Design and Performance Evaluation of Intelligent LSPs in Multiprotocol Label Switching Networks

A Thesis

Submitted in fulfillment of the

requirements for the award of the degree of

Doctor of Philosophy

Submitted by

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May 2016

Certificate

I, Anju Bhandari hereby certify that the work which is being presented in this thesis entitled **"Design and Performance Evaluation of Intelligent LSPs in Multiprotocol Label Switching Networks"**, in fulfillment of requirements for the award of the degree of **DOCTOR OF PHILOSOPHY** being submitted to the Computer Science and Engineering Department (CSED) of Thapar University, Patiala, Punjab, India is an authentic record of my own work carried out under the supervision of **Dr. V. P. Singh** (Assistant Professor, CSED, Thapar University, Patiala, Punjab, India).

The matter presented in this thesis has not been submitted either in part or full to any other University or Institute for award of any degree.

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This is certified that the above statement made by the candidate is correct to the best of my knowledge.

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Anju

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List of Abbreviations

ATM	Asynchronous Transfer Mode
BGP	Border Gateway Protocol
CoS	Class of Service
CR-LDP	Constraint Based Label Distribution Protocol
CR-LSP	Constraint Based Label Switch Path
Diff Serv	Differentiated Service
FEC	Forward Equivalence Class
FLCS	Fuzzy Logic Control System
FR	Frame Relay
FTP	File Transfer Protocol
IETF	Internet Engineering Task Force
IGP	Interior Gateway Protocol
INT Serv	Integrated Service
IP	Internet Protocol
IPv4	Internet Protocol version
IS-IS	Intermediate System to Intermediate System
ISPs	Internet Service Providers
L2	Layer 2
LDP	Label Distribution Protocol
LER	Label Edge Router
LIB	Label Information Base
LSP	Label Switch Path
LSR	Label Switching Router

LsS	Label Switched Path Setup System
MPLS	Multiprotocol Label Switching
MPLS-TP	Multiprotocol Label Switching Transport Profile
NFV	Network Function Virtualization
ns	Network Simulator
OSPF	Open Shortest Path First
QoS	Quality of Service
RSVP	Resource Reservation Protocol
RTT	Round Trip Time
SDN	Software Defined Networking
TCP/IP	Transmission Control Protocol/ Internet Protocol
TE	Traffic Engineering
TSS	Traffic Splitting System
UDP	User Datagram Protocol
VoIP	Voice over Internet Protocol
VPN	Virtual Private Network
WRP	Wireless Routing Protocol

Abstract

Multi Protocol Label Switching (MPLS) is defined by the Internet Engineering Task Force (IETF). It is a network expertise that broadcasts traffic efficiently and supports Quality of Service (QoS) on the Internet. In the present research work, fuzzy based control methodology has been adopted that deals with the uncertainties and high variability appearing in the network. The essential design of traffic regulation is successful liberation of packets by implementing fuzzy based congestion control methodology.

Based on the systematic literature survey and studying associated matter related to the problem area, a fuzzy based solution is developed that does not change the existing conventional algorithms but uses operations of them in order to improve the network performance. The selection of the fuzzy logic method is due to the simplicity and expert defined rules governing the routing system. It can be modified and tweaked easily to improve the performance.

The work presented is an effort of implementing a fuzzy based decision making component for high volume traffic MPLS networks by implementing Traffic Engineering, Quality of Service and Multipath routing. The approach explicitly proves to be successful in solving the issues and challenges pertaining to stability, scalability in high volume and dynamic traffic. Furthermore, it handles congestion by higher link utilization and provides efficient rerouting of traffic along with fault tolerance in the network. Fuzzy Controller consists of two sub fuzzy systems- Label Switched Path setup System (LsS) and Traffic Splitting System (TSS). The computation of dynamic status of Load and Delay is utilized by LsS to arrange the paths in order of preference. The attained Link Capacity and Utilization Rate are employed by TSS for maintaining congestion free path. The system is to facilitate better decision making for splitting the traffic in different promising paths. This is apparent from the series of simulations carried out on different traffic scenarios.

Chapter 1
Introduction

1.1 Background

The Multi Protocol Label Switching (MPLS) uses short sized labels instead of IP address for routing. It is open and modular in nature that allows addition of more features at any time. It has been observed by the working groups (Telecommunication Standardization Sector of the International Telecommunications Union (ITU-T) and The Internet Engineering Task Force (IETF)) that the high volume traffic is exponentially increasing day by day. *Rosen (2001)* suggested that an enhancement for improving the performance of network come easy by using MPLS. It has been studied and recommended by researchers/technicians that the promotion of packet based technologies becomes necessary, which reduces Operational Expenses (OpEx) and Capital Expenses (CapEx) in the operations of networks. So, it is realized that there is an urgent need of an effective and reliable solution like Multi Protocol Label Switching (MPLS) technology. It is concluded by *Lin N et al. (2010)* that MPLS is an elegant infrastructure for Next Generation High Speed Networks, standardized by *Request for Comments (RFC) 3031*. It supports the utilization of Quality of Service (QoS) and Traffic Engineering (TE) for provisioning End to End (E2E) and Service Level Agreement (SLA) assurance.

The architecture of MPLS is structured into two planes called the Data Plane (DP) and the Control Plane (CP). The major significance of structure is that DP and CP are segregated. DP assists in managing configuration and detection of faults. The CP is responsible for establishing Label Switched Path (LSP) by signaling through Label Distribution Protocol (LDP). MPLS possesses technically sound features like maximizing scalability, availability, predictability, manageability and dynamic path creation. Hence, the organizations (Internet Service Providers) are converging towards the IP/MPLS networks.

1.1.1 Multi Protocol Label Switching Architecture

MPLS evolved from numerous prior technologies in the mid-1990s that were aimed at making IP routing more efficient and more competitive with protocols like Frame Relay (FR) and Asynchronous Transmission Mode (ATM). The primary source of MPLS standards was Toshiba’s “Cell Switch Router (CSR)”, Cisco’s "Tag Switching" and IBM’s “Aggregate

Route-based IP Switching (ARIS)". These switching techniques could not cope up with packets at 10Gbit/s rates. *Lawrence J (2001)* introduced the mechanisms that create routes for the traffic through IP networks. It remains the basis for the core of the MPLS even today.

Sabatini R (2015) suggested intelligent Air Traffic Management System fulfilling the requirements of next generation traffic scenario.

The demand for advanced applications like Video Conferencing, Tele-medicine, Distance education and Voice over Internet Protocol (VoIP) is increasing and the need of low latency networks has also risen. MPLS provides Quality of Service Routing (QoSR) and improves Traffic Engineering (TE) for existing latency sensitive networks.

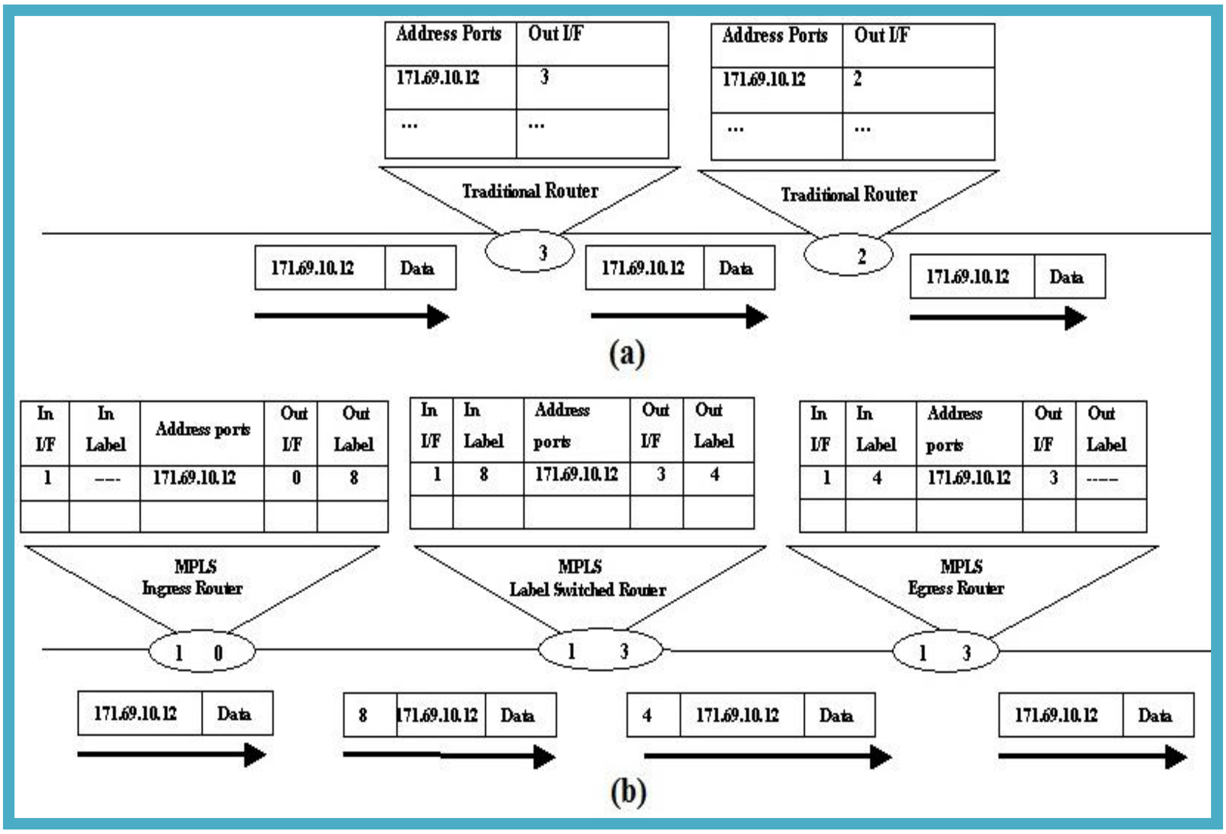

Figure 1.1: Structure of (a) Traditional Router (b) MPLS Router

In traditional IP routers as shown in Figure 1.1(a), the router processes every packet before forwarding to the next router. *Tran P N et al. (2008)* studied that the processing includes filtering of IP addresses and mapping the long IP addresses passed by the IP packet and finding the next hop from the local routing table(s). It is slower due to fact that long packet takes longer processing time. Instead of this, MPLS lookup is certainly less complex and time consuming than a corresponding lookup in an Internet Protocol (IP) router. The amount of processing time at every intermediate router gets reduced using High Speed Routers. In Figure 1.1(b) packet enters in MPLS network through In interface (I/F) 1, Ingress Router attach the label 8 and exits through Out interface (I/F) 0.Then it enters in Label Switched Router, it swaps the label by 4 and exits through Out I/F 3.Then, Egress Router strips off the label and exit from the router through Out I/F 3. Inspite of this, in traditional router, packet enters in network moves from one hop to another hop through Out I/F 3 and so on, until reaches at its destination.

Acharya A (2002), RFC 3353 explains that MPLS provides ability to engineer traffic flow, QoS and prioritize packet forwarding without losing flexibility of the network as explained in next given sections. According to current demand and research, it has been observed that MPLS supports guaranteed throughput, stable low Latency, End-to-End WAN management with 99.99% availability and global reach. MPLS is playing great role in successful deployment of cloud computing and mission critical applications. *Doss R et al. (2010)* have worked on mission-critical wireless sensor networks.

1.1.2 The Coming Age of Multiprotocol Label Switching Networks

RFC 5218 formally defines MPLS, a huge success. Only 20 bits of information is added by MPLS to a packet called as label information. A Time-to-Live (TTL) field of 8 bits, 3 bits to mark a packet's service class, and 1 for bottom of stack delimiter bit as shown in Figure 1.2.

