values for the CTM management traffic.

The loading/disruption link utilization was computed as 0.381 for 2500 NEs. This value is lower compared to both loading ($\rho = 0.612$) and no-loading ($\rho = 0.926$) cases, even though the total Ethernet packets collected for the loading/disruption case is more than the loading case while less than that of no-load case. Thus, the total number of packets collected does not relate to the degree of link utilization but, rather, statistical methods have to be employed to compute the resultant utilization. The lower link utilization suggests that SDCC link has been less utilized due to the offline NE.

The effect of link utilization on queue size was investigated so as to determine the amount of queuing buffer required at different utilizations. It was observed that increasing the utilization from 0.38 to 0.67 (corresponding to 4400 NEs), for the combined Socks and SNMPv2 traffic, the queue size would increase from 1 to 10. The queue will again be increased to 100 if the link utilization is further increased from 0.67 to 0.83 as we increase the number of NEs to 5450. Therefore, even though the SDCC link would achieve link utilization of 0.83 for 5450 NEs, the queue size would be 100 which is undesirable. Therefore, for safe operation, while adhering to a queue size of 1 ($\rho = 0.38$) at the CTM server, the number of manageable NEs was computed as 2495 under loading/disruption conditions. This value is close to the CISCO specification of 2500 manageable NEs for the CTM server, although it should be considered aggressive as there is some short-term bias affecting the calculation.

The effects of power loading coupled with power disruptions have been studied in this thesis and the work will be useful for high-speed computer networks administrators. The results and findings of this thesis will benefit the SONET network administrators by increasing their awareness of the limitations of SONET network management systems so as not to expand the network beyond 2500 NEs. They will also understand the behavior of SONET management traffic in a power disruption environment and that the CTM is able to function in the disruptive environment simulated in this thesis. Further, this research provides the ability to optimize the deployment of SONET optical systems, based on the utilization of the management traffic presented, in order to tackle network problems associated with network loading and power disruptions.

C. FUTURE RESEARCH AREAS

The traffic and statistical analysis have allowed the nature of the CTM server traffic be thoroughly investigated under the condition when the SONET fiber network is fully loaded and disruption injected. A number of future possible research areas have been identified as follows.

1. Varying the Number of Network Elements and Network Topology

As the current work is performed on four NEs connected in a ring configuration, the results may possibly be different if more NEs are added. It is proposed that at least two NEs to be added to the current network. With two additional NEs, a total of six NEs would be available which allows all six of them to be connected in single ring network or a dual ring network. The results would be very useful for a network administrator to decide on which configurations optimize the CTM 4.6 management system.

2. Performance Analysis of SONET SDCC Link Performance

The current work has analyzed the performance of the CTM 4.6 in managing the Network Elements under network loading and disruptive conditions. As the analysis was investigated at the IP layer, the SDCC link performance was not analyzed. It would be an interesting research area to analyze the physical optical layer performance to understand what happens to the SDCC link when the network is disrupted and how the link recovers from the disruption.

3. Correlation between Network Outages and Network Utilization

This study has investigated the performance of the CTM server traffic under loading and disruption. As the disruption was simulated randomly, i.e., the frequency at which the NE is switched off and the number of NEs turned off, further investigation could be made to ascertain whether is there any correlation between the degree of outages and statistics or self-similarity nature of the CTM server management traffic.

4. Comparing CTM 4.6 with Third-party Network Management Systems

As SONET/SDH is an open optical transport standard, there exists several network management systems on the market which claim to support SONET/SDH equipment. Purchase and evaluation of third-party SONET/SDH network management systems to compare the differences in performance as well as scalability is recommended. Examples of third-party SONET/SDH management systems are the Navis® Optical Management System (OMS), marketed by Lucent Technologies [23], and the Alcatel 1350 Management Suite [24].

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