Society for Science and Education
United Kingdom

TNC Transactions on Networks and Communications

Volume 3, Issue 5
ISSN: 2054 -7420

Links Utilization in MPLS Networks Operating with Traffic Engineering Signal Protocols

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ABSTRACT

Multiprotocol Label Switching (MPLS) is a technology that ensures efficient transmission with high speed and lower delays. Traffic Engineering (TE) signal protocols are usually used for active management of the MPLS networks for efficient utilization of resources. This paper presents performance investigation of MPLS TE signal protocols to get a guideline to utilize transmission links efficiently. Comparison is made between two TE signal protocols, namely Resource Reservation Protocol (RSVP) and Constraint-based Routing Label Distribution Protocol (CR-LDP). Simulation results are presented for three MPLS networks having different topologies, which are implemented in OPNET (version 14.5) environment to support different applications in the absence and presence of quality of service (QoS) algorithms. The results reveal that MPLS network with CR-LDP TE signal protocol has better performance in the term of link utilization. The RSVP reserves certain paths for transmission while the CR-LDP utilizes almost all of the available links.

Key words: MPLS Networks, Traffic Engineering Signal Protocols, Quality of Service.

1 Introduction

Multi Protocol Label Switching is raised from the Internet Engineering Task Force's (IETF) effort to standardize a number of proprietary multilayer switching solutions that were initially proposed in the mid-1990s. MPLS integrates layer 3 (routing) and layer 2 (switching) functionalities [1]. MPLS introduces connection-oriented forwarding model by replacing the routing of IP packets based on the IP header information with the short four-byte label-based switching, as shown in Figure (1).

The mechanism does not build forwarding decision based on the traditional destination IP address on sophisticated lookup routing table. This fixed-length switching concept is to some extent similar to that used in ATM and Frame Relay networks, and it is independent of the used layer 2 technologies. MPLS has been designed to provide an admirable solution to present shortcomings of IP routing in the area of Traffic Engineering (TE), Quality of Service (QoS), Virtual Private Networks (VPN) and Differentiated Services (DiffServ) [2]. In comparison of DiffServ with MPLS which is evolving as a futurity protocol. MPLS is desirable over DiffServ since it utilizes "Multi Protocol Architecture" depending on simple label switching technique. Traffic can be simply differentiated thereby ensuring QoS based on traffic types. Applications like VPNs need MPLS to achieve high quality end-to-end service. The new and better network topologies-

DOI: 10.14738/tnc.35.1448
Publication Date: 14th September 2015
URL: http://dx.doi.org/10.14738/tnc.35.1448

Any Transport over MPLS (AToM), MPLS over Voice over Internet Protocol (VoIP) and video traffics etc. have resulted in perceivable QoS [3].

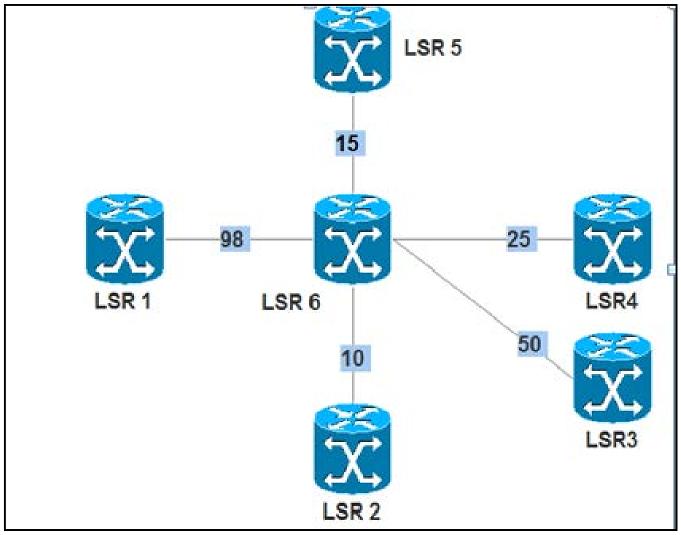


Figure (1): MPLS forwarding label between routers. LSR denotes Label Switching Router

MPLS enabled network can provide efficient TE services, flow based services, better traffic shaping, etc. In [4], routing based traffic flow shaping is introduced, where total traffic is split over multiple Label Switching Paths (LSPs) in the MPLS network. This method is powerful for solving some of the routing problems like mismatch and bottleneck problems. Network with MPLS can propose good QoS to delay critical traffic such as meetings, VoIP and video conference. Network failure such as crash of network elements, link faults or congestion are easily managed in MPLS networks [5].

MPLS can be considered a technology to forward the packets in IP intangible networks. The Entire MPLS network can be split into two parts namely MPLS edge and MPLS core [6]. MPLS edge is the border of the MPLS network consisting of egress and ingress routers. MPLS core bound intermediate Label Switching Routers (LSRs), through which Label Switched Paths (LSPs) are established [7].

A traffic engineering matter in the Internet consists of setting up paths between the edge routers in a network to meet traffic needs while attaining low congestion and improving the utilization of network resources. Practically, the usual key purpose of traffic engineering is to eliminate the utilization of the most heavily used links in the network, or the maximum of link utilization. As the maximum link utilization qualitatively reveals that congestion sets in when link utilization rises higher, and hence it is necessary to eliminate the link utilization throughout the network such that no bottleneck link occurs. It is known that this problem of reducing the maximum link utilization can be achieved by the multi-commodity network flow formula of powerful routing, which leads to dividing traffic over multiple paths between source and destination pairs [8]. This paper addresses link utilization in MPLS-based networks incorporating TE signal protocols and Qos algorithms.

2 Related Work

In 2010, Shyry and Ramachandran [9] discussed the effect of MPLS on network performance with the aid of the Nash equilibrium algorithm. The results show that optimized performance can be obtained by reducing the latency and raising the link utilization. But rising link utilization leads to a gradually increase of the congestion in the network. To overcome this specific problem, a formulation called dual programming formulation was performed which has group of constraints that have to be satisfied along with Open Shortest Path First (OSPF) protocol so as to eliminate the maximum link utilization.

In 2011, Pelsser and Bonaventure [10] discussed the Service Provider's (SP's) requirements for the utilization of MPLS LSPs across Autonomous System (AS) boundaries. A minimum set of extensions was introduced to Resource Reservation Protocol-Traffic Engineering (RSVP-TE) that allows setting inter-AS LSPs in accordance with the Service Provider requirements. The results show how LSP protection techniques can be extended to provide links or node failure protection for the border routers and inter-AS.

In 2012, Bongale [5] compared link utilization among networks running Routing Information Protocol (RIP), Open Shortest Path First (OSPF) and MPLS. The results showed that networks configured with OSPF and RIP routing technicalities are not capable of managing the incoming traffic efficiently. When the network traffic increases, shortest path from source node to destination node is heavily congested and lead to loss of transmitted data, while MPLS is capable of handling incoming traffic effectively by portioning the traffic over unutilized links. This will ensure packets, that entering into MPLS core, to reach the destination with minimum queuing delay. The results also indicate that MPLS-TE is most appropriate for enormous traffic volume. OPNET simulator was used to get the results and performance was compared considering data consisting of voice traffic and web browsing only.

In 2012, Aziz et al. [11] presented a QoS performance study of real-time applications such as video conferencing and voice in terms of Packet Delay Variation (PDV) over DiffServ in the absence and presence of MPLS-TE in IPv4/IPv6 networks using OPNET simulator. The interaction of Assured Forwarding (AF) traffic aggregation, Expedited Forwarding (EF), link congestion, in addition to the effect of performance metric like PDV were also studied. The performance of DiffServ and MPLS-TE combination in IPv4/IPv6 network was elucidated and analyzed. The results show that IPv6 encounter more PDV than their IPv4 counterparts.

In 2013, Bhandure et al. [12] studied MPLS and Non-MPLS networks and presented an overview of the MPLS technology and related IETF standards. The results show that MPLS is faster and has better performance than traditional IP routing. Performance was compared by observing parameters such as number of transmitting received packets, Jitter (delay variation) and end-to-end delay. GNS 3.0 simulator was used to simulate the networks. The simulations were setup using a traditional IP network without TE (composed of OSPF and BGP) and MPLS network (composed of OSPF and BGP).

In 2013, Ibrahim [13] discussed the performance of MPLS-TE signal protocols, namely the Resource Reservation Protocol (RSVP) and Constraint based Routed–Label Distribution Protocol (CR-LDP), with different applications including voice, video and data. Performs evaluation of the two protocols shows that CR-LDP outperforms the RSVP in terms of response time and the average transmitted and received packets in all applications. The link utilization capability of these protocols was also addressed with different transmission loads.

In 2014, Sulaiman and Alhafidh [14] discussed the performance analysis of multimedia traffic over MPLS communication networks with TE. The performance metric ofMPLS-TE and IP model networks was compared. The compared parameters were end-to-end delay, delayvariation, packet send and receive, File Transfer Protocol (FTP) responsetime. The results show that MPLS-TE performance is better than traditional IP network model.

Most of the previous works focuse on traffic performance comparison between both MPLS and Non-MPLS networks by using simulation tools. This paper focuses mainly on the performance of MPLS networks when TE is taking into account with some signaling protocols (CR-LDP and RSVP) and QoS algorithms. Emphasize is being placed on the key role played by link utilization.