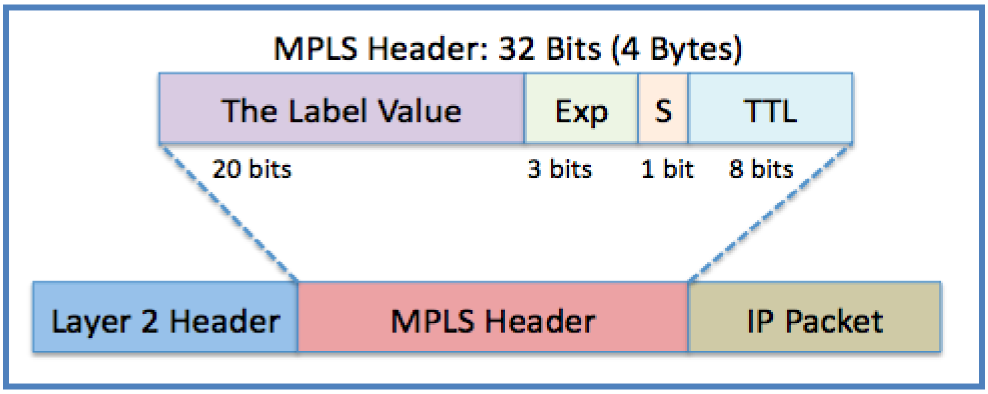

Figure 1.2: MPLS Header and Position in generic format

The label, alike to an IP address, is used for forwarding a packet. Unlike an IP address, though, the label does not have any structure or format. A label has local significance and changes at every hop of the network. Relabeling of a labelled packet is called Label Swapping. Operation of adding a label is called Label Pushing. Operation of removing a label is called Label Popping. Forwarding based on labels rather than IP addresses gives little extra advantage. IP follows the destination-based forwarding paradigm, which essentially means all forwarding is done based on the destination address in the IP header. The establishment of MPLS is due to its simplicity and suppleness with minor overhead declared by *Winter R(2011).*

1.1.3 Traffic Engineering applied on MPLS

The basic idea is to give best possible QoS with target applications and possible routes to pass through. The overall cost of ownership must be reduced. The basic terms used to persuade the traffic routing and splitting are as follows:-

TE Tunnel: Unidirectional tunnel Labeled Switch Path.

Ingress Node or Head End: It is a point from where all contained tunnels are created and configured.

Egress Node or Tail End: The destination of the tunnel is called the Egress node.

Resource Reservation Protocol (RSVP): Liable for building tunnels/ paths.

Constraint based routing (CBR): Routing based on single or compound Constraints.

Basic Mechanism of Tunneling is done by Link State protocol. This protocol helps in carrying the network link attributes in their link-state advertisements (LSAs) or link-state packets.

Based on the constraints defined, the traffic routes are computed with the help of some efficient solution like **Fuzzy Controller** based algorithms.

Traffic Signaling of the route is maintained by Resource Reservation Protocol with Traffic Engineering extensions (RSVP-TE).This is further extended by *Swallow G (2005)* as fast reroute Extensions.

MPLS technology basically pools the intelligence of routing algorithms with the enactment of switching technology mainly using soft components. A set of switching nodes is capable of switching and routing on the origin of label appended to each packet format. These router /switch nodes are called Label Switched Routers (LSRs) and are the key component within the network. The LSR components have a competence of accepting the routing and switching operations. There are two types of Label Edge Routers (LERs) or Edge Label Switched Routers namely as Ingress LSR and Egress LSR as shown in Figure 1.3. Ingress classifies the labels, assigns them at the entrance and Egress removes them at the exit.

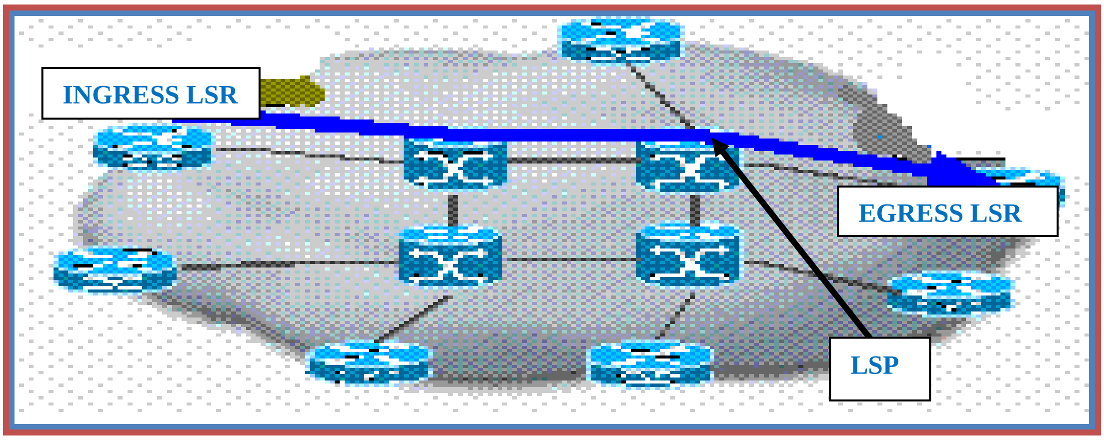

Figure 1.3: Components of MPLS

The exchange of information between each other in the network and among networks is done using Interior Gateway Protocol (IGP) inside a network and Exterior Gateway Protocol (EGP) between independent networks. MPLS network uses labels to forward traffic across the network as shown in Figure 1.4. The MPLS signaling is performed by LSRs using Label Distribution Protocol (LDP) and RSVP. Combining QoS and TE on these protocols results in Constraint Based Label Distribution Protocol (CR-LDP) and RSVP-TE is studied by *Lin N Yang T, and Song L X (2010)*. The labels define the flow of packets between the two endpoints. When packets enter the network, labels are imposed on the packets and the label determines the next hop.

MPLS network uses labels to forward traffic across the network as shown in Figure 1.4. *Awduche D O (1999, 2001)* suggested that, MPLS signaling is performed by LSRs using LDP and RSVP. These labels delimit the traffic flow of individual packets between the two endpoints. In this way a high-speed switching of data packets is conceivable as the fixed-length labels are interleaved at the beginning of the packet to switch packets quickly between links. The LSP established either prior to data transmission (control-driven) or upon detection of a certain flow of data (data driven). *Barakovic J, Bajric H, and Husic A (2006)* defined that the LSP originates from the edge of MPLS domain. The Labels are allotted to each individual data packets based on the Forwarding Equivalence Classes (FECs). The Packets that belong to the same FEC end up with same outcome. The concept of FEC is connected as a traffic representation that describes the QoS level requirements for that particular network flow.

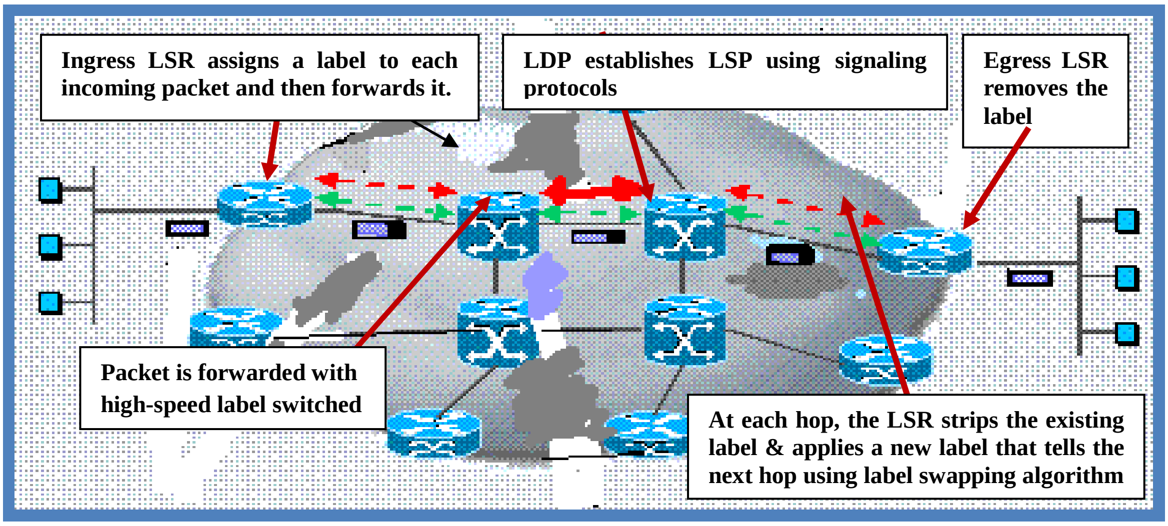

Figure 1.4: MPLS Operation

Route selection is a function, which performs the actual setting of the LSP and is done using either implicit routing or explicit routing. *Pepelnjak I, and Guichard J (2002)* have explained Implicit establishing up of the LSP, which need information about the topology as well as QoS related information for the MPLS domain. The LSP is explicitly routed if sets up on the basis of computation of constraints using some network supervision, that is self-governing of the default IP routing protocol.

Swapping of the label takes place at the intermediate nodes by updating Label Information Base (LIB) at each participating node and then packets are forwarded to the next hop. LSR supports routing using Open Shortest Path First (OSPF), Intermediate state- Intermediate state (IS-IS), and performs forwarding too. Implicit routing protocols OSPF, IS-IS, Interior Gateway Protocol (IGP) and Border Gateway Protocol (BGP) are not able to work in highly loaded network. As each LSR independently chooses the next hop. It does not readily support traffic engineering or policy related to QoS and security and thus causes congestion. Explicit routing RSVP-TE, QoSR and CBR are able to perform better in highly loaded network.

A single LSR identifies some or all the LSRs in the LSP for a FEC. Explicit routing provides all the remunerations of MPLS, including traffic engineering and policy routing. Dynamic explicit routing offers the best scope for TE. The enhanced version-2 of OSPF defined by *Katz D (2003)* works successfully in MPLS with the combination of metrics which are valuable in CBR like maximum link Data Rates, current Capacity Reservation, Packet Loss Rate and Link Propagation Delay is declared in *RFC 3630*.

1.2 Key Motivating Factors of MPLS

1. The packets above the 10 GBps require longer prefixes, which causes longer prefix match in hardware like Ternary Content Addressable Memory (TCAMs).
2. MPLS technology progression facilitates working with Synchronous Optical Network (SONET), ATM, Ethernet and Frame Relay. MPLS has outdated these techniques due to extraordinary features.
3. There is an urgent need to route packets to take a non-IGP-shortest-route, this has become possible due to MPLS technology.
4. The concept of Virtual Routers is realized with the use of MPLS technology, the main use is for Internet Protocol based Virtual Private Network (IP- VPN) and Layer -3 Virtual Private Network (L3VPN).
5. Multiprotocol Label Switching- Transport Protocol (MPLS-TP) has taken over the role of SONET and Synchronous Digital Hierarchy (SDH) for connection based applications.
6. MPLS separates the "Traffic Signaling" of the network from the data, it is called the "Control plane".
7. MPLS separates the "Data Load/Payload" of the network traffic signaling. It is called the "Forwarding Plane", this is basically anything that goes "through" the router, and not "to" the router.
8. The foundations of IPv6 Segment Routing and the Tera Stream architecture are other names of MPLS.

1.2.1 Current Traffic Engineering Mechanism

As the traffic scenarios change due to variability in traffic volume and pattern, simple constraints management is no longer effective solution and the whole process becomes very critical. The network has the capability to define routes dynamically, plan resource commitments based on demand and optimize network utilization. Each flow of packets has firm QoS requirements and a deterministic traffic demand. Hence, with the traffic estimation method and algorithms it is possible to set up routes on the basis of these individual flows. Instead of simply changing the route on a packet-by-packet basis, the routes are changed on a flow-by-flow basis.

Barakovic J et al. (2006) and Porwal M (2008) investigated that using recognized traffic demands of each flow, traffic engineering substantially increases usable network capacity and compute routes intelligently. *Swallow G (1999)* defines that the notion of Traffic management and Engineering helps to have a network infrastructure that is dependable and offers consistent network arrangement by picking slightest congested path as shown in Figure 1.5.

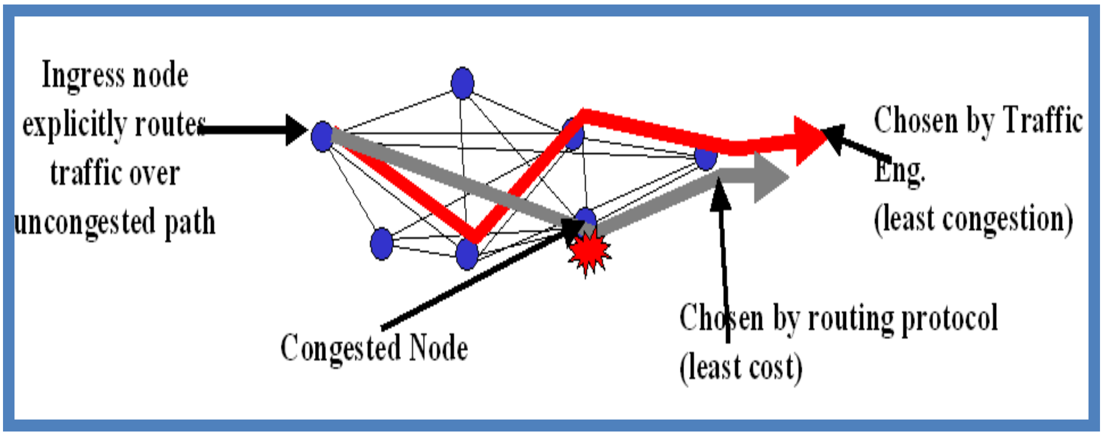

Figure 1.5: Traffic Engineering

Optimized and effective utilization of network resources takes place by efficiently mapping, monitoring and controlling the traffic.

1.2.2 Support of multiprotocol in MPLS

MPLS architecture is independent of the routing protocols. It is due to position of MPLS, as layer 2.5 as shown in Figure 1.6. *Sinha R (2003)* suggested that the interpretation of labels is independent of the control protocols. So, new protocols can easily be supported. MPLS integrates the best of layer 2 and layer 3 technologies. MPLS works in ATM, Ethernet and any other network as shown in Figure 1.7.

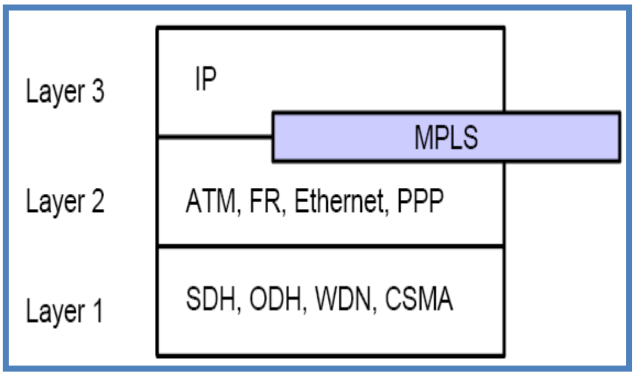

Figure 1.6: MPLS as layer 2.5

MPLS is used with different networking technologies, which is an augmentation to the way a connectionless Internet Protocol (IP) is derived. IP routers are required to upgrade for supporting the MPLS features. MPLS enabled routers can coexist with regular IP routers. *Fowler S et al. (2010)* declared that the universal nature of MPLS appeals the users who currently have mixed network technologies and seek ways to optimize resources and expand QoS support.

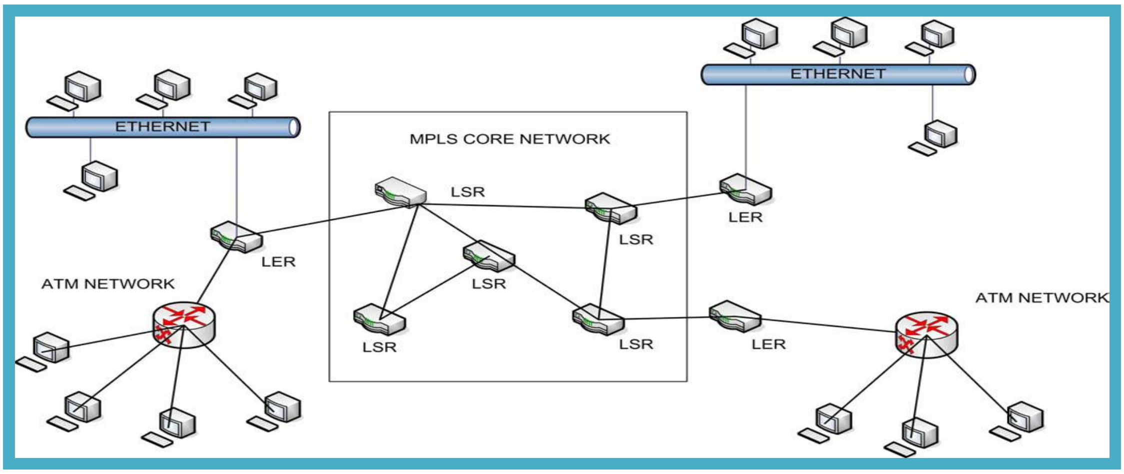

Figure 1.7: MPLS Network

However, backward compatibility with older routers in the network, LANs with mixed version peers experiences lot of issues in terms of computations related to routing metrics. The calculations become numerically unstable. There would always be some un-scaled part of network. This would impact the routing calculation related bandwidth, delay, link state etc. Similar issue crop up when there is a larger network of heterogeneous routers and switch network. Not only these network metrics will be impacted, the next section introduces the challenges that come across when network undergo up scaling. The thesis is based on following network factors as studied in Table 1.1. The monitoring of link utilization has been done in order to reduce the chance of congestion in LSPs. Load balancing is the best remedy of congestion free network.

Table 1.1: Selection of Network factors

S. No	Network Factor	Impact on Packet Traffic volume
1.	Link Utilization	As volume of traffic increases and network properties are scaled up, there is a need of maintaining additional information and updating discovery services. The combination of old and new routers, the heterogeneous switch and network routers are not giving apparent image of QoS. The link utilization metric computations are ambiguous in nature and not deterministic.
2.	Load Balancing	The traffic volume remains highly variable in nature and the data stream rate is too high in irregular intervals. Taking load balancing decision based on historical data sometime become not maintainable in terms of accuracy. The router is able to distribute the traffic over the certain paths with additional advantage of minimum delay. Routing traffic as per the metrics calculated from the traffic become risky. The routing algorithms are unable to differentiate between the link quality of one path from another due to influence of multiple factors that are overlapping and are without crispy boundary values. Load distributor in MPLS routers distribute load based on widest disjoint set of paths or resource metrics, its response preventive or reactive. The problem remains NP hard problem, as the values need to be calculated dynamically.
3.	Delay	For end-to-end paths, in which the bandwidth is constant, the use of the scaled bandwidth has sufficient resolution to allow for differentiation up to 10 GB. Most paths traverse links considerably slower in the distribution access layers and effectively remove the scaled bandwidth as a useful path differentiator.

1.3 Statement of the Problem

In traditional approach, traffic is considered as alike and packets get discarded on congestion. It provides low bandwidth network services which is unacceptable and very challenging for high-speed networks. Applications having no specific requirements for latency are supported by it.

Heavy traffic creates unavoidable problems due to the following reasons.

1. Traffic patterns become less predictable.
2. Changes in delay are more rapid.
3. The routing algorithm often cannot meet to a stable solution which leads to oscillations and causes further degradation in performance.
4. Algorithms cause computation overhead.
5. Impression of global state generating improper decisions.
6. Threat of stability to statistical variation due to less appropriate selection of performance metrics.
7. Rise in time complexity and storage complexity hampers the performance of network.

Some algorithms studied in literature survey are based on Quality of Service Routing (QoSR), which are not able to give reliable traffic scenario of the network. Some of them are based on TE, which have also not been able to give relief from congestion. The algorithms discussed had not been able to fully utilize the resources which results in uneven utilization of resources which results in slowing the existing system. So, it is desired to integrate the features of TE, QoSR and artificial intelligence to bring efficiency in the system.

The main objective of this research work is to ***Design and Evaluate Performance of intelligent LSPs in MPLS networks.*** The sub-objectives are as follows:-

1. Identification of optimal fuzzy parameters responsible for high performance in MPLS networks.
2. Designing of algorithms for intelligent LSPs based on identified fuzzy parameters.
3. Testing and validation of the algorithm.

1.3.1 Fuzzy approach for selection of LSPs

Fuzzy design methodology possesses features like fuzzy metric having lower costs and better end product performance. Those problems which are very complex for the traditional mathematical modeling is easily solved by Fuzzy approach. Fuzzy logic seems closer to the way our brain works, as studied by *Zadeh (1965).*

Resende et al. (2003), Yaghmaee et al. (2006), Din N M et al.(2005, 2008) and Khan J A et al. (2004) recommended that Fuzzy metric is more powerful method than a simple metric and yields better network performance in terms of a packet loss, link path, link delay, link utilization, path length, bandwidth, reliability, load, communication cost, and throughput. It is defined as an optimal path determination variable, which varies continuously and gives the best path for a source-destination pair when multi-paths exist. Sophisticated route selection has been done through single or multiple metrics. The approach is advantageous in the situation where a metric value need not be rigid but somewhat flexible in a range of values.

1.4 Problem Formulation

The proposed approach aims to increase the throughput of highly loaded conditions for network, as in that case all links are going to be congested and it is not possible for QoS to be realized. In Figure 1.8, Rule Base (RB), Membership Function (MF) and Inference Engine (IN) gives Degree of Strength (DS), which is an input to design an algorithm. It is advisable to distribute traffic over all available links, which throws diverse options for making the best decision. It provides alternate paths and categorizes them in the preferential order with respect to priority based paths and equally efficient paths.

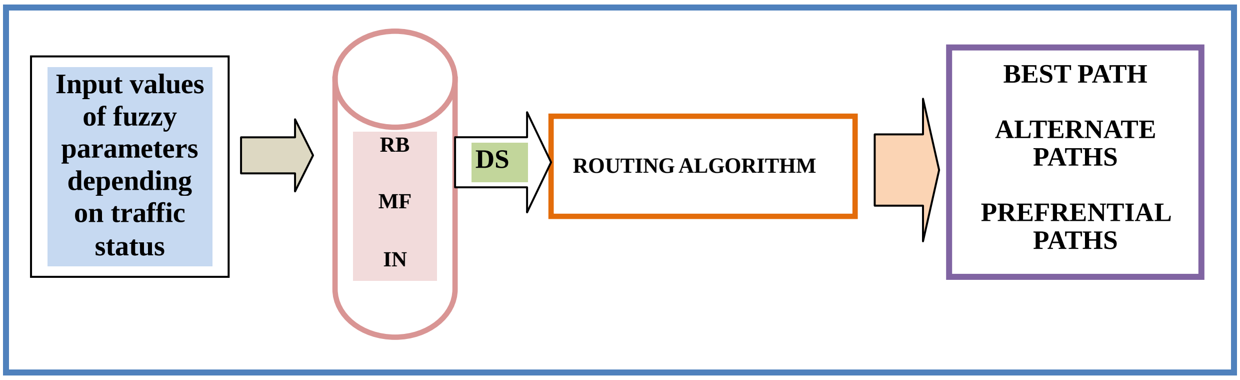

Figure 1.8: Computation of Fuzzy based LSPs

Fuzzy Mixed Metric (FMM), a combination of suitable fuzzy metrics. It is used to select appropriate LSP and other alternate LSPs followed by the traffic in order to obtain congestion free network. The designed algorithm aims to balance traffic by fuzzy based LSPs in the network as shown in Figure 1.9.