3 Background

This section introduces brief description of MPLS network and TE signal protocols.

3.1 MPLS Network

In MPLS, packets are sent to their destinations by labeling them and forwarding them. Short, fixed-length labels are added to the IP packets when they enter the network. Consequently, instead of using the IP header information, the labels are used to forward the packets to their destinations. To do this, a new protocol is developed for classifying the labels. Extensions to existing protocols are also used to ease this [15].

MPLS can be considered a technology to forward the packets in IP intangible networks. The Entire MPLS network can be split into two parts namely MPLS edge and MPLS core [16]. MPLS edge is the border of the MPLS network consisting of egress and ingress routers shown in Figure (2). MPLS core bound intermediate Label Switching Routers (LSRs), through which Label Switched Paths (LSPs) are established [16].

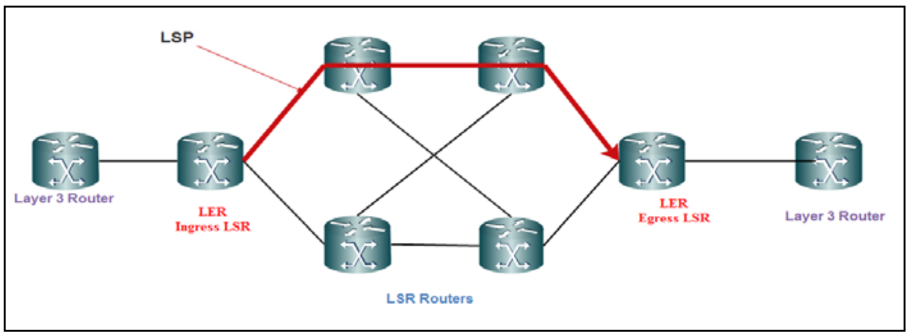


Figure (2): MPLS domain network

General terms correlating with MPLS network and their explanation are specified in the following

- Label Description: A short, fixed length packet identifier.
- Label Edge Router (LER): A device that operates at the edge of the access network and MPLS network.
- Label Switching Router : A router which is located in the MPLS domain and forwards the packets based on label switching.
- Forward Equivalence Class (FEC) : A description of a group of packets sharing the same transport requirements.
- Label Switched Path (LSP) : A route established between two Label Edge Router (LER) which work as a path for forwarding labeled packets over LSPs.

The two planes , namely control plane and data plane, highlight the operation of MPLS are shown in Figure (3) [17].

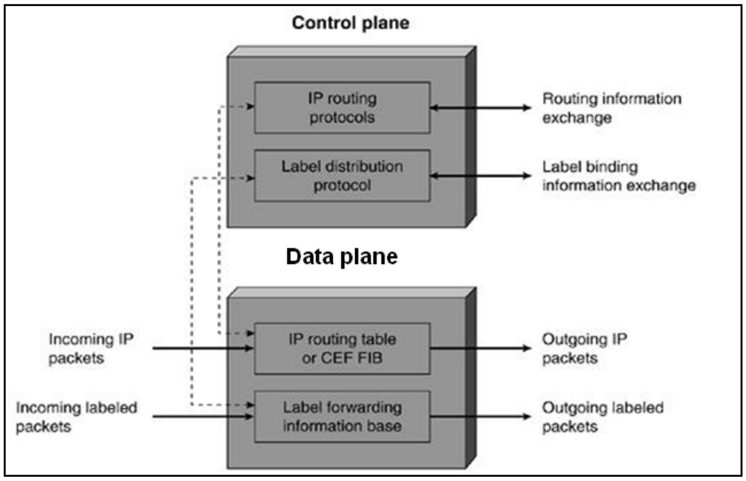


Figure (3): MPLS planes [17]

3.2 Traffic Engineering Signal Protocols

With the standardization of MPLS by IETF, traffic engineering obtained its popularity due to the supported features of the MPLS for Traffic Engineering more than the traditional IP networks. The main structure blocks of the MPLS Traffic Engineering Model are Path Management, Network State Information Dissemination, Traffic Assignment and Network Management [16]. Due to the online and offline usability of the MPLS network and the capability to list at any point of time, Traffic Engineering has gained its popularity [18].The packets in MPLS network are forwarded using the level swapping. This forwarding of packets gives more control for expeditiously forwarding packets [17]. Figure (4) shows the relation between Interior Gateway Protocol (IGP), MPLS and constraint-based routing for the path selection in a network. The path selection procedure depends on the availability of the protocols. In absence of MPLS, the path selection is done by IGP and in the presence of the MPLS the path selection or the signaling protocols of the MPLS are implemented [19].

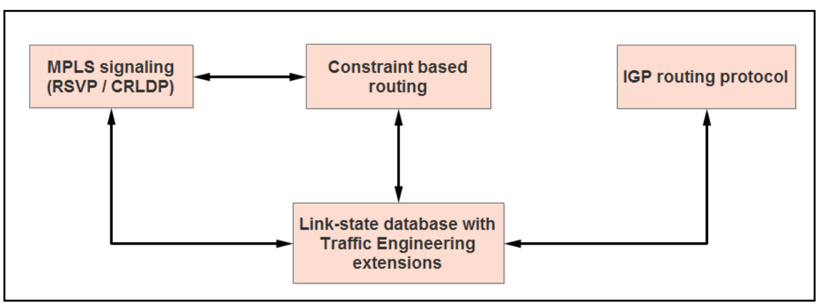


Figure (4): Interaction of the various components of an MPLS-based Traffic Engineering solution [19].

Traditionally IP packets were forwarded looking into its destination address at every router in the path. The packets were forwarded based on the shortest path metric, which is the cost calculated using the time it takes to reach the next hop. When the traffic in the network increases, the link with shortest path becomes heavily congested while the links with higher paths are underutilized resulting in the uneven loads in the links available, on the cost of traffic resources. The development of MPLS addresses these problems with the use of constraint based routing (CBR). The dynamic use of the measuring tools and the accountability of all the possible multiple paths and its characteristics (bandwidth, policy and topology) by CBR makes it easier for implementation of Traffic Engineering efficiently [17].

Signaling protocols are used to set up the paths for the packets to follow, these paths are usually known as Label Switched Path. There are many protocols which can be used for paths selection, but here only the signaling protocols that support Traffic Engineering are explained [18]. In this paper, two types of signal protocols are used, Constraint-Based Label Distribution Protocol (CR-LDP) and Resource Reservation Protocol (RSVP).

3.3 Constraint-Based Label Distribution Protocol

Label Distribution Protocol (LDP) is designed by a working group at IETF from the ground up for the particular reason for distributing MPLS labels, consequently setting up LSPs in the MPLS domain. LDP works closely with IGP routing protocols and is usually called "hop-by-hop" forwarding. LDP does not support TE because it always chooses the same physical path that traditional IP routing would select. The reason behind setting up an LSP that follows the same path as traditional IP instead of just using traditional IP routing was primarily to accelerate the forwarding in routers. In traditional IP routing the next hop for each packet is found by a longest match prefix lookup on the IP header in the routing table. These lookup could in some cases, where the routing tables were large, be time consuming and it was surmised that data forwarding with label switching instead of IP lookups would speed up data forwarding. However, the forward speed of IP packets is not a matter anymore. Because of the development in routing technology, LDP is not frequently used for label distribution nowadays. There is an extension to the original LDP protocol that presents the new functionality of the LDP protocol called CR-LDP [20].

CR-LDP is an extent of LDP to support constraint based routed LSPs. The term constraint implies that in a network and for each group of node there exists a group of constraint that must be satisfied for the link or links between two nodes to be selected for an LSP. LSRs that use CR-LDP to interchange label and FEC mapping information are called LDP peers, they interchange this information by forming a LDP session [21].

3.4 Resource Reservation Protocol

An alternate signaling protocol to LDP and CR-LDP is the resource reservation protocol traffic engineering (RSVP-TE). RSVP-TE is an extension of the resource reservation protocol which was designed to support the integrated services (intserv) architecture. The intserv architecture was improved by IETF in the mid 1990s with a view to introducing QoS in the IP network.

The following two service classes were defined in intserv [17], [22]

i. ***Guaranteed service***: This service provides firm bounds on the end-to-end queuing delay with no packet loss for all conforming packets.

ii. ***Controlled-load service***: This service provides the user with a QoS that closely approximates the QoS of the best effort service that the user would receive from an unloaded network. Specifically, a user might assume the following:

- A very high percentage of transmitting packets will be successfully transported by the network to the receiver. The percentage of packets not successfully transported must widely approximate the basic packet error rate of the transmission links
- The end-to-end delay experienced by a very high percentage of the transported packets will not greatly achieve the minimum end-to-end delay experienced by any successfully transported packet.

RSVP is soft state protocol, which means that when a path has been setup by RSVP it has to be regularly updated to keep the recourses reserved. The requests for reservation are made from the receiver end of the path, so RSVP is a receiver-oriented protocol. When RSVP is used for LSP setup the ingress router starts by sending a PATH message on the path where an LSP will be set up. Each transportation router on that path has to exam if it has the possibility to set up the requested LSP. If the requested LSP is discard, an error message is returned upstream until it reaches the ingress router. Furthermore the path message is sent to the next transportation router in the path until it arrives the egress router [23].