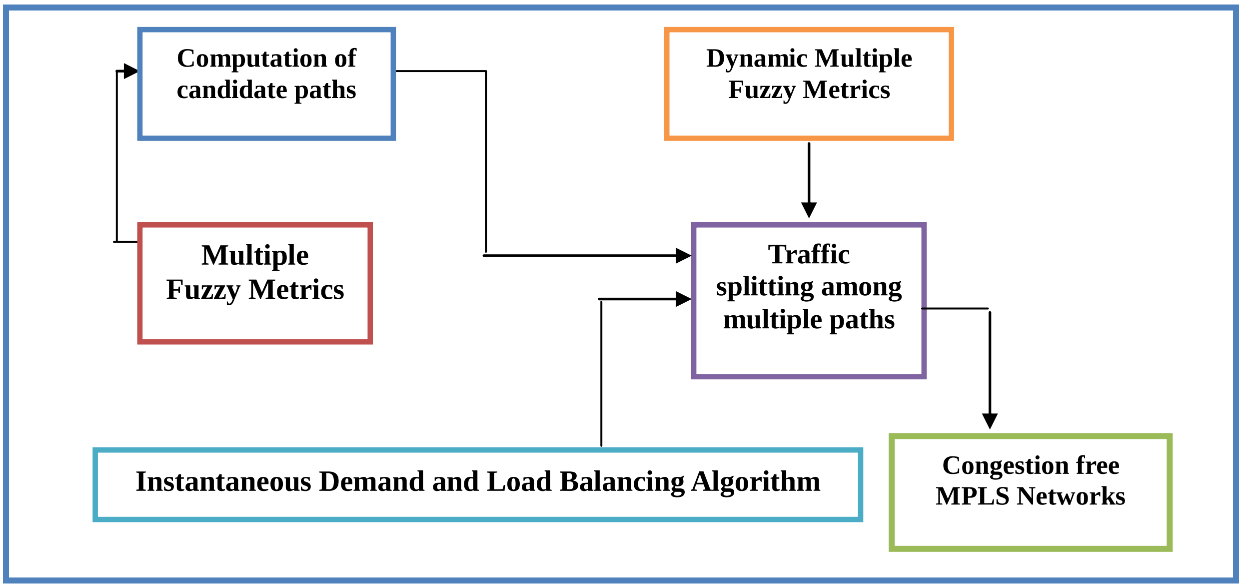

Figure 1.9: Design of Network Traffic Management Model

The computed fuzzy based LSPs are evenly utilized for forwarding packets to avoid the situation of underutilization or over utilization of paths. None of the path remains idle for longer time and proper utilization of resources takes place. Hence, it is better for congestion to be prevented.

1.4.1 Adopted Methodology

The following steps have been carried out to achieve the objectives:-

1. A detailed study of related literature about MPLS architecture, role and significance of each component of MPLS has been done.
2. Fuzzy Metric (FM) with appropriate input parameters and output parameters has been proposed. The Fuzzy Logic methodology is implemented with the help of MATLAB Fuzzy Logic Toolbox as follows: -
   - 2.1. Computation of Degree of Strength (DoS) of input parameters with respect to linguistic terms.
   - 2.2. Computation of Output Mixed Metric.
   - 2.3. Computation of Fuzzified decision in respect to output linguistic terms.
3. Validation of the work has been done by the comparison of the performance of existing algorithm and proposed algorithm. Consequently, it is found that the algorithm has generated better path and alternate paths with appropriate fuzzy metric.

According to the current work, Fuzzy Traffic Manager (FTM) resides in the ingress node. It works on the execution of Fuzzy Logic Control System (FLCS) as demonstrated in Figure 1.10.

This fuzzy based control methodology has been adopted that deals with the uncertainties and high variability appearing in the network. The basic idea of traffic regulation is to improve the delivery of packets by implementing fuzzy based congestion control methodology. It conserves fast system reaction and robust performance in changing network conditions. It utilizes the resources efficiently and routes optimally. Hence, overall network performance gets improved. The selection of the fuzzy logic method is based on its simplicity and process expert defined rules leading the routing system. It can be modified and tweaked easily to improve the performance. Analysis of the state of the art reveals that still, there is no protocol designed and evaluated. Hence, in this research work, the abilities of Fuzzy Logic (FL) have been utilized to develop a technique for fuzzy based traffic conditions.

The work presented in this thesis is an effort to develop a fuzzy based decision making component for high volume traffic MPLS networks, by implementing TE, QoS and dynamic multipath routing.

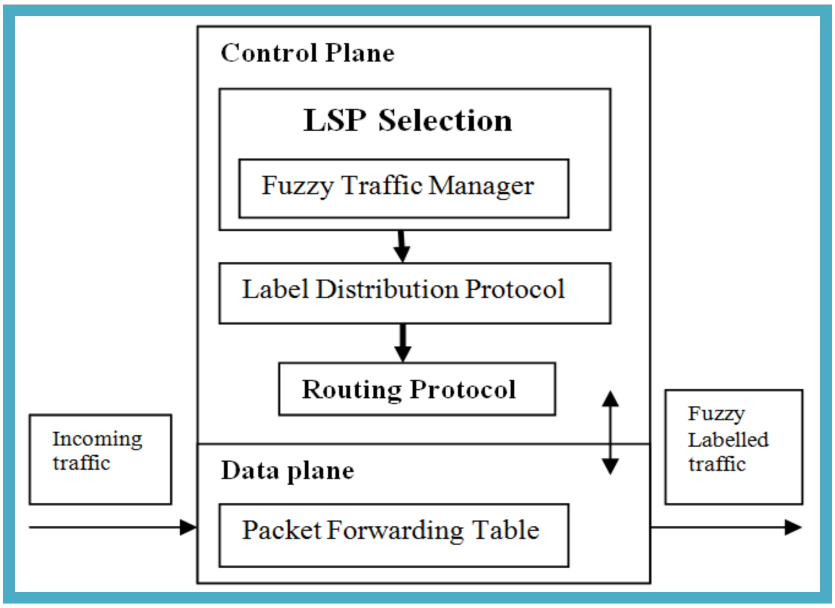

Figure 1.10: Fuzzy Traffic Manager in the LSP selection component of an ingress node

The approach explicitly proves to be successful in addressing the issues and challenges pertaining to better efficiency, stability and scalability in high volume traffic. The technical feature as given in Table 1.2 concludes the characteristics of existing techniques.

Table 1.2: Technical details

S. No.	Features	Details
1.	Limitations of existing technologies	Complex, Incapability to scale, Vendor dependence, Inconsistent policy
2.	Need for new Architecture	Changing traffic pattern-match, Consumerization of IT, Augment of cloud application, Data handling
3.	Motivation of FTM	Control plane - Data plane programmability, Platform independency, User-driven control, Deployment is easy

1.5 Contributions of the Thesis

The complex and challenging issue of congestion control in high traffic volume is the key issue of our research study. In this thesis we build following contributions:-

1. Investigated the suitable parameters responsible for congestion control.
2. Investigated the suitable fuzzy inference engine for building reliable fuzzy rules for the system.
3. Appropriate fuzzy parameters are used for LSP selection by LsS Controller. The selected LSP fulfills the source utilization and reduces the congestion at some desired level.
4. Suitable fuzzy parameters are used by TSS controller perform traffic splitting among the specific number of LSP. It controls congestion control as traffic gets diverted to more number of paths when utilization rate rises.

In particular, a significant contribution has been made in formulating an effective, robust generic intelligent selection and congestion control methodology using fuzzy logic. It is easily adopted in MPLS networks to solve the problem of congestion control. The developed fuzzy control methodology is offering significant improvement in congestion control in MPLS network under varying operating conditions. Thus, it has been proved that it provides high QoS with optimum link utilization, low losses and delays.

1.6 Organization of the Thesis

Including this introductory Chapter 1, this Thesis consists of seven chapters.

A comprehensive survey of existing routing protocols is given in Chapter 2. The main objective of the survey is to understand existing routing strategies in the current networking environments. The literature survey aims to find cumulative knowledge growth, methods in Traffic Engineering and focused on problems of Traffic Congestion and Traffic Splitting. Investigation of gaps has been also done to find fragmentary work done by others in a MPLS technology. It demonstrates the existing validity measures and indices for the validation of routing algorithms. The related literature as summarized in this chapter indicates the gaps in the existing approaches applied on MPLS Networks.

Third chapter demonstrates the application of fuzzy logic in networks. A systematic methodology of fuzzy logic modeling is a generic tool giving high end product performance is explained in this chapter. Those problems which are very multifaceted for the traditional mathematical modeling or any other methods can be solved by Fuzzy approach. The approach is advantageous in the situation where a metric value need not be rigid but flexible in a range of values. The complete process of fuzzy logic is explained in this chapter in detail.

Chapter 4 gives brief justification about the selection of ns-3 simulator. Impetus behind using ns-3 is illustrated. The ns-3 has well organized modular architecture and can be easily expandable has been explained in this chapter.

In Chapter 5, the Fuzzy Logic Control System (FLCS) is explained in detail. Mathematical formulation for updating input parameters of two sub-controllers (LsS and TSS) has been given in designed strategy. LsS selects LSPs according to two input fuzzy variables (Load and Delay) and gives output fuzzy metric LsS_value. The variables Load and Delay are suitable QoS factors on which selection of appropriate path depends. TSS performs the traffic splitting or load balancing using two input fuzzy variables (utilization rate and link capacity) and gives output performance fuzzy metric TSS_value.

An intelligent decision of traffic splitting is performed among the computed number of LSPs required by Traffic Splitting Algorithm (TSA). The available number of rules in the Rule Base matrix LsS and TSS represents intermediate situations and provides the control mechanism with a highly dynamic action. Thus, the developed algorithm is able to achieve a balance of traffic volume for every possibility in the network.

Sixth chapter includes discussion on the strategy used for simulation and evaluation. The details of the platforms used for simulation are explained. A systematic synthesis has been conducted to bring coherence of previous work. In this process we reviewed the common MPLS concepts, MPLS methodologies, MPLS perspectives within the realm of high speed networking. The ns-3 Discrete Event Simulation Model has been found to be best suited for the simulation in this context. For conducting the case studies, three traffic scenarios were identified using systematic literature survey as well as by reading case studies in telecom industries. The complete statistical comparison of proposed algorithm FLCS and existing algorithm Open Shortest Path First (OSPF) is obtained and discussed.

Chapter 7 concludes the research work. Indicators and directions for the future research on the topic under consideration are also discussed. The Routing Protocols enriched to address more specific and challenging networking environments are discussed along with the future scope. The proposed strategy adopted for all kinds of networks. Hence, it easily adopted in future networking. This done by considering the issues and relevancy to the Software Defined Networks (SDN). The implementation of Fuzzy logic in SDN brings better results.

1.7 Conclusion

MPLS uses short labels instead of longest prefix match for switching traffic. This reduces the switching delays. It operates between network and data layer (below the IP layer and on the top of Link layer). It enables interoperability with higher productivity. The LSRs are the routers, which do the traffic forwarding on the basis of label rather than logical 32 or 64 bit address. In a nutshell, it has been found that MPLS is basically answering the complex questions for improving the network performance. The MPLS mechanism needs to decide which “label” to be attached with which “packet” when packets enter in a network. The label carries information as where the packet moves forward to the network interface.

Chapter 2
Literature Review and General Consideration

2.1 Introduction

Many telecom, IT, utilities companies are gravitating towards Multi-Protocol Label Switching Networks as their backbone communication technology. It possesses the features of future generation networks like high scalability, reliability and traffic engineering. This section discusses the taxonomy of algorithms used for building Multi-Protocol label switching (MPLS) protocol stack. It provides a coherent framework for comparative studies of existing approaches. It discusses the routing algorithms based on combination of shortest path and traffic engineering, combination of explicit constraints and traffic engineering, bandwidth guaranteed label switched paths and multipath routing. The emerging algorithms in context of high volume traffic management give predictable services, superior traffic delivery and ease of manageability with high availability. *Costa L M H K (1999, 2000, 2001, and 2002)* defined QoS based routing that it assures the harmony between user and network service provider about bandwidth, delay and loss probability. Traffic Pattern based routing optimizes network resources for current and future quality assurances. As, existing main stream algorithms are not able to cope up with the impact of scalability on the network, it leads to issues related to load balancing and traffic congestion for mission critical applications. *Guizani M et al. (2006, 2014)* studied the challenges and research advances of next generation networks and *Dave M et al. (2013)* surveyed on recovery schemes.

2.1.1 Basic Definitions and Terminologies

Traffic Splitting

Traffic Splitting refers to the way the network links divided with respect to the payload to achieve desired performance. Traffic splitting does not always means splitting because in some cases the algorithm works on equal cost paths like in the case of OSPF. It also means that managing the data in such way that it will be advantageous in tunneling and fixing routes dynamically. This can be done with or without MPLS Traffic Engineering modules.

Traffic Engineering

It is defined as the optimization mechanism of network in which traffic is regulated among different paths on the basis of time dependent functionalities and state dependent functionalities. Time dependent based rely on long span scale and state dependent based rely on the updated value of route statistics.