4 Simulated Network Topologies and Setup Parameters

This section presents a full description of network setup and topologies that used in the simulation. An investigation of MPLS Traffic Engineering signal protocols capabilities to utilize the transmission link in the absence and presence of QoS is also presented. Different applications including voice, video, File Transfer Protocol (FTP), Telnet, print, Electronic mail (E-mail), database and Hyper Text Transfer Protocol (HTTP) are used for the performance evaluation. The parameters that are considered throughout the study are Throughput (the average number of bits successfully transmitted or received by the transmitter or the receiver channel per unit time, in bits per sec) and Link utilization (the percentage of the throughput to the data rate of the link used in the transmission).

The simulation environment used in this work is based on Optimum Network Engineering Tool (OPNET) 14.5 simulator. OPNET is a real-time simulator suitable mainly for the design and analysis of network models. The VoIP traffic is sent between the workstation (voice 1) and work station (voice 2). The same terminology is followed with video traffic, which is sent between the workstation (video 1) and workstation (video 2). For other applications, (HTTP, FTP, Database, E-mail, Print and Telnet), the traffic is sent between workstations and servers.

4.1 Network Topologies

The following parameters are considered in the simulation

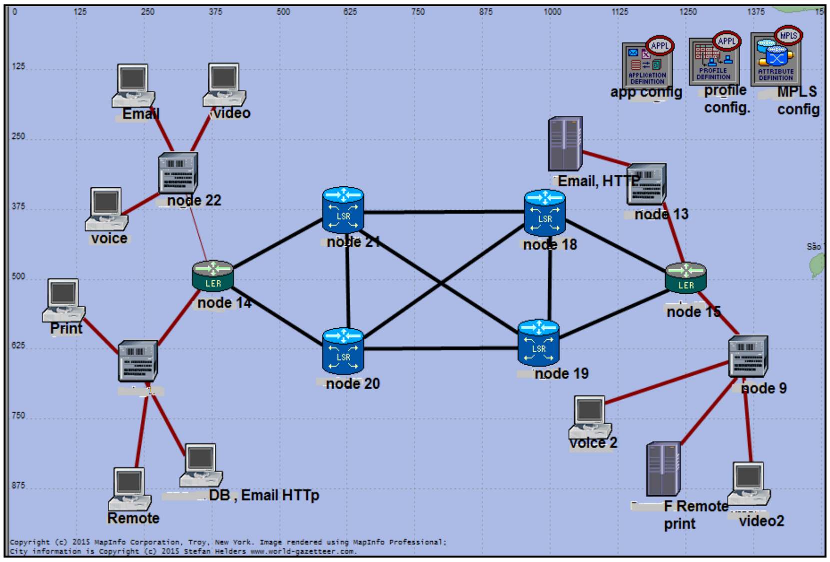
(i) DS1 links (data rate 1.544 Mbps) are used in the core network.

(ii) Network applications are divided into low, medium and high loads.

Figures (5a)-(5c) show the topologies of the three simulated MPLS networks using the two TE signal protocols (RSVP and CR-LDP). The first network has six routers, two LER routers and four LSR routers as shown in Figure (5a). In the second network, the number of routers increases. The network uses eight LSR routers and two LER routers, as shown in Figure (5b). The third network has same number of routers as the second network but with increasing number of links (38 links) as shown in Figure (5c).

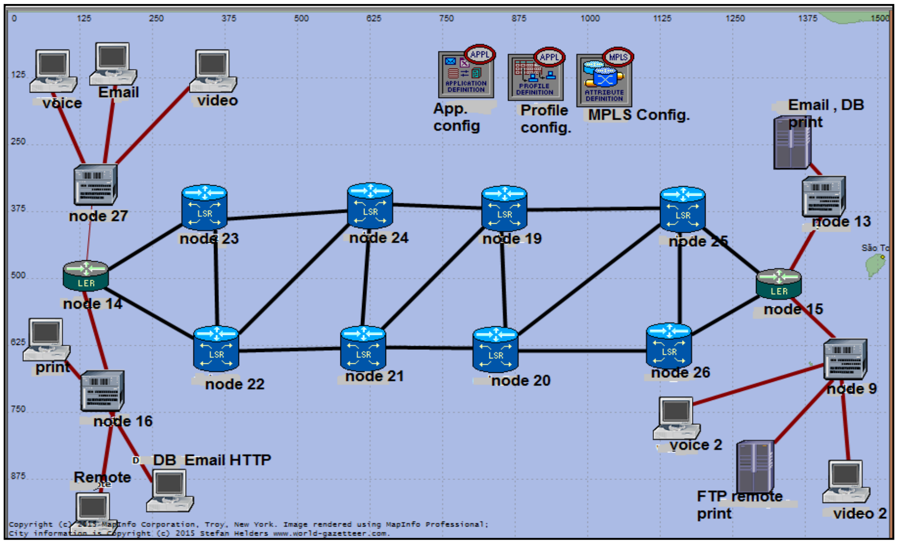
Table (1): Numbers of elements used in the simulated three networks.

Networks	Number of Elements		
	LSR Router	LER Router	Link
First	4	2	20
Second	8	2	28
Third	8	2	38

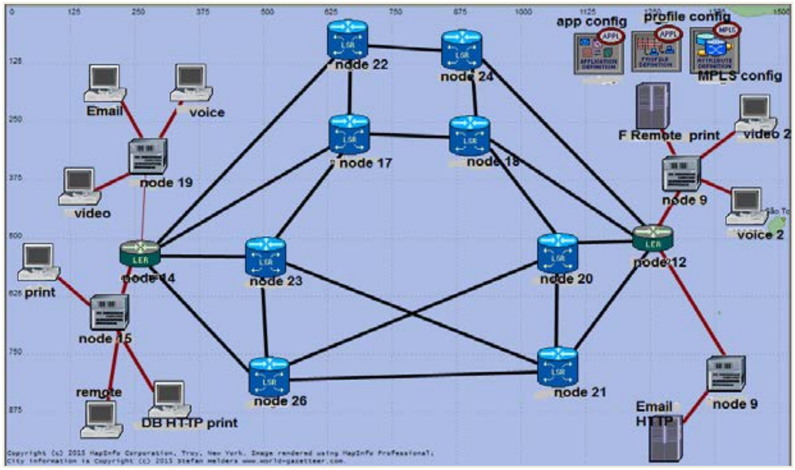


(a)

Figure (5): MPLS network topologies used in the simulation.
(a) First network (b) Second network (c) Third network.



(b)



(c)

Figure (5): continued.

4.2 Parameters used in the Simulation

Table (2) shows the parameters of the applications to be used during the simulations. Voice work stations use G.711 codec with data rate of 64 kbps. There are many factors that indicate the quality of voice which include choice of codec, packet loss, and delay. For VoIP applications, it is required that end-to-end packet delay shouldn't exceed 150ms in order that the quality of the established VoIP call is acceptable [25]. The voice delay in G.711 can be divided into two contributing components, which are explained as follows

(i) The delay provided by the G.711 codec for encoding and packetization is 1 and 24ms, respectively. Therefore, the delay at the transmitter according to these two delays with compression is approximated to a fixed delay of 25 ms.

(ii) At the receiver, the delay comes from decompression, buffering, playback, and depacketization delay. The total delay due to these factors mentioned above is approximated to a fixed delay of 45 ms.

Table (2): Applications parameters

VoIP Applications	
Encoder Scheme	G.711 (PCM)
Type of Service	Interactive Voice
Video Applications	
Frame rate	10 frames/sec
Frame Size	128*120 pixels
Type of Service	Streaming Multimedia
FTP Applications	
File Size	5000 byte
Type of Service	best effort
HTTP Applications	
HTTP Specification	HTTP 1.1
Page Properties	1000 byte
Type of Service	best effort
Print Applications (color file)	
File size	3000-90000 byte
Type of Service	Best effort

Telnet Applications	
Terminal Traffic (normally distributed)	Mean =144, variance=60 byte
Type of Service	Best effort
E-Mail Applications	
E-Mail Size	2000 byte
Type of Service	best effort
Database Applications	
Transaction Size	512 byte
Type of Service	Best effort

The maximum acceptable network delay can be determined from the above transmitter and receiver delays to be 80 *ms* nearly (150-25-45) *ms*, where the 150 *ms* represents the maximum acceptable end-to-end delay, so that the quality of the established VoIP call is acceptable [26]. Video workstations transfer 10 frames per second (sec); each frame be formed of 128x120 pixels. FTP work stations used files of size 5000 bytes [27]. HTTP work stations use pages of size 1000 bytes, HTTP 1.1 is employed in this study, HTTP 1.1 is a revision of the original HTTP (HTTP 1.0). In HTTP 1.0 a separate connection to the same server is made for every resource request. HTTP 1.1 can reuse a connection multiple times to download images, page inter-arrival times are exponentially distributed with mean 60 sec [28]. Emails are sent with inter-arrival times exponentially distributed with mean 360 sec. For database application, the transactions arrive with inter-arrival times exponentially distributed with mean 12 sec. Telnet application initiates commands from terminal to telnet host, these commands consist of a normally distributed amount of bytes with mean 144 and variance 60. Best-effort service means that the user obtains unspecified variable bit rate and delivery time, depending on the current traffic load of the network [26].

5 Link Utilization in the Absence of QoS

In this section, the link utilization of the three MPLS networks operating with CR-LDP and RSVP under different load conditions (low, medium and high) are studied and compared. No Qos algorithms are applied here. The term uplink refers to the paths carrying data from the work stations side to the server's side and the term downlink refers to the paths carrying data from the server's side to the work stations side.

The first MPLS Network used in the simulation is shown in Figure (5a) and examined here under low-load condition. Figures (6a) and (6b) show the link utilization for the uplink paths and down link paths of the MPLS network with CR-LDP TE signal protocol, respectively. Figures (6c) and (6d) present the uplink and downlink utilization of the MPLS network with RSVP TE signal protocol, respectively.

Tables (3)-(5) list the average link utilization of all paths when the two TE signal protocols are used in the three networks, respectively. Results are given for the three load conditions (low, medium, and high). The numbers given in the tables are the time averages of the results obtained in the simulation (such that given in Figure (6)).

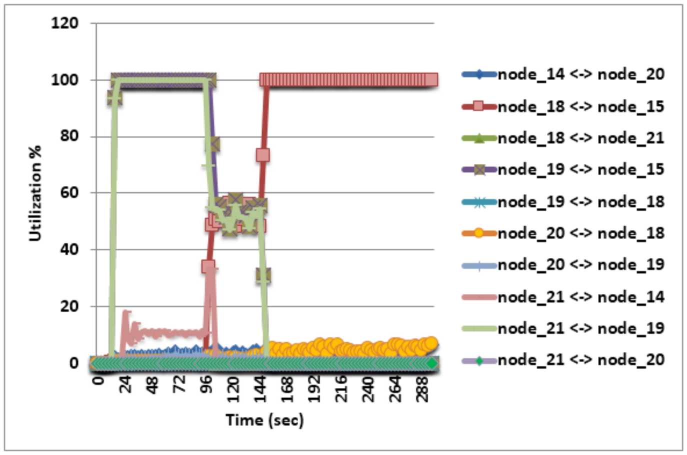


Figure (6a): Link utilization of the uplink paths of network 1 with CR-LDP TE signal protocol (low load)

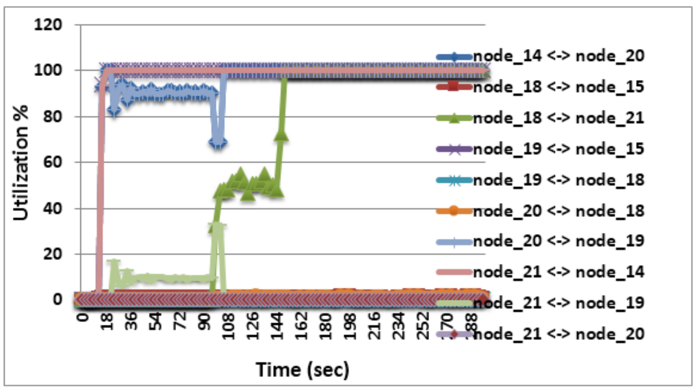


Figure (6b): Link utilization of the downlink paths of Network 1 with CR-LDP TE signal protocol (low load).

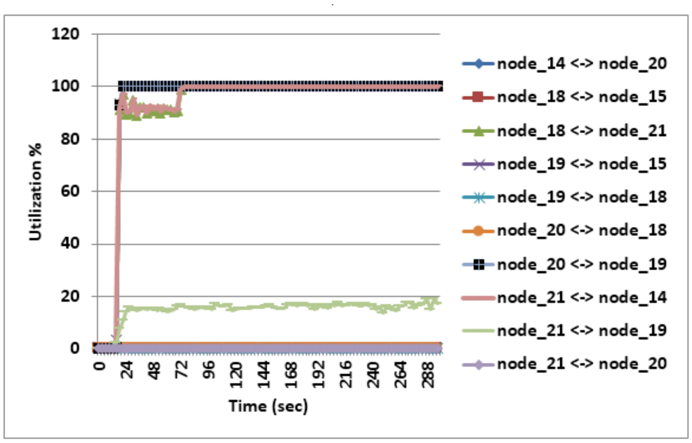


Figure (6c): Link utilization of the uplink paths of Network 1 with RSVP TE signal protocol (low load).

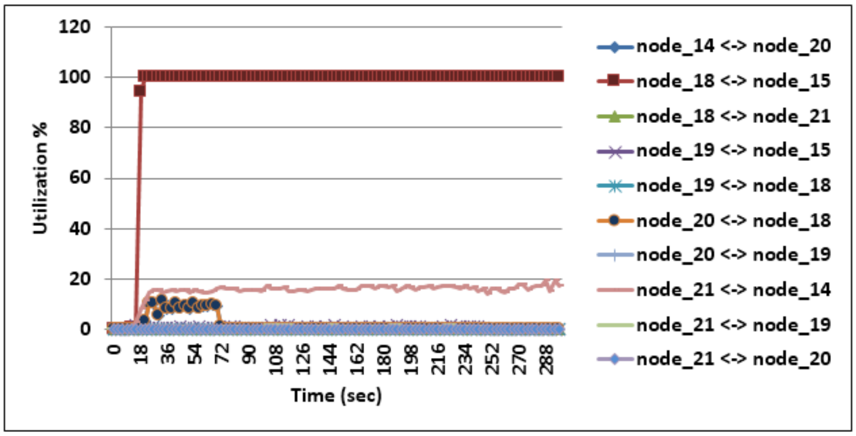


Figure (6d): Link utilization of the downlink paths of Network 1 with RSVP TE signal protocol (low load).

Table (3): Average link utilization of Network 1 operating with CR-LDP and RSVP TE signal protocols in the absence of QoS.

Link	Utilization %					
	Low load		Medium load		High load	
	CR-LDP	RSVP	CR-LDP	RSVP	CR-LDP	RSVP
14→20	3.20	92.03	18.80	11.42	18.80	11.42
20 →14	89.35	2.05	35.32	59.68	35.32	59.68
18→15	46.06	0.00	92.03	8	92.03	8
15→18	1.07	92.04	3.90	93.37	3.90	93.37
18→21	0.43	90.06	2.39	33.26	2.39	33.26
21→18	45.55	0.00	91.86	6.49	91.86	6.49
19→15	49.29	92.07	4.28	87.19	4.28	87.19
15→19	93.34	0.00	92.02	1.86	92.02	1.86
19→18	0.00	0.00	0	0	0	0
18→19	0.00	92.22	0	0	0	0
20 →18	2.18	0.00	14.90	0	14.90	0
18→20	0.00	1.99	1.52	59.69	1.52	59.69
20→19	1.10	92.02	3.91	11.01	3.91	11.01
19→20	89.34	0.00	34.80	93.32	34.80	93.32
21→14	4.46	90.17	59.61	33.79	59.61	33.79
14→21	93.34	0.00	59.61	1.36	59.61	1.36
21→19	48.30	0.00	0.40	87.01	0.40	87.01
19→21	4.06	92.04	57.23	0	57.23	0
21→20	0.00	0.00	0	0	0	0
20→21	0.00	0.00	0	0	0	0

Table (4): Average link utilization of Network 2 in the absence of QoS.

Link	Utilization %					
	Low load		Medium load		High load	
	CR-LDP	RSVP	CR-LDP	RSVP	CR-LDP	RSVP
14→23	37.58	11.68	37.58	11.68	0.62	92.64
23→14	6.58	71.86	6.58	71.86	88.66	0.00
20→19	0.00	0.00	0.00	0.00	0.00	0.00
19→20	0.00	0.00	0.00	0.00	0.00	0.00
20→25	0.43	0.00	0.43	0.00	0.00	0.00
25→20	6.58	17.95	6.58	17.95	3.46	0.00
20→26	56.43	83.51	56.43	83.51	80.87	0.00
26 →20	12.51	0.00	12.51	0.00	0.33	92.62
21→19	0.00	0.00	0.00	0.00	0.00	0.00
19→21	0.00	0.00	0.00	0.00	0.00	0.20
21→20	56.85	83.52	56.85	83.52	80.87	0.18
20→21	87.30	18.07	87.30	18.07	3.77	92.62
21→24	0.00	0.00	0.00	0.00	0.00	0.00
24→21	0.00	0.00	0.00	0.00	0.00	0.00
22→14	87.30	19.88	87.30	19.88	3.86	92.64
14→22	58.02	84.82	58.02	84.82	92.05	16.04
22→21	56.86	83.52	56.86	83.52	80.92	0.18
21→22	58.02	18.10	58.02	18.10	3.86	92.62
22→24	1.17	1.31	1.17	1.31	11.14	15.86
24→22	0.00	1.80	0.00	1.80	0.00	0.24
23→22	0.00	0.00	0.00	0.00	0.00	0.00
22→23	0.00	0.00	0.00	0.00	0.00	0.00
23→24	37.58	11.69	37.58	11.69	0.62	92.64
24→23	6.58	72.29	6.58	72.29	89.08	0.00
24→19	38.74	12.98	38.74	12.98	11.75	92.77
19→24	6.58	74.07	6.58	74.07	89.08	0.24
25→15	39.17	12.98	39.17	12.98	11.79	92.77
15→25	92.43	92.04	92.43	92.04	92.62	0.44
25→19	6.59	74.1	6.59	74.1	89.19	0.00
19→25	38.74	12.98	38.74	12.98	11.88	92.77
26→15	56.42	83.09	56.42	83.09	80.44	0.00
15→26	12.51	0.00	12.51	0.00	0.00	92.63
26→25	0.00	0.00	0.00	0.00	0.00	0.00
25→26	0.00	0.00	0.00	0.00	0.00	0.00

Table (5): Average link utilization of Network 3 in the absence of QoS.