Load balancing is one of the most important mechanisms to engineer traffic for utilization of available resources. Three basic methods of load balancing are (1) Round Robin forwarding when all paths have equal cost. (2) Time Dependent Approach relies on time span. (3) Hashing based approaches. The history of MPLS and related techniques is encapsulated in Table 2.1.

Table 2.1: History of innovations in MPLS

Year	RFC	Innovations
1994	2734	Toshiba presents CSR
1996	2026	Ipsilon/ CISCO, IBM Announces LS plane
1997	3036	IETF MPLS working work formed
2000	4761	CISCO, GMPLS, Optical Control Plane (OCP)
2001	3031	First MPLS RFC released
2003	3468	MPLS signaling protocols
2006	4761	ITU presents T/MPLS
2008	5317	IETF, ITU presents MPLS interoperable design team
2009	5654	Requests of MPLS-TP
2010	5960	MPLS-TP stated Data Plane (DP) Architecture
2011	6427 6445 6378 6375 6215	MPLS fault mgmt MPLS fast route MPLS-TP linear protection MPLS-TP loss & delay measure UNI-NNI
2012	6639	Management Information Base (MIB) based MPLS-TP
2013	7426	SDN launched for WAN
2014	7167 7325	Point to Multipoint (P2MP) in MPLS-TP MPLS forwarding
2015	7048	ForCes model concluded by Working Group (WG)
2016	Internet draft 2016	Segment routing with MPLS DP

2.1.2 Standards Update: Beyond the expected goals

The demand for advanced application like Video Conferencing, Tele-medicine, Distance education and Voice over Internet Protocol (VoIP) is rising and the need of low latency networks has also risen. MPLS provides QoSR and improves TE for current latency sensitive networks. However, it has also been noted that MPLS has been used for many applications that were unforeseen when MPLS was initially designed. *Winter R (2011),* defines that next progressive iteration in terms of technology of MPLS is culmination of Generalized MPLS (GMPLS). The GMPLS is the perception of forwarding packets based on time slots or even based on wavelengths. *Dominguez et al. (2004) and Wang et al. (2003)* confirmed that the MPLS stack is basically a Pseudo-wire technology, which works as a network convergence and migration technology where Layer 2 frames (e.g., Ethernet) are passed over MPLS network.

2.1.3 DiffServ-aware Traffic Engineering

The combination of DiffServ and MPLS in a high speed networks is defined as DiffServ-aware Traffic Engineering (DS-TE) Systems. Such systems basically have Traffic Engineering Automated Manager (TEAM) component that act as central authority defined by *Anjali T et al. (2004, 2005).* This fundamental authority acts as routing and bandwidth manager. It can fine tune itself to the demands of QoS by reconfiguring. Currently, under the aegis of TEAM, new arrangements for LSP setup/tear-down, traffic engineering and network measurement have been explored by many researchers and industry folks.

2.1.4 MPLS Transport Profile

The organisations, viz, IETF and ITU-T have put joint effort to systematize a new transport stack for the MPLS technology. The main activity is to extend MPLS with necessary Operations, Administration and Maintenance (OAM) tools that are widely acceptable in industry. The packet switch technology assembled with circuit-switched QoS comes across with best effort, but for MPLS-TP, the contributors of both standards work together on its requirement as shown in Figure 2.1.

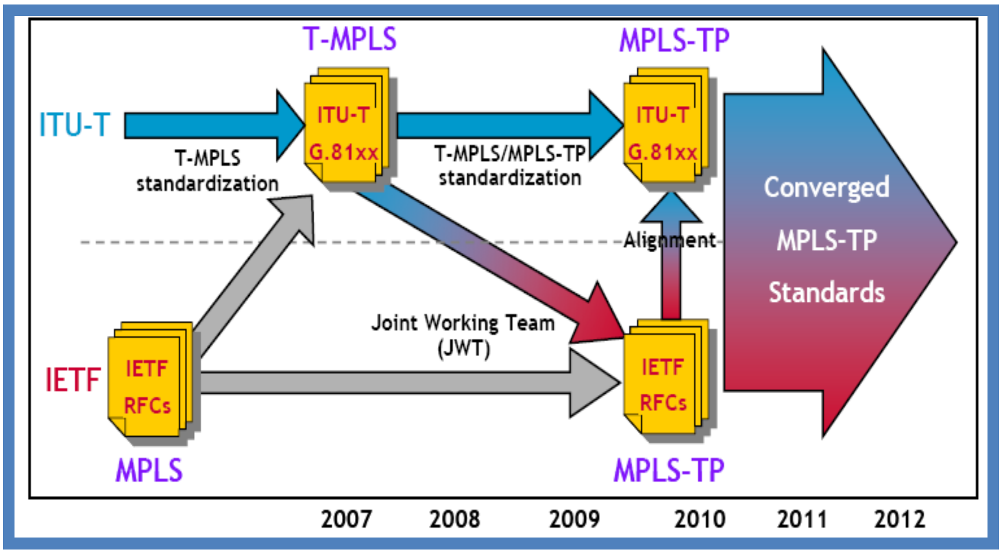

Figure 2.1: Convergence towards MPLS-TP Standards

Hence, the objective of this standardization is to build more MPLS extensions that are essential in order to meet the complex packet level transport requirements over the network. The MPLS-TP technology is introduced by *Anderson L (2008),* as a subset of MPLS functions due to fact that it does not use full stack functions of MPLS technology. It is rather an essential subset of MPLS with added enhancements even in the absence of IP, MPLS-TP work properly and provides its full functionality as specified. To bring together the packet-oriented technology into transport networks comes from the fact that the traffic in today's network is mostly IP traffic. MPLS-TP assures to handle packet-based services more proficiently than traditional circuit-switched transport network technology. The MPLS technology options are already deployed in many core networks today and are a connection-oriented packet-switched technology. It has become the key basis of interworking with the core network of large service providers easily, and some operators are already thinking on deploying MPLS is not just in their core networks but also in the aggregation and access networks boundaries, some of which is just might be MPLS-TP.

2.1.5 Features of Routing Optimization

There are multiple algorithmic implementations for optimizing the performance of high speed networks. These methods dynamically analyse, regulate and predict the behaviour of packets that "pass on" over that network. The routing path optimizations select an alternative path rather than depending on the conventional "short path" methods. It can be an effective means to improve the network service capability. The routing algorithms for optimization are classified into MPLS-TE and IP-TE as shown in Figure 2.2.

It is inferred that MPLS based algorithms support flexible route formation, scalability with less overheads whereas IP based algorithm are based on shortest path formation and possesses high overheads.

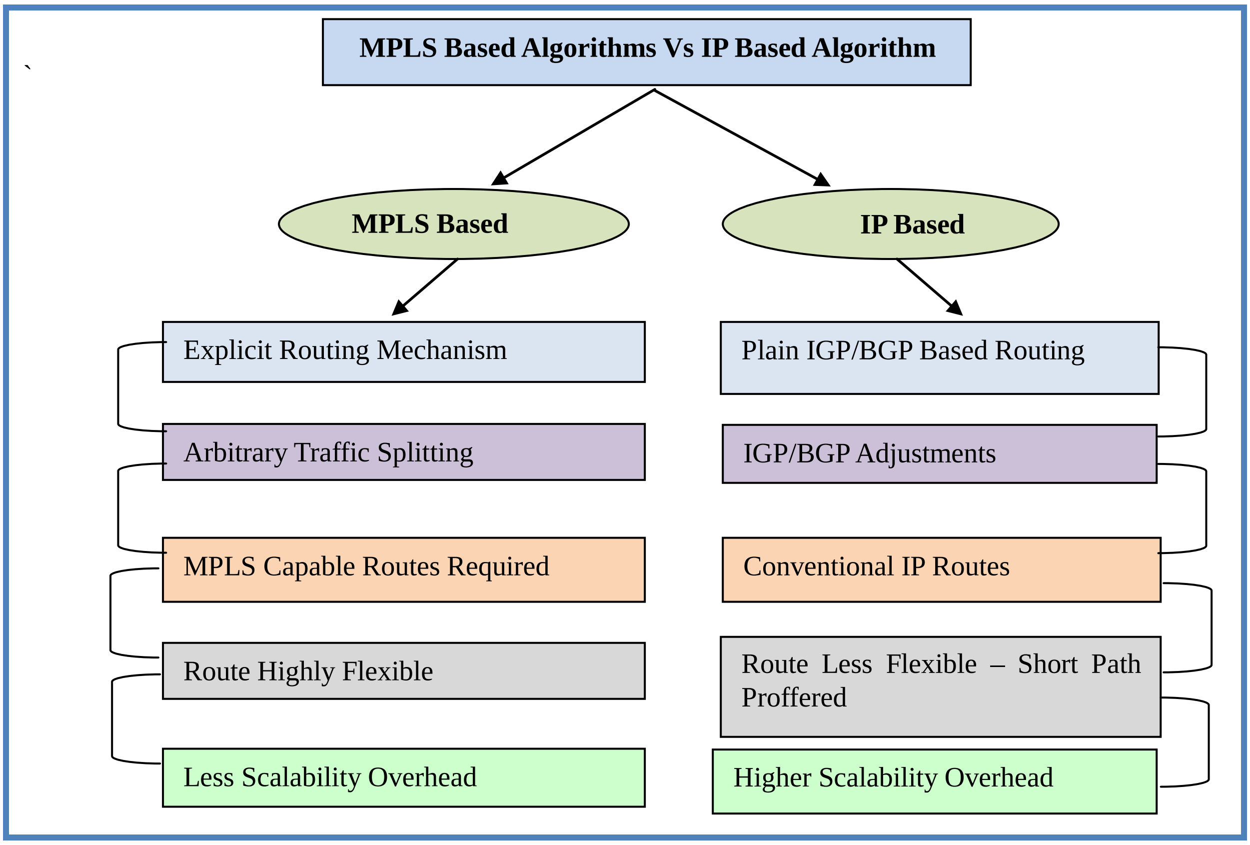

Figure 2.2: Comparisons of MPLS-TE and IP-TE Algorithms

The infrastructure is composed of effective and simplified management tools that provide easy configuration and control of the network. *Wang N, Ho K, Pavlou G, and Howarth M (2008)* defined that MPLS based algorithms are further divided into online and offline and IP-based algorithms categorized into inbound and outbound with TE approaches as shown in Figure 2.3 respectively.

The offline approaches are simple and least complex and possesses less overhead. An online approach on the other hand supports next generation networks.