LINK	Utilization %					
	Low load		Medium load		High load	
	RSVP	CR-LDP	RSVP	CR-LDP	RSVP	CR-LDP
12→18	0.00	6.95	14.28	8.16	21.80	92.29
18→12	93.07	92.18	5.68	43.68	0.00	4.16
12→20	93.07	0.00	93.07	0.00	0.00	13.34
20→12	0.00	7.15	2.30	1.00	2.20	2.82
12→21	0.00	0.00	0.00	1.00	93.06	1.18
21→12	2.22	0.88	1.03	3.41	1.74	91.86
12→24	0.00	92.50	5.68	43.95	0.00	4.14
24→12	0.00	6.95	14.28	8.17	21.80	91.98
14→17	93.08	0.00	0.17	59.60	93.37	22.22
17→14	0.00	0.88	0.00	0.00	0.00	6.74
14→22	1.20	0.50	93.09	1.09	4.44	5.52
22→14	12.26	63.90	93.06	92.18	0.00	25.22
14→23	0.00	12.87	12.37	44.05	0.00	4.16
23→14	93.06	29.59	14.28	8.28	21.80	92.29
14→26	93.07	92.50	5.68	0.00	0.00	0.00
26→14	0.00	7.03	0.00	0.00	0.00	0.00
17→18	0.00	0.00	93.09	60.14	93.37	25.25
18→17	0.00	0.00	0.00	92.58	0.00	18.40
18→20	1.20	6.13	0.00	0.00	0.00	0.00
20→18	12.26	92.51	0.00	0.00	0.00	0.00
21→20	0.00	0.00	0.00	0.00	0.00	6.79
20→21	0.00	0.00	93.09	60.16	93.36	22.58
21→23	12.26	64.11	0.00	1.00	0.00	1.19
23→21	1.20	0.50	1.03	3.37	1.74	92.29
22→17	0.00	0.00	0.00	0.00	1.74	0.00
17→22	2.22	1.00	0.00	0.00	0.00	0.00
22→24	0.00	0.00	1.02	3.43	0.00	92.29
24→22	0.00	0.00	0.00	1.00	93.06	1.20
23→17	2.22	1.00	0.00	0.00	0.00	0.00
17→23	0.00	0.00	0.00	0.00	0.00	0.00
23→26	0.00	0.00	0.00	0.00	0.00	0.00
26→23	0.00	0.00	0.00	0.00	0.00	0.00
24→18	0.00	0.00	0.00	0.00	2.20	0.00
18→24	0.00	0.00	0.00	0.00	0.00	0.00
26→20	0.00	7.38	2.30	1.00	0.00	2.84
20→26	93.07	0.00	93.07	0.00	0.00	13.62
26→21	0.00	5.78	10.08	0.00	0.00	2.83
21→26	0.00	29.76	0.00	92.56	0.00	11.92

Investigating the results in Tables (3)-(5) show the following findings

(i) The MPLS network with CR-LDP TE signal protocol has better performance in term of link utilization. The RSVP reserves certain paths for transmission, while the CR-LDP utilizes most of the available links. Table (6) shows the total number of links utilized by the two protocols for the three networks.

Table (6): Total number of links utilized by the MPLS networks with two TE signals protocols

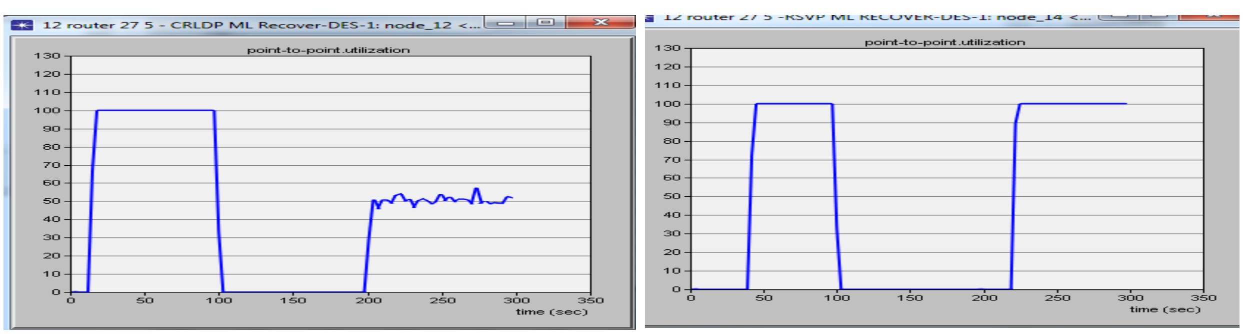
Network	TE signal protocol	Total number of utilized links		
		Low load case	Medium load case	High load case
Network 1	CR-LDP	15	15	16
	RSVP	10	11	14
Network 2	CR-LDP	25	23	22
	RSVP	17	21	18
Network 3	CR-LDP	22	24	28
	RSVP	14	15	20

(iii) The CR-LDP TE signal protocol manages almost equally to recognize t the size of the load transmitted in both directions. Therefore, equal utilization of the links in both directions is observed.

(iv) The CR-LDP capabilities for utilizing transmission links is affected by network topology. The difference also can be noticed in the number of utilized links as given in Table (6).

(v) When Network 3 operates under high load condition, the RSVP TE signal protocol reservation of certain links leads to congestions in some paths (path 14→22, path (22→14). However, it uses these two paths at nearly full rate (93%) in the uplink which reveals the inability of this protocol to manage the utilization between uplink traffic and downlink traffic on the same path.

The investigation is carried further to address the ability of MPLS networks operating with CR-LDP and RSVP TE signal protocols to detect and recover fault links. The results are given for Network 3 only since other networks have similar behavior. Figure (7a) shows CR-LDP TE signal protocol capabilities to detect transmission links failure and the speed of recovery. Figure (7b) presents RSVP TE signal protocol capabilities to fault links detection and speed to recover it. Fail link time is considered at 100 sec and recover time is set to 200 sec. The results show that both CR-LDP and RSVP detect the fail links at the same time. For fault link recovery, the results show that the CR-LDP protocol is faster than RSVP protocol in terms of recovered links. Unlike the RSVP protocol, the CR-LDP protocol starts using the link immediately after the link being reconnected.



(5a) **(5b)**

Figure (7): Utilization of (node12→ node18) link. CR-LDP TE protocol (b) RSVP TE protocol

6 Links Utilization of QoS-Supported MPLS Networks

This section presents performance investigation of MPLS Traffic Engineering signal protocol capabilities to utilize the transmission link under Quality of Service (QoS) conditions. The used QoS algorithms are First-In First-Out (FIFO), Priority Queuing (PQ), Weighted Fair Queuing (WFQ) and Custom Queuing (CQ). The results are represented for the three networks addressed in Section 5 with the same parameters and applications. The average link utilization of the first network under different QoS algorithms is listed in Tables (7)-(9) for low- , medium-, and high-load conditions, respectively. Results related to the second and third networks are given in the Appendix.

Tables (10a)-(10c) list total number of links utilized by the two protocols in the three networks when applying QoS for the three load conditions, respectively. These tables show that the four queuing algorithms have similar effect (in term of utilized links) on MPLS networks operating with CR-LDP TE signal protocol. This is not true when the RSVP TE signal protocol is used.

7 Conclusions

The performance of the MPLS CR-LDP and RSVP Traffic Engineering signal protocols has been evaluated and compared in the term of link utilization with and without applying QoS. Different networks scenarios and different applications, including video conferencing, voice, E-Mail, FTP, HTTP, DB, print and telnet traffic have been.. The main conclusions drawn from this study are

(i) MPLS network with CR-LDP TE signal protocol has better performance in the term of link utilization. The RSVP reserves certain paths for transmission while the CR-LDP utilizes almost all of the available links.

(ii) The CR-LDP protocol is even better in terms of link management between uplink traffic and downlink traffic on the same path.

(iii) The CR-LDP TE signal protocol is faster than RSVP protocol in terms of discovery of recovered links, it starts using the link immediately after the link being reconnected.

(iv) There is inefficient link utilization with the RSVP protocol in which the reservation of specific links for transmission produces transmission failure and packets drop at high loads.

(v) The MPLS TE signal protocol capability of link utilization is almost independent of network topology or number of utilized links.

(vi) Applying QoS improves the performance of RSVP TE signal protocol while the number of utilized links increases. For CR-LDP the same number of links is used before and after applying QoS.

Table (7): Average link utilization of Network 1 operating with QoS under low load condition.

Link	Utilization %							
	CR-LDP				RSVP			
	FIFO	PQ	WFQ	CQ	FIFO	PQ	WFQ	CQ
14→20	70.70	70.36	70.98	70.97	14.90	15.23	15.05	15.12
20 →14	1.72	27.00	31.00	30.79	0.86	0.80	1.06	1.04
18→15	47.98	54.23	45.98	46.01	69.42	69.42	56.71	56.74
15→18	75.37	70.96	70.35	70.33	0.87	0.87	1.28	1.29

18→21	49.18	45.12	49.20	49.27	0.33	0.34	0.74	0.75
21→18	0.85	9.79	1.21	1.31	69.36	69.36	54.44	54.42
19→15	25.72	26.88	27.92	27.97	12.52	12.63	12.65	12.63
15→19	15.014	1.57	14.19	13.98	69.73	69.98	69.96	69.95
19→18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18→19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20 →18	46.88	48.92	44.97	44.90	2.39	2.61	2.41	2.50
18→20	0.00	26.17	21.28	21.18	0.55	0.54	0.55	0.55
20→19	24.08	21.58	26.37	26.42	12.52	12.63	12.65	12.63
19→20	1.72	1.02	9.94	9.82	0.33	0.27	0.52	0.50
21→14	54.13	45.53	53.53	53.51	69.69	69.94	69.95	69.95
14→21	2.64	15.02	2.92	3.02	69.63	69.37	54.45	54.43
21→19	1.80	5.51	1.76	1.76	0.00	0.00	0.00	0.00
19→21	13.31	0.60	4.53	4.44	69.41	69.72	69.44	69.45
21→20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20→21	0.00	0.00	0.00	0.00l	0.00	0.00	0.00	0.00

Table (8): Average link utilization of Network 1 operating with QoS under medium load condition.

Link	Utilization %							
	CR-LDP				RSVP			
	FIFO	PQ	WFQ	CQ	FIFO	PQ	WFQ	CQ
14→20	70.70	70.97	71.02	70.36	17.13	17.38	66.34	66.32
20 →14	30.95	17.39	22.84	22.90	69.92	70.00	66.95	66.95
18→15	23.28	23.95	28.06	31.66	69.52	69.53	67.35	67.39
15→18	70.39	12.33	71.02	70.98	12.30	12.33	12.26	12.26
18→21	49.23	50.00	49.63	49.23	0.00	0.00	12.07	12.07
21→18	2.06	69.32	2.07	10.59	69.31	69.32	1.05	1.16
19→15	52.62	51.74	48.98	55.34	12.13	12.15	0.00	0.00
15→19	14.11	69.46	1.99	1.72	69.43	69.46	68.76	68.71
19→18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18→19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20 →18	21.37	21.90	26.19	21.27	5.06	5.32	66.34	66.32
18→20	21.30	12.33	21.75	22.09	12.30	12.33	0.20	0.20
20→19	49.58	49.41	45.19	49.22	12.07	12.07	0.00	0.00
19→20	9.86	68.44	1.28	1.00	68.93	68.44	66.77	66.77
21→14	53.55	50.61	50.17	49.79	0.50	1.02	14.06	14.02
14→21	6.25	69.40	6.02	18.28	69.37	69.40	1.14	1.25
21→19	4.24	3.71	40.00	7.97	0.00	0.00	0.00	0.00
19→21	4.52	1.02	0.74	0.75	0.50	1.02	2.00	1.95
21→20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20→21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table (9): Average link utilization of Network 1 operating with QoS under high load condition.

Link	Utilization %							
	CR-LDP				RSVP			
	FIFO	PQ	WFQ	CQ	FIFO	PQ	WFQ	CQ
14→20	70.45	70.45	70.50	71.05	70.02	28.98	27.20	27.48
20 →14	61.84	61.0	62.46	61.20	69.63	69.98	18.03	17.59
18→15	60.82	61.30	62.38	70.39	1.03	69.53	17.29	17.68
15→18	70.39	70.39	70.43	70.39	0.98	69.41	65.92	65.60
18→21	21.26	21.47	21.63	7.07	0.98	1.07	65.91	65.59
21→18	15.96	16.56	15.86	7.07	0.00	68.41	0.00	0.00
19→15	36.83	34.77	36.19	36.74	69.90	21.86	69.56	69.46
15→19	30.24	28.81	29.54	29.41	70.40	19.87	20.40	19.85
19→18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18→19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20 →18	48.51	48.72	48.20	44.42	1.03	8.11	17.29	17.68
18→20	49.27	49.07	48.96	49.31	0.00	68.35	0.00	0.00
20→19	22.08	21.88	22.47	26.99	69.00	20.88	9.92	9.81
19→20	14.39	17.89	14.19	18.32	69.63	6.99	18.03	17.59
21→14	37.18	32.50	37.07	32.39	1.75	13.95	67.73	67.43
14→21	30.63	29.36	29.52	16.96	2.23	69.39	65.87	65.51
21→19	15.00	13.13	13.99	9.98	2.23	0.98	65.87	65.51
19→21	16.19	11.27	15.69	11.42	0.77	12.89	2.38	2.27
21→20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20→21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table (10a): Total number of links utilized by the two protocols when applying QoS (low load condition).

Network	TE signal protocol	Total number of utilized links			
		FIFO	PQ	WFQ	CQ
Network 1	CR-LDP	15	16	16	16
	RSVP	15	15	15	15
Network 2	CR-LDP	18	18	18	18
	RSVP	15	16	16	16
Network 3	CR-LDP	20	19	20	19
	RSVP	25	23	23	239

Table (10b): Total number of link utilized by the two protocols when applying QoS (medium load condition).

Network	TE signal protocol	Total number of utilized links			
		FIFO	PQ	WFQ	CQ
Network 1	CR-LDP	16	16	16	16
	RSVP	14	14	13	13
Network 2	CR-LDP	15	15	15	15
	RSVP	20	21	20	20
Network 3	CR-LDP	25	25	25	25
	RSVP	22	23	24	22

Table (10c): Total number of link utilized by the two protocol when applying QoS (high load condition).

Network	TE signal protocol	Total number of utilized links			
		FIFO	PQ	WFQ	CQ
Network 1	CR-LDP	16	16	16	16
	RSVP	15	15	14	15
Network 2	CR-LDP	18	18	18	18
	RSVP	20	17	1	19
Network 3	CR-LDP	22	22	22	22
	RSVP	21	18	20	20

REFERENCES

[1] A. Hussain, S. Nazeer, T. Abdullah, B. Yaseen and A. Salam "Network Resilience in Multiprotocol Label Switching" Journal of Asian Scientific Research, Vol.2, No.4, PP. 221-227, April 2012.

[2] B. Forouzan, "Data Communications and Networking", McGraw-Hill Higher Education, 4th Ed., PP. 101-110, 2006.

[3] Dr. R. Naoum and M. Maswady, "Performance Evaluation for VoIP over IP and MPLS", World of Computer Science and Information Technology Journal, Vol. 2, No. 3, PP. 110-114, May 2012.

[4] T.J. Shi, G. Mohan, "An Efficient Traffic Engineering Approach Based on Flow Distribution and Splitting in MPLS Networks", Computer Communications, Vol. 29, No. 9, PP. 1284-1291, May 2006.

[5] A. Bongale, "Analysis of Link Utilization in MPLS Enabled Network using OPNET IT Guru", International Journal of Computer Applications, Vol. 41, No.14, PP. 35-40, March 2012.

[6] H. Perros, "An Introduction to ATM Network", 1st Ed., Cary, USA, 2001.

[7] R. Peterkin "A Reconfigurable Hardware Architecture for VPN MPLS based Services", MSc. Thesis, School of Information Technology and Engineering, University of Ottawa, April 2006.

[8] Y. Lee, Y. Seok, Y. Choi and C. Kim "A Constrained Multipath Traffic Engineering Scheme for MPLS Networks", Electronic Telecommunication Research Institute, 2002.

[9] S. Shyry and V. Ramachandran, "Finagling Congestion in Selfish Overlay Routing Belittling Link Utilization" , Proc. IEEE, PP. 308-311, November 2010.

[10] C. Pelsser , O. Bonaventure "Extending RSVP-TE to support Inter-AS LSPs", Proc. CiteSerr,Vol 41, No.5, PP. 122-128, May 2011.

[11] T. Aziz, N. Islam khan and A. Popescu ,"Effect of Packet Delay Variation on Video/Voice over DIFFSERV-MPLS in IPV4/IPV6 Networks", International Journal of Distributed and Parallel Systems, Vol.3, No.1, pp.27-47, January 2012.

[12] M. Bhandure, G. Deshmukh and Prof. V. J n, " Comparative Analysis of Mpls and Non -Mpls Network", International Journal of Engineering Research and Applications, Vol. 3, No. 4, PP. 71-76, August 2013.

[13] S. Ibrahim, " Performance Evaluation of Traffic Engineering Signal Protocols in MPLS Network ", M.Sc. Thesis, Al-Nahrain University, April 2013.

[14] A. Sulaiman and O. Alhafidh" Performance Analysis of Multimedia Traffic over MPLS Communication Networks with Traffic Engineering", International Journal of Computer Networks and Communications Securitik Vol. 2, No. 3, PP. 93 -101, March 2014.