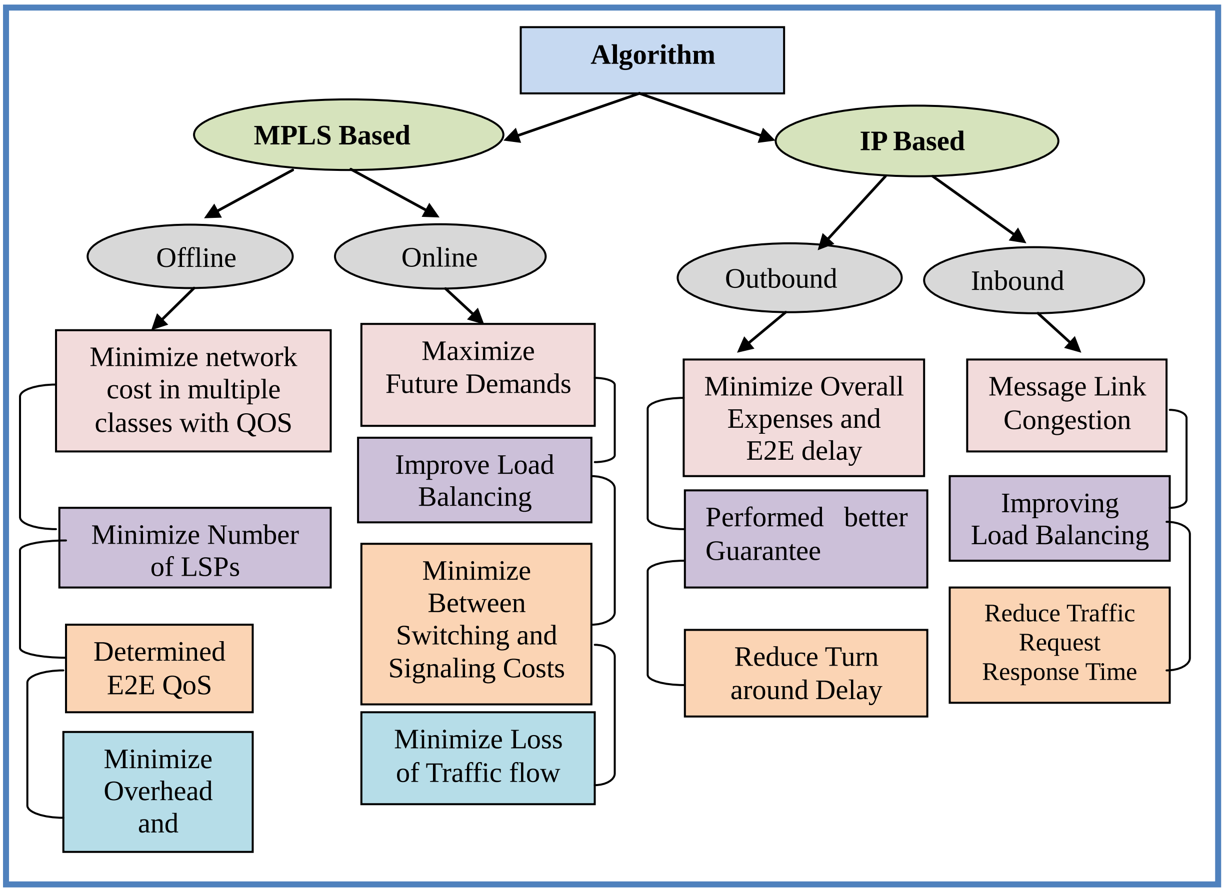

Figure 2.3: Categorization of MPLS based and IP based Algorithms

2.2 Review of algorithms used in MPLS

In Table 2.2, the taxonomy of Algorithms used in MPLS technology stack has been summarized. The optimization objectives vary from algorithm to algorithm. The main goal of all these methods is to study highly effective traffic management. Routing algorithms of different categories with their merits and limitations are presented here.

Table 2.2: Taxonomy of Algorithms used in MPLS technology

Category/ Optimization objective	**Algorithm**			**Merits**	**Demerits**
Shortest path And traffic engineering (SPTE)	Minimum Hop Algorithm (MHA)	Widest Shortest Path algorithm (WSP)	Shortest Widest Path (SWP)	Shortest path optimization	Does not consider traffic constraints, slow convergence
Explicit constraints and traffic engineering (ECTE)	Minimum Interference routing Algorithm (MIRA)	New Minimum Interference routing (New-MIRA)	Widest Shortest Path Switching (WSS)	drop of E2E delay	Larger convergence time to recover global optimum route
Bandwidth Guaranteed label switched paths (BGLSP)	Bandwidth Guarantee with Low Complexity (BGLC)	Bandwidth Constraint QoS routing algorithm with Traffic Engineering (BCTE)	Multiprotocol Label Switching Module (MPLS-M)	Objective (BGLSP) = objective (SPTE + ECTE) beneficial in optical internetwork	Requires frequent link bundling and restoration path computation
	Rate Controlled Static Priority (RCSP)	Dynamic On line Routing algorithm (DORA)	Bandwidth Constraint Routing Algorithm (BCRA)		
Congestion Control Using Alternate Paths (CCA)	Enhanced variable splitting ratio algorithm (ESLA)			Beneficial till $N \leq 25$ Highly Effective load sharing	Minimal benefit $N \approx 100$
Applying Artificial Intelligence on MPLS (AI)	Fuzzy Mixed Metric (FMM)			Multiple objective function	Higher control overheads

2.2.1 Current Status and Performance Analysis of MPLS based Schemes

MPLS algorithms are classified as Shortest Path and Traffic Engineering (SPTE), Explicit Constraints and Traffic Engineering (ECTE), Bandwidth Guaranteed Label Switched Paths (BGLSP), Congestion Control using Alternate paths (CCA) and Artificial Intelligence (AI).

Kodialam M et al. (2000) has discussed various routing algorithms like Minimum Hop Algorithm (MHA), Widest Shortest Path Algorithm (WSP) and Shortest Widest Path (SWP) based on the concept of combination of Shortest Path and Traffic Engineering. MHA finds links with the aim of having sufficient residual capacity for the new LSP and picks route having minimum number of links. Selecting the minimum number of links creates a situation of congestion and causing few links over or underutilized in the network. Consequently, it does not provide a reliable and continuous service, as it cannot accept the future requests. WSP selects feasible shortest path having largest residual capacity. It is an improvement over MHA.

This facilitates the load optimization process and balances the identical Hop count paths for dissimilar traffic request is studied by *Al Ani (2008)*. However, it, still prefers to simply use all available capacity primarily shortest path instead of using longer paths even having more capacity that leads to underutilization. SWP selects path with least available bandwidth and least number of hops. It improves resource utilization but have a shortcoming of constantly using up of some of the links only, while other paths remain underutilized.

2.2.2 Combination of Constraints and Traffic Engineering

Kodialam M et al. (2003) have also discussed that MIRA and NewMIRA are based on the combination of TE and their constraints. MIRA works on the potential traffic of Ingress-Egress routers as weight to calculate the shortest path. The highest flow between the source-destination sets and the link weights of the entire network links are hard to compute. This result in the less attention paid to other links of source-destination pairs. NewMIRA overcomes the drawback of earlier MIRA in terms of the overall bandwidth blocking effects in routing.

Mahmood Z Al-Ani et al. (2009) proposed an efficient routing algorithm WSS, that selects path having more residual bandwidth than required. It considers minimum weight link and minimum hops. It overcomes the drawback found in WSP, MHA, and MIRA. This shrinks interference level, complexity and average CPU time.

2.2.3 Bandwidth Guaranteed Label Switched Paths

Many researchers have given attention to the problem of routing bandwidth guaranteed label switched paths. This challenge of creating bandwidth guaranteed label switched paths occurs when LSP setup requests appear and the future packet requests are not known.

Wang B (2002) has studied about QoS metrics and suggested that the LSP selection results in effective utilization of resources using dynamic parameters like delay and losses. He proposed an algorithm taking into account critical links and residual bandwidth information. Simulations results show that it performs well in comparison to MHA, SWP, WSP and MIRA in terms of LSP rejection rate. Hence, it offers better performance and overall network resource utilization.

Rasiah P et al. (2002) have developed procedure for optimum path computation and LSP setup using RSVP-TE and CR-LDP named as Rate Controlled Static Priority (RCSP) scheduler. RCSP has two elements, the rate controller and the scheduler. It defines delay bounds at the nodes for connections belonging to diverse priority levels. This algorithm evaluates optimal routes having guaranteed QoS**.** In the MPLS differentiated service domain, connections with higher priority are assigned with lower delay bounds at the nodes while connections with lower priority have greater delay bounds.

Boutaba R et al. (2002) have demonstrated an algorithm DORA based on current network information to identify and reduces usage of those links through which more number of paths going. It reduced the ability of collision in the network links.

Munadi Rendy et al. (2003) have introduced the new routing management scheme using MIRA, which diminishes the traffic interference resulting minimizing the network congestion. The network optimization could be achieved by critical link analysis and managing the routing of traffic in the network. Routing management with MIRA is skilful to power network performance, in terms of received packets, throughput and delay. *Wang and Crowcraft J (1996)* defines algorithm that hits upon optimum path with respect to bandwidth and delay. It gave higher blocking rate as it did not consider packet loss in route computation.

Zhenyu Li et al. (2003) have developed BCTE, that sets up bandwidth guaranteed LSPs in MPLS networks. The algorithm basically operates on max-flow problems and introduces path saturation as routing parameter, which reduces call-blocking probability and balances the network traffic load. It suggests that WSP concentrates on the traffic load on some links with shortest path for request, thus overall network performance cannot be in actual fact utilized, but BCTE has less call blocking rate and lower path load with higher load utilization.

Anjali T et al. (2003) concluded that algorithms can be categorized as Link Constraint, Link

Optimization or Path Constraint, Path Optimization. Link deals with constraint of bandwidth, load and path deals with delay, jitter and latency.

Alidadi A et al. (2009) implemented an algorithm BGLC. It compared the algorithm with MHA, SWP, WSP, MIRA, NewMIRA and BCRA. BCRA selects shortest path based on smallest sum of weights of links where load is raised to some threshold. The algorithm BGLC, fixes the routing paths and reserves the resources on each network link along the route. Thus, implementing the features of TE leads to better utilization of network. It is efficient for delay constraint applications since it has opted the shortest and uncongested path to reach destination node. Wide-range of simulations sessions were evaluated and the enactment of the algorithm in terms of available bandwidth between head node and tail node has been checked. Comparing it by means of other routing algorithms, e.g., MHA, WSP, SWP, and MIRA, it performs better. It suggests that BGLC is the best and MHA is the worst amongst MHA, WSP, MIRA and BCRA in terms of mean path length, maximum flow, call blocking ratio and CPU time.

Dana et al. (2009) has proposed an algorithm, which firstly selects a path with lowest hop count. Thus, by using minimum resources optimized path is obtained. Secondly, if the hop count is equal for some paths then apply traffic load balancing to identify the better alternative paths. Conserve links with large capacity for large resources to minimize the probability of congestion occurrence for the future requests.

Ouadghiri D E et al. (2009) have presented module MPLS-M, it avoids the congestion by distributing the traffic on the whole network in order to optimize the use of resources. It reduces the number of lost packets and increases the throughput at destination nodes. According to the study given by *Ouadghiri D E et al. (2009, 2012)*, the shortest path is determined by the conventional routing to achieve the destination which cannot be the only possible path. So, it causes congestion when different kind of traffic uses the same path.

Phang K K et al. (2009) have studied a heuristic dynamic routing algorithm TE-QOSPF-Mix which offered improved trade-off between bandwidth optimization and hop-count. The simulation results exhibit better bandwidth acceptance and lower packet loss ratio.

Pant R et al. (2010) have presented a heuristic approach for path selection based on blocking probability of requests. It works well by combining best of load balancing (to avoid bottleneck links) and load packing (to reduce resource defragmentation).

Al-Ali A et al. (2014) proposed CBR algorithm for MPLS network, based on the weight calculation of paths. It has been studied that basically MPLS network supports specific constraints for desired QoS levels. The efficient routing algorithm works on demand bandwidth constraint with low calculation complexity and high network utilization. The simulation results illustrated that the algorithm scaled better levels of network utilization and blocking percentage.

2.2.4 Congestion Control Using Alternate Paths

Multipath routing allocates and performs routing using numerous paths. This approach offers better level of fault tolerance, bandwidth aggregation, payload balancing and enhancement in QoS metrics such as delay with the employment of resource redundancy and diversity in the network. The essentials are – path discovery services, path maintenance services, traffic distribution and path disjoint. Path discovery finds accessible paths exhausting pre-defined conditions. The Path Disjoint measures resource diversity between paths. The Path maintenance service specifies when and how new possible paths are attaining hold of the states of currently vacant paths. The Traffic distribution service identifies how concurrently vacant paths are going to be utilized. It also checks how packet data to the same destination is to be splitted and divided over multiple paths. *Sharma A K (2007, 2010, 2015, 2016)* developed Congestion Control Schemes for Optical Networks.

Anjali T et al. (2005) proposes an approach composed of 3 techniques for LSP Setup, capacity allocation and routing in MPLS networks. LSPs are created according to bandwidth requirement and current traffic on the LSP. Capacity allocation evaluates the utilization of the LSP and adjusts the capacity whenever required.

Kyeongja L et al. (2006) have proposed a traffic splitting algorithm which first finds multiple candidate paths based on criteria (hop ,error ratio, bandwidth, count) and then it would split traffic among these paths to reduce the concentrated link utilization in the high speed network. The hybrid performance is efficient in load balancing and proved through evaluated results.