[15] S. Ibrahim and M. AL-Quzwini, "Performance Evaluation of MPLS TE Signal Protocols with Different Audio Codecs for Voice Application", International Journal of Computer Applications, Vol. 57, No.1, pp. 56-60, November 2012.

[16] H. Perros, "An Introduction to ATM Network", 1st Ed., Cary, USA, 2001.

[17] R. Peterkin "A Reconfigurable Hardware Architecture for VPN MPLS based Services", MSc. Thesis, School of Information Technology and Engineering, University of Ottawa, April 2006.

[18] T. Latif and K. Malkajgiri, "Adoption of Voice over Internet Protocol," Lulea University of Technology, 2007.

[19] O. Dokun and A. Gift "PDH (Plesiochronous Digital Hierarchy) /SDH-SONET (Synchronous Digital Hierarchy / Synchronous Optical Networking)", International Journal of Mathematics and Engineering Research, Vol 3, No 1, January 2015.

[20] A. Kumar and S. G. Thorenoor, "Analysis of IP Network for Different Quality of Service." In International Symposium on Computing, Communication, and Control (ISCCC), Proc .of CSIT Vol. 1. IACSIT Press, Singapore. 2011.

[21] P. Ivaniš and D. Drajic "The Simulation Model of Optical Transport System and Its Applications to Efficient Error Control Techniques Design", Electronic, Vol. 13, No. 2, December 2009.

[22] K. Januu and R. Deekona," OPNET Simulation of Voice Over MPLS With Considering Traffic Engineering", M.Sc. Thesis, School of Engineering, Blekinge Institute of Technology, Sweden, June 2010.

[23] J. Evans and C. Filsfils,"Deploying IP and MPLS QoS for Multiservice Networks", 1st Ed., Elsevier Inc, San Francisco, USA, 2007.

[24] V. Alwayn, "Advanced MPLS design and Implementation, Cisco Systems", Cisco press 201, West 103rd Street Indianapolis, 2001.

[25] K. Salah and A. Alkhoraidly "An OPNET-Based Simulation Approach for Deploying VoIP", International Journal of Network Management Int. J. Network, DOI: 10.1002, PP. 159–183, 27 January, 2006.

[26] H. Asif and G. Kaosa, "Performance Comparison of IP, MPLS and ATM Based Network Cores using OPNET", IEEE Computer Society, August, 2006.

[27] A. Hadi, "Modeling Computer Laboratories in University that Contains Eight Colleges by Using OPNET Software", Journal of Kerbala University, Vol. 7, No.1, PP.108-123, 2009.

[28] S. Kuribayashi," Proposed Optimal LSP Selection Method in MPLS Networks", International Journal of Computer Networks & Communications Vol.3, No.1, PP. 241-250, January 2011

Appendix: Effect of QoS on the Performance of Networks 2 and 3

Table (A1): Average link utilization of Network 2 operating with QoS (low load).

Link	Utilization %							
	CR-LDP				RSVP			
	FIFO	PQ	WFQ	CQ	FIFO	PQ	WFQ	CQ
14→23	69.78	70.21	70.10	70.21	69.89	70.1	66.09	65.98
23→14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20→19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19→20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20→25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
25→20	0.22	0.40	1.05	0.31	0.00	0.00	0.00	0.00
20→26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
26 →20	69.73	70.37	70.00	70.15	13.04	12.72	14.07	14.03
21→19	0.70	0.83	0.78	0.71	0.00	0.00	0.00	0.00
19→21	0.15	0.23	0.91	0.21	69.48	69.49	64.55	64.55
21→20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20→21	69.76	70.40	70.05	70.18	0.00	12.72	14.07	14.07
21→24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24→21	0.00	0.00	0.00	0.00	2.89	0.00	0.00	0.00
22→14	69.56	69.89	69.76	69.89	70.08	70.16	70.06	70.06
14→22	1.77	2.03	1.91	2.12	70.08	2.29	2.58	2.55
22→21	0.70	0.85	0.79	0.72	0.00	0.00	0.00	0.00
21→22	69.78	70.42	70.09	70.20	70.08	70.16	70.06	70.06
22→24	1.10	1.17	1.15	1.43	2.90	2.29	2.59	2.55
24→22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
23→22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
22→23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
23→24	69.77	70.20	70.09	70.20	69.89	70.15	66.08	65.98
24→23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24→19	69.78	70.21	70.10	70.20	69.91	70.18	67.92	67.87
19→24	0.00	0.00	0.00	0.00	69.49	69.50	64.55	0.00
25→15	69.53	69.85	69.74	69.86	69.90	70.18	67.92	67.87
15→25	0.37	0.63	1.94	0.53	69.90	69.50	67.92	64.55
25→19	0.19	0.27	0.95	0.25	69.49	69.50	64.55	64.55
19→25	69.78	70.41	70.10	70.20	13.04	12.72	14.07	14.03
26→15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15→26	69.73	70.37	70.00	70.15	0.00	0.00	0.00	0.00
26→25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
25→26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table (A2): Average link utilization of Network 2 operating with QoS (medium load).

Link	Utilization %							
	FIFO CR-LDP	PQ CR-LDP	WFQ CR-LDP	CQ CR-LDP	FIFO RSVP	PQ RSVP	WFQ RSVP	CQ RSVP
14→23	69.90	70.16	70.21	70.17	1.66	1.47	14.10	14.05
23→14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20→19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19→20	46.14	0.00	0.00	0.00	0.00	69.50	0.00	0.00
20→25	0.00	0.00	0.00	0.00	0.00	57.53	0.00	0.00
25→20	43.22	43.99	44.20	43.40	7.00	14.16	1.30	1.28
20→26	0.00	0.00	0.00	0.00	0.24	0.12	1.10	1.04
26 →20	0.27	0.22	1.11	0.31	2.10	0.00	70.08	70.15
21→19	0.00	0.00	0.00	0.00	63.03	0.38	3.05	2.92
19→21	23.88	26.39	26.21	26.70	9.10	70.18	0.00	0.00
21→20	0.00	0.00	0.00	0.00	0.24	57.64	1.10	1.03
20→21	46.40	44.19	45.30	43.70	0.00	0.00	70.12	70.19
21→24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24→21	0.00	0.00	0.00	0.00	70.10	70.21	0.00	0.00
22→14	69.57	69.77	69.77	69.79	70.07	70.17	70.12	70.11
14→22	0.00	0.00	0.11	0.00	70.07	70.18	56.88	56.68
22→21	0.00	0.00	0.00	0.00	63.28	58.02	4.14	3.95
21→22	69.80	70.07	70.10	69.84	0.00	0.00	70.12	70.19
22→24	0.00	0.00	0.00	0.50	6.82	12.19	52.74	53.67
24→22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
23→22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
22→23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
23→24	69.90	70.16	70.20	70.16	1.66	1.47	14.10	14.05
24→23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24→19	69.90	70.16	70.20	70.16	8.47	13.65	66.068	66.26
19→24	0.00	0.00	0.00	0.50	70.03	69.50	0.00	0.00
25→15	69.64	69.81	69.84	69.82	70.13	70.26	68.92	68.78
15→25	69.78	70.07	70.08	70.22	70.14	14.03	1.30	1.28
25→19	23.90	26.43	26.23	26.86	63.03	0.00	0.00	0.00
19→25	69.90	70.17	70.21	70.31	2.10	14.03	68.92	68.88
26→15	0.00	0.00	0.00	0.00	0.24	0.12	1.10	1.04
15→26	0.27	0.21	1.08	0.30	0.00	0.00	70.09	70.15
26→25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
25→26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table (A3): Average link utilization of Network 2 operating with QoS (high load)

Link	Utilization %							
	CR-LDP				RSVP			
	FIFO	PQ	WFQ	CQ	FIFO	PQ	WFQ	CQ
14→23	60.07	10.12	8.32	69.49	28.33	15.51	35.20	35.71
23→14	0.00	0.00	0.00	0.00	14.28	0.38	69.82	69.66
20→19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.13
19→20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.69
20→25	0.00	0.00	0.00	0.12	69.48	0.00	0.00	0.00
25→20	49.30	49.38	44.20	10.20	0.40	0.00	0.40	0.40
20→26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
26 →20	0.22	0.59	1.11	69.25	69.93	69.80	17.66	16.02
21→19	21.47	21.55	21.68	6.47	0.00	0.00	53.99	53.87
19→21	21.25	21.64	26.21	4.54	0.00	0.00	0.00	0.00
21→20	0.00	0.00	0.20	0.19	69.48	0.00	0.00	0.00
20→21	49.50	49.91	45.30	70.47	69.97	69.51	18.05	53.87
21→24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24→21	0.00	0.00	0.00	0.00	0.00	69.80	0.00	16.41
22→14	70.05	70.34	70.33	70.36	69.48	70.41	18.05	16.42
14→22	69.93	70.20	0.11	18.20	69.63	12.14	54.00	0.00
22→21	21.50	21.68	21.88	6.65	69.48	0.00	54.00	53.87
21→22	70.31	70.28	70.10	6.65	69.97	0.00	18.05	0.00
22→24	48.70	48.88	48.71	11.83	0.00	69.51	0.00	0.00
24→22	0.00	0.00	0.00	0.00	0.00	0.38	0.00	0.00
23→22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
22→23	0.00	0.00	0.00	0.00	0.00	12.51	0.00	0.00
23→24	6.11	10.17	8.37	69.49	28.33	15.51	35.20	35.71
24→23	0.00	0.00	0.00	0.00	14.29	12.60	69.82	69.82
24→19	53.75	57.14	57.04	70.66	28.33	70.81	35.20	35.71
19→24	0.00	0.00	0.00	0.00	14.29	70.81	69.82	69.82
25→15	70.06	70.16	70.23	70.15	0.00	70.81	70.44	70.26
15→25	70.28	70.20	70.08	14.61	14.29	69.80	70.22	70.22
25→19	21.26	21.65	21.62	4.68	14.23	12.51	69.83	69.22
19→25	70.26	70.36	70.21	70.37	28.33	0.00	70.45	70.22
26→15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15→26	0.21	0.55	1.09	69.25	69.48	0.00	17.65	16.02
26→25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0
25→26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table (A4): Average link utilization of Network 3 operating with QoS (low load)

LINK	Utilization %							
	RSVP				CRLDP			
	FIFO	PRI	WFQ	CUST	FIFO	PRI	WFQ	CUST
12→18	70.52	71.15	55.22	44.40	12.78	12.73	13.44	0.64
18→12	0.52	0.54	0.53	0.55	0.63	12.79	0.63	0.63
12→20	0.54	0.54	0.53	12.70	0.19	0.20	0.23	12.40
20→12	0.60	0.69	0.63	0.62	48.12	48..01	47.85	43.48
12→21	0.11	0.17	12.30	0.15	70.25	70.19	70.22	70.18
21→12	0.57	12.72	0.57	0.57	12.17	0.00	12.17	0.00
12→24	0.52	0.54	0.53	0.54	0.63	12.79	0.63	0.63
24→12	70.52	71.15	55.21	44.39	12.76	12.73	13.44	0.64
14→17	70.89	70.54	66.83	66.76	0.00	0.00	0.00	0.00
17→14	12.06	0.00	0.00	0.00	0.00	0.00	0.47	0.13
14→22	0.60	0.69	0.63	0.62	70.29	70.22	70.29	70.84
22→14	1.04	1.04	1.04	13.21	0.21	0.20	0.55	12.43
14→23	0.52	0.54	0.53	0.54	0.65	13.04	0.65	0.65
23→14	70.52	71.15	55.22	44.39	13.02	12.98	13.70	0.65
14→26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
26→14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17→18	70.88	70.53	66.82	66.75	22.30	22.21	22.45	27.37
18→17	12.56	0.50	0.52	0.51	0.00	0.00	0.79	0.15
18→20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20→18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
21→20	12.06	0.00	0.00	0.00	0.00	0.00	0.48	0.13
20→21	70.88	70.54	66.83	66.75	0.00	0.00	0.00	0.00
21→23	0.11	0.17	12.30	0.15	70.12	70.06	70.08	70.06
23→21	0.57	12.72	0.57	0.57	12.17	0.00	12.17	0.00
22→17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17→22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
22→24	0.57	12.72	0.57	0.57	12.42	0.00	12.42	0.00
24→22	0.11	0.16	12.30	0.15	70.18	70.18	70.22	70.18
23→17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17→23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
23→26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
26→23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24→18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18→24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
26→20	0.60	0.69	0.63	0.62	48.05	48.08	47.93	43.66
20→26	0.54	0.54	0.53	12.70	0.21	0.22	0.25	12.66
26→21	0.00	0.00	0.00	0.00	22.37	22.28	22.53	27.45
21→26	0.51	0.50	0.52	0.51	0.00	0.00	0.00	0.00

Table (A5): Average link utilization of Network 3 operating with QoS (medium load).

LINK	Utilization %							
	RSVP				CR-LDP			
	FIFO	PQ	WFQ	CQ	FIFO	PQ	WFQ	CQ
12→18	1.09	0.19	1.18	13.31	1.11	1.15	1.106	13.23
18→12	14.1	1.97	1.82	1.82	1.08	13.16	1.02	13.17
12→20	0.00	0.00	12.17	0.00	1.00	1.00	1.00	1.03
20→12	0.11	0.12	0.00	0.00	2.56	2.56	2.34	2.74
12→21	13.17	0.48	1.02	1.02	12.22	12.32	12.30	0.17
21→12	3.83	4.07	4.20	3.83	70.31	70.06	70.46	70.06
12→24	14.09	1.97	1.82	1.82	1.08	13.16	1.02	13.17
24→12	1.09	0.19	1.18	13.31	1.11	1.15	1.11	13.23
14→17	70.55	70.51	55.37	66.79	0.00	0.00	0.00	0.00
17→14	68.89	57.73	43.67	43.65	22.12	22.09	21.97	22.25
14→22	1.13	13.37	13.22	1.12	7.05	7.22	6.94	7.40
22→14	1.69	13.43	14.09	1.77	49.13	49.12	49.32	49.00
14→23	14.09	1.97	1.82	1.82	1.10	13.42	1.04	13.43
23→14	1.09	0.19	1.18	13.31	1.12	1.17	1.12	13.49
14→26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
26→14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17→18	70.57	71.13	68.00	67.78	4.58	4.75	4.70	4.76
18→17	70.57	71.17	45.57	45.41	70.27	70.24	70.29	70.23
18→20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20→18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
21→20	68.89	57.74	43.67	43.65	22.19	22.16	22.05	22.31
20→21	70.54	4.07	55.36	66.79	0.11	0.11	0.11	0.11
21→23	13.17	0.48	1.02	1.02	12.22	12.32	12.30	0.17
23→21	3.83	0.00	4.21	3.83	70.56	70.19	70.81	70.18
22→17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17→22	0.00	0.48	0.00	0.00	0.00	0.00	0.00	0.00
22→24	3.83	4.06	4.21	3.83	70.57	70.18	70.80	70.18
24→22	13.17	0.00	1.02	1.02	12.47	12.57	12.55	0.18
23→17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17→23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
23→26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
26→23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24→18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18→24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
26→20	0.11	0.12	0.00	0.00	2.69	2.58	2.37	2.76
20→26	0.00	0.00	12.17	0.00	1.00	1.00	1.02	1.04
26→21	1.02	13.26	13.13	1.03	4.52	4.69	4.62	4.70
21→26	1.69	13.43	1.93	1.77	48.22	48.22	48.40	48.06

Table (A6): Average link utilization of Network 3 operating with QoS (high load).

LINK	Utilization %							
	RSVP				CR-LDP			
	FIFO	PRI	WFQ	CUST	FIFO	PRI	WFQ	CUST
12→18	12.05	0.00	0.00	0.00	0.32	0.62	2.31	12.43
18→12	13.38	27.23	19.02	31.33	0.00	0.00	0.00	0.00
12→20	0.00	0.00	0.00	12.17	0.00	0.00	0.00	0.00
20→12	6.92	7.71	10.77	10.13	2.90	13.10	5.55	3.62
12→21	2.41	2.15	2.33	2.40	0.46	1.36	2.44	.68
21→12	0.00	0.00	0.00	0.00	70.10	70.11	70.16	70.50
12→24	13.38	27.23	19.03	31.34	12.10	0.00	0	0
24→12	12.05	0.00	0.00	0.00	0.32	0.61	2.31	12.43
14→17	70.84	70.51	54.63	54.64	10.00	10.00	22.01	10.05
17→14	1.50	13.68	42.43	42.40	24.84	23.03	22.32	23.19
14→22	9.33	1.00	25.24	12.33	7.40	25.90	14.01	11.89
22→14	69.25	57.69	20.76	24.32	46.18	48.28	49.01	47.50
14→23	13.38	27.23	19.02	31.33	0.00	0.00	0.00	0.00
23→14	12.05	0.00	0.00	0.00	0.33	0.62	2.33	12.68
14→26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
26→14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17→18	70.84	70.54	68.1	56.67	14.51	22.66	30.56	18.31
18→17	70.75	71.37	63.19	54.56	70.80	71.08	71.11	70.45
18→20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20→18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
21→20	1.5	13.68	42.43	42.41	24.97	23.65	22.50	23.26
20→21	70.84	70.51	54.63	54.63	10.04	9.96	22.27	10.08
21→23	2.41	2.15	2.33	2.40	0.46	1.36	2.44	0.68
23→21	0.00	0.00	0.00	0.00	70.23	70.26	70.33	70.34
17→22	0.00	0.00	0.00	0.00	00.00	0.00	0.00	0.00
22→24	0.00	0.00	0.00	0.00	70.23	70.38	70.33	70.85
24→22	2.41	2.15	2.33	2.40	0. 47	1.36	2.46	0.69
23→17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17→23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
23→26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
26→23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24→18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18→24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
26→20	6.92	7.71	10.77	10.13	2.92	13.38	5.57	3.65
20→26	0.00	0.00	0.00	12.16	0.25	0.25	0.25	0.25
26→21	2.43	2.30	14.48	2.21	4.52	12.82	8.58	8.29
21→26	69.26	57.70	20.76	12.16	46.1	48.24	48.99	47.34