Domingo P J et al. (2006) proposed an efficient multipath routing approach. Dijkstra Transverse algorithm DT(p) is path validation at depth p, it offers the opportunity to use an alternative path provisionally in order to lessen the packet loss percentage. Simulations outcomes rendered that this plan significantly improves the high speed network response time.

Asokan R et al. (2008) have proposed an improved variable splitting fraction procedure for operative load balancing on the network. It divides the part of network traffic (splitting ratio) from a maximum loaded payload route to a minimum loaded payload route.

Alouneh S et al. (2009) have proposed multipath routing approach which partitioned “n” MPLS packets to “N” disjoint LSPs across the MPLS networks. It handles single or multiple failures allowing (n-k) paths to fail at a single time. The experiment consequences revealed that the processing time of the approach at ingress and egress routers endpoints do not impose major delay in packet transmission. This approach is really critical where the network is used for critical applications.

Klinkowski M et al. (2010) have focused on a multipath routing approach to improve network routines by splitting the network payload traffic over multiple routing paths options, thus reducing the payload on more congested network links that may or may not be having same attributes (Link Quality). This approach routed the traffic load over each candidate path. The calculation used in it is highly time consuming even for a small network. Table 2.3 shows the Objectives and the observations of CCA .

Table 2.3 Features of CCA working for MPLS protocol stack

Algorithm	Objective/Criteria	Observations/Performance analysis
Hsu W H (2010)	Multipath selection algorithm (MSA) works as follows:- Step1. Find multiple paths. Step 2. Allocated initial traffic in an available bandwidth. Step 3. Adjust dynamically traffic based on RTT.	Results of throughput, average delay, packet loss and variance of available bandwidth of every LSP are obtained. The approach is feasible with higher efficiency.
Halabi W (2012)	Assembled the expected bandwidth demand for the near future and expected transfer of large amounts of global IP-based traffic.	Investigated routing method , traffic grooming schemes and connection setup on IP/MPLS based ASON/GMPLS multi-domain multilayer test framework.
Sergio Sanchez lopez(2002)	LSP blocking ratio is investigated under different loads as follows:- LSP blocking ratio (%) = $\Delta LSP_{i\,rejected} / \Delta LSP_{i\_totalrequest}$,	Blocking ratio is lesser when a QoS parameter is incorporated for the selection process. For maximizing throughput low complexity algorithms are developed according to different network loads which execute very closely to the equivalent prime algorithms.
Dilmohan Narula (2010)	Executed 2 experiments on diverse scenarios and obtained t LDP over RSVP tunneling method.	Better presentation in alleviating the problem of packet drops.
Hock D (2008)	Linear line up for the optimization the complete route by clearly calculated paths.	Single path and route entire traffic along those generated multiple paths. The algorithm proved as convergent and stable.

Fowler S et al. (2005, 2010) have developed and validated a method based on path selection that choose the minimum time delay between the Head Node and the Tail Node whenever a new buffer of traffic flow comes. This way it is able to maximize the resource utilization, and automatically leads to a higher number of packets reaching the other end of the network or simply, it can be said that throughput is increased. Alternative routing paths definitions become important when the links become burdened to give higher level of performance. A tradeoff is reached between the overhead generated due to complex overhead computations and path selected outcomes and in the process it does not leads to any further congestion in the case of already congested networks. *Thulasiraman P and Thulasiram R K (2009)* have proposed routing algorithm “HOPNET:” based on ant colony optimization for mobile ad hoc network.

2.2.5 Applying Artificial Intelligence in Networks and other realms

The available literature as summarized above indicates the list of gaps in the existing approaches applied on MPLS Networks described in Chapter 1.

Some algorithms discussed in above section are based on QoSR, which are not able to give reliable traffic scenario of the network. Some of them are based on TE, which have also not been able to give relief from congestion. The above algorithms discussed have not been able to fully utilize the resources and a number of the routes get over utilized or underutilized. So, it is advisable to combine the features of TE, QoSR and FL on the networks.

There is a complication of the problems and technical hitches in implementing the conventional controllers to eliminate the problems. *Zinonos Z, Chrysostomou C and Vassiliou V (2014)* concluded that there is a need to investigate intelligent control techniques to derive nonlinear control law, such as fuzzy logic (FL), as a solution to control systems in which dynamics and nonlinear ties need to be addressed. *Chrysostomou C et al. (2003)* implemented FL in networks based on these techniques. *Alandjani G, Johnson E E (2003)* had applied fuzzy routing in ad-hoc networks. The main idea is that the FL control is designed with a good understanding of the system. The limitations of complex system’s parameters and mathematical model can be avoided on using FL, as studied by *Gong S (2010*), *Chakraborty S (2003)* applied fuzzy logic in pattern recognition.

Genetic Algorithm is applied on CSMA/ TDMA *by Verma H et al. (2010, 2012). Nahid Ebrahimi Majd et al. (2006)* modified Dijkstra’s algorithm that combines propagation delay, bandwidth and loss probability to find best path, named as Fuzzy Mixed Metric (FMM). It gives more priority to loss probability metric than any other metrics. He justified in his work that Fuzzy approach enhances the throughput and overall network performance. FMM is more efficient and overall drop is minimum than *Wang et al.* and Single Mixed Metric

(SMM) as studied by *Costa, L H M, Fdida S and Duarte O C M (1999, 2000, 2001, 2002).*
Din N M et al. (2008) have initiated the fuzzy logic predictor for estimating bandwidth for the real time traffic. The expected bandwidth indicator is utilized as the token bucket policing rate and can be fed back as the actual bandwidth engaged by the network for admission control decision making. The fuzzy predictor is simple in construction with only two fuzzy inputs as Average Rate and Available Bandwidth and one output as Utilization. The improved network feat raises efficiency and in the long run shrinking network costs by finest possible treatment of resources. *Jena R K, Sharma G K et al. (2008)* have proposed multi-objective genetic algorithm for mesh based-NoC. *Pandey B, Mishra R B et al. (2009)* developed an integrated intelligent computing model for the interpretation of EMG based neuromuscular diseases, it justifies the versatility of artificial intelligence techniques.
Alandjani G et al. proposed a multipath routing approach, which discovers multiple paths from source to destination. It increased the robustness. The Fuzzy Logic Controller determines path based upon the traffic importance and network status. It gives higher reliability and lower delay for important traffic.
Upadhyay S et al. (2008, 2015) suggested Fuzzy Routing and multipath QoS Routing resulting into better network performance.
The work of *Yaghmaee M H et al. (2001, 2002, 2005, 2006, 2008, 2012)* is noteworthy in fuzzy routing. Fuzzy Logic Controller (FLC) model has been developed to support the Internet differentiated services (Diff-SERV). It was revealed that every traffic class is using fuzzy model on excessive traffic load which increases the packet loss probability and remains nearly constant.

2.3 Lessons Learned

The purpose of this systematic review is to identify the key issues and narrow down to specific problems related to traffic management of the MPLS networks. Following are the lessons learned from the above studies.

1. Traffic Engineering becomes important when algorithms have equal costs e.g OSPF, the network is running on single area OSPF for IP routing.
2. There is a need of Traffic Engineering which keeps the existing physical links with characteristics unchanged and does not introduce any new IP address in the network.
3. Algorithm like OSPF does not support load balancing on multiple metrics. Hence, there is a need for more sophisticated algorithms to balance out.
4. The IP world is now moving away from constant traffic flow rates and now having high variability rate in traffic flow.
5. The scaling up of the network by increasing the factor leads to impact on numerical computations of algorithms for calculating the paths. The conventional routing protocol failed to differentiate the high capacity link from low capacity link.
6. MPLS possesses multiprotocol feature which leads to increase in scalability.
7. There is a need to use fuzzy logic approach as the network system. It has multiple protocols, multiple hardware implementation working together.

2.3.1 Open Issues in Managing High Volume Traffic

With the recent development of network technology and growth of network intensive applications, there is need to produce more optimized solution. The various protocols vary in terms of their functional principles like operating conditions and performance behaviors. A detailed comparison is provided for various proposed algorithms but still there are many techniques which can be further investigated keeping in view of this emerging area as shown in Table 2.4. The computation of Throughput is one of the most significant indices for determining the performance of an algorithm, *Wadhwa M (2010)* has worked on Throughput analysis for a contention-based dynamic spectrum sharing model.

Table 2.4: Study of Identified Gaps

Concept	Author	Gap(s)
Load balancing /Traffic splitting	*Chaun H L (2006)* initiated an approach which establishes and routes traffic among alternate paths before the existing paths are pre-empted. *Hsu W H et al.* (*2010)* proposed load balancing approach which maximizes resource utilization, and delivery of packets. The selection of alternative paths when links become overloaded to give superior performance over routing algorithms.	The information collection of requirement characterization and the network state are very tricky tasks in extremely vibrant networks, due to which researchers started using FL for solving these problems. However to determine a feasible route that satisfies a set of constraints is studied by various researchers but still it is one of the major challenges.
Queue management	*Chrysostomou C et al. (2003)* proposed a Fuzzy Logic Control (FLC) to control congestion in highly burst traffic. It builds a fuzzy system capable of predicting the QoS show of every active queue in a DiffServ node. Active Queue Management (AQM) performs well in Best-Effort and Diff-Serv environments with the integration of the fuzzy logic control methodology.	This Methodology works in high speed network environments, like mobile/wireless networks, rate-based multimedia transport support for TCP friendly congestion control and video streaming.
Fuzzy routing policies	Fuzzy algorithms developed by *Zhou B (2004), Majd N E, and Yaghmaee M H (2006), Drummond A C (2008)and Alavi S E (2014)* are based on different fuzzy parameters to give desirable output in different networks. These algorithms are based on the combination of different parameters like propagation delay, bandwidth and loss probability to form FMM, which produces better path in MPLS networks. The results show that the fuzzy approach has a lower average setup time for establishing a connection than the previous existing approach and also augmented the throughput and overall network performance.	Several heuristics and approximation algorithms have been projected for this crisis. But nearly all of them are suffering from either excessive computational cost or low performance and are not practical solutions.

2.4 Some desirable properties of routing protocols for MPLS

1. The routing algorithm should be sensitive to the changes in network for the interval of Pico second.
2. The routing algorithm is able to differentiate the link quality and link capacity of network. It should deliver differentiated QoS as per subscriber requirement.
3. The routing algorithm is able to deliver Differentiated QoS as per subscriber requirement.
4. The routing algorithm should be able to identify condition that lead to under or over utilization of links.
5. The routing algorithm must be able to make sense of vague values that might come due to influence of multiple factors working together.
6. The algorithm must have the ability to match the metric of incoming and outgoing routes learned via current metric values patterns.
7. The computations of the routing algorithms should have minimum overhead.
8. The protocol must be able to work with older packet formats and the newer ones in a mixed network with resubmission operations etc.

2.5 Conclusion

The modeling of the packet arrivals are based on Gaussian, Exponential discrete stochastic event model. These packets are initiated by the subscribers or network users' behavior and kind of applications in usage. That means the behavior of the users and nature of applications they are using is also required to be taken into account while studying model of packets running in the network. Today, high end users are using content rich applications and data scientists are using grids and clusters to solve many problems. This leads to variability in traffic patterns. The computers are working for 24 hours, computing and analyzing data from diverse resources and delivering results at different geographic destinations. This has been achieved with seamless integration of legacy of technologies with new ones. MPLS is only gem, which has made these scenarios workable. But, this literature survey shows that MPLS technology is still evolving and its long road towards higher level of scalability. In this survey it has been found that existing MPLS routing algorithms are working below 100 Gbps capacity and now the new world demands higher level of bandwidth, computational and storage requirements. Due to this fact, practically it has been found that existing algorithms need to be augmented. There is a requirement for composite metric like fuzzy metrics to take decision to next level of scalability considering the reliable system to support future capacity.

Chapter 3
Fuzzy Logic: Theory and Applications

3.1 Introduction

There are basically two kinds of systems viz., deterministic and non-deterministic systems. The deterministic systems are those, whose output can be predictable and non-deterministic systems are those, whose output cannot be predicted due to multiple possible outcomes of each input. So, "What kind of system is MPLS based Network?", is to be investigated.

The example of non-deterministic system is Air Traffic Management System. It's characteristics are similar to MPLS based network for building better traffic management system. The first key question, "Is it possible that accidents can occur in Air Traffic Management System?, when ?, how ? and where ?".

Another pertinent question, "Is it possible that no accidents occur in future?" This is clear from these questions, that it cannot be predicted or determined with "confidence: when ? how? and where ? Similarly, it is hard to determine when packets in MPLS network will collide to create congestion and cause cascading issue. The reason for such uncertainty is due to the multiple variables influencing each other. These systems might have a property of random patterns that analyzed statistically but not predicted precisely. Due to this fact, the MPLS networks best considered as Fuzzy System. For a fuzzy system to work smoothly, the study of fuzzy controllers and perception of Fuzzy Mathematics is required. Some key observations that MPLS networks are non-deterministic system are as follows.

1. The problem of MPLS Network Management is basically a traffic management problem.
2. The MPLS Networks have states that are discrete in nature with respect to time and space dimension.
3. The MPLS networks have properties that are both stochastic (with random components) and dynamic (time is a variable).
4. The initial conditions of MPLS networks do not guarantee outcomes due to state change and system size increase.
5. The payload gain in MPLS network occur at any moment and is relative to the subscribers.
6. The number of subscribers increases the entropy of the system.

7. The increase in capacity of network and in number of packets bring more overlapping of the metrics.
8. The network system becomes non-linear in nature and rate of change is hard to calculate.

3.2 Basics of Fuzzy Logic

The computational problems of vagueness and imprecision are solved by Fuzzy logic mathematics. As required in this present study, first thing which we need to do is building fuzzy sets that define the degree of network performance metric(s). The basic details are as follows:

3.2.1 Fuzzy Set of the Problems

In classical set theory, the sets have unique members and have full membership as its boundaries are fully defined with sharp edged curve. A fuzzy set is defined as a set without a crisp shape. The margins overlapping or discrete and consequently fuzzy sets have partial memberships. The classes are having defined boundaries due to the fact, these metrics have influence of other metrics. As shown in figure 3.1, fuzzy logic evaluates near to exact value of the problem and is having continuous curve. Classical approach gives results as direct sharp values either 0 or 1. Fuzzy approach gives result with continuous values like 0, 0.1, 0.2…1.0.

3.2.2 Fuzzy Membership Functions

The membership function classifies the degree of truth of problem under study. These membership functions do not classify probabilities but the degree of membership of the set variables. The membership function defines how a discourse of universal set of variables be mapped to interval of [0,1] and is often given the designation μ. Here, in present research work it is a set of all the variables influencing the traffic engineering operations.

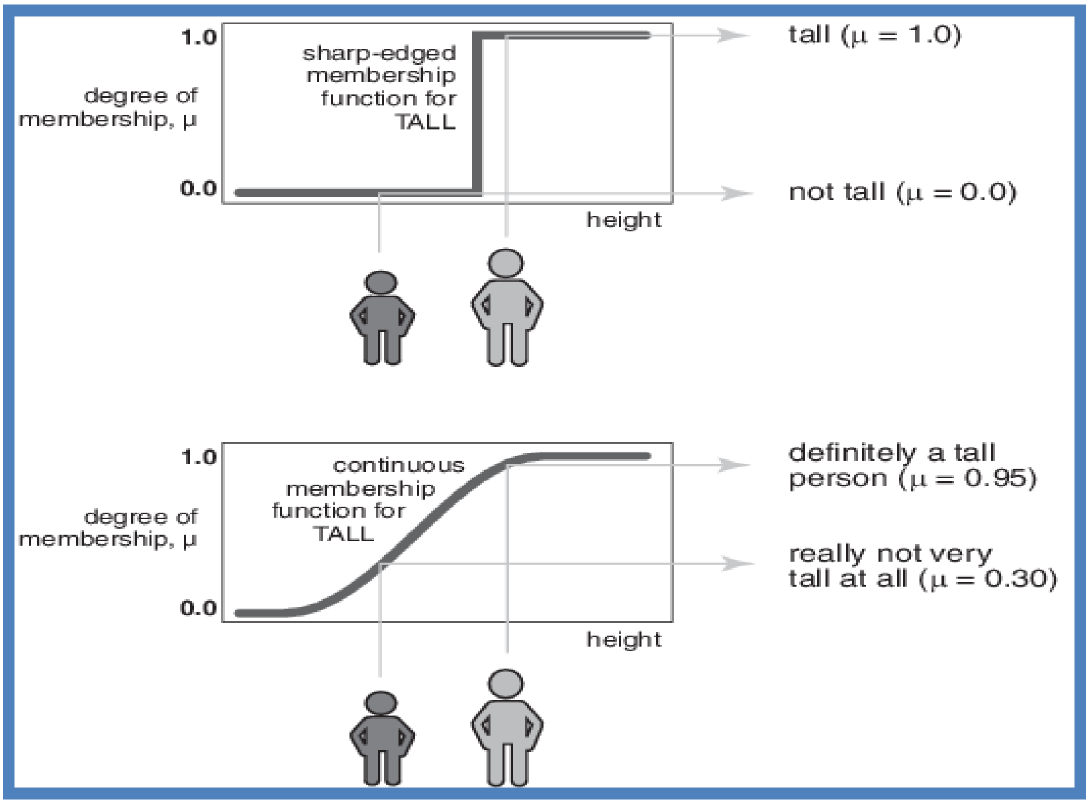

Figure 3.1: Classical (Sharp edged) Vs Fuzzy Set (Continuous)

3.2.2.1 Types and shapes of Membership Functions

There are various types of membership functions. The most commonly used membership functions are formed with the help of straight lines. For example, the *triangular* membership function as revealed in Figure 3.2 for the fuzzy input variables Load, Delay and Output variable LsS_Value. The membership function of variable LsS_value is displayed as triangular. The triangular membership has a straight line, possesses the benefit of simplicity. The *trapezoidal* membership function has a smooth top shape, and is just a truncated triangle curve. Some membership functions that are normally used are the Gaussian and Bell-shaped curves.

3.2.2.2 Selection of the Type of Membership Function

It is always desirable to have membership function values that never reach 0 or 1, in order to represent the uncertainty. The better way to do hit and trial to build an understanding of membership function shape to get optimal results. A main criterion of selection depends upon the size and nature of the problem. Many researches also weight on setting the interval and number of membership functions as most important criteria for choosing particular shape of the membership function.

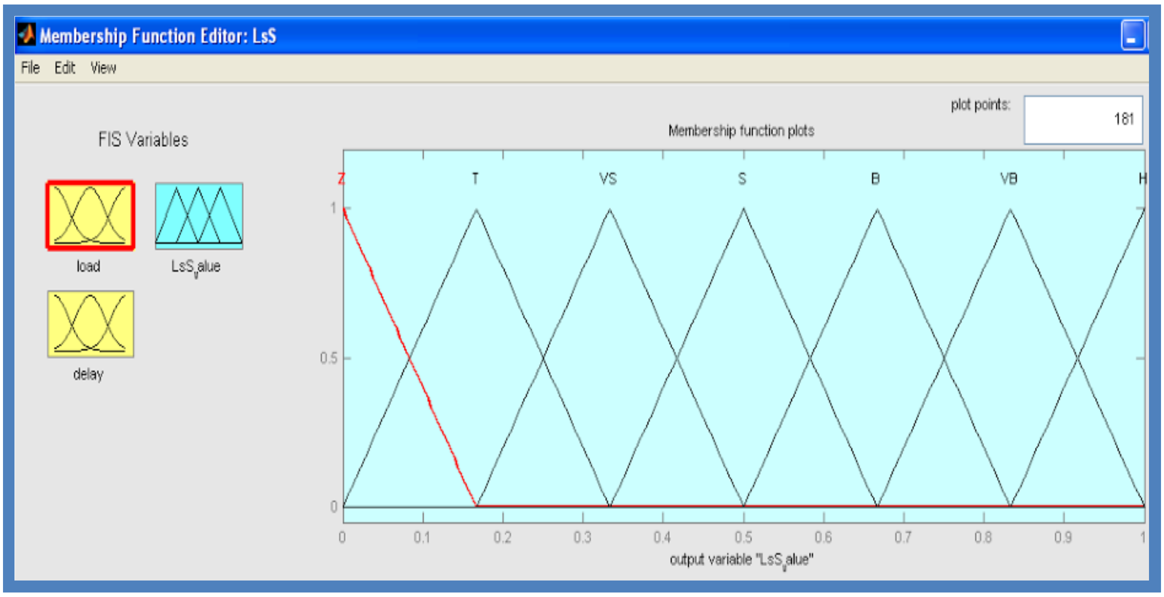

Figure 3.2: Triangular Membership function for fuzzy variables

Review on this aspect given by *Council N L (2000)*, shows that for most of the problems, triangular memberships is appropriate. Gaussian membership functions are popular methods for specifying fuzzy sets. The advantage of using curves is that their values remain horizontal and nonzero at every point, which is necessitate of these fuzzy functions .The Bell shaped is more complex, advisable to use when straightforward shapes are not producing desired level of correctness.

3.2.2.3 Fuzzy Interval

It is uncertain, normal set and at least one segment represented as continuous and mean interval. In context of our research work, either triangular or trapezoidal shaped functions are most suitable due to their simplicity.

3.2.2.4 Fuzzy Set Logical Operation

These are generalized logical operations of crisp sets or mathematics that is based on well-defined boundary. Following are the standard fuzzy logic operations, initially defined by *Zadeh L A (1965)*, three basic operations fulfill the needs of most typical fuzzy logic based systems.

- *Fuzzy Intersection (AND):* It represents the "min" operation as shown in equation 3.1. The *min* operator denotes the intersection of the two given fuzzy sets *A* and *B*.

$$\mu_C(x) = Min[\mu_A(x), \mu_B(x)]\text{, where x €X} \qquad \ldots(3.1)$$

- *Fuzzy Union (OR):* It represents the "max" operation as shown in equation 3.2. The *max* operator denotes the union of the two fuzzy sets *A* and *B*. That is, the elements of given *A* and *B sets* are operated one-by-one and the maximum of them is taken.

$$\mu_C(x) = Max[\mu_A(x), \mu_B(x)]\text{, where x €X} \qquad \ldots (3.2)$$

- *Fuzzy Complement (NOT):* The fuzzy complement of a set is the set of all element not in that set as shown in equation 3.3.

$$\mu_A(x) = 1 - \mu_{A'} \qquad \ldots (3.3)$$

The above defined fuzzy logic operators are the classical ones used, because of their computational simplicity.

3.2.2.5 *if-then* Rule Base

The fuzzy sets and fuzzy logic operators are fundamentally referred as "subjects" and "verbs" of fuzzy logic sets, respectively. The *if-then* rule statements are utilized to convey the qualified statements that encompass fuzzy logic.
A single fuzzy *if- then* rule is in the form as displayed in following rule (3.1):-

if x is A and y is B then z is C ...(3.1)

Where *A*, *B* and *C* are *linguistic values* defined by fuzzy sets on the ranges (universe of discourse) x, y, and z respectively. These linguistic values are part of their corresponding *linguistic variables*. The if-part of the rule (3.1) is referred as a "*antecedent"*, while the" then" portion is referred as the "*consequent"*. The antecedent as well as the consequent of a rule can have multiple elements.

For present research work, we have used fuzzylite API to build fuzzy rules. A typical fuzzy system consists of defined inputs of the systems. These inputs need to be processed by use of conditional rules. These rules make sense in human knowledge and form the "Rule Base". A fuzzy system executed on every rule of rule base toward a fuzzy inference. However, the operations performed on these rules are simple, which is beneficial in concern of computational dispensation.

3.2.3 Inference Process

The fuzzy inference is the procedure of representing a given set of input variables to an output variables using fuzzy logic. The fuzzy inference method defined by Mamdani is the most popular *Mamdani and Assilian (1975)* for building controlling systems in many domains. *Misra S et al. (2009)* applied Fuzzy Logic (FL) for creating routing protocol using steps given below.

3.2.3.1 Fuzzification of the Input Variables

The fuzzification of the input variables is carried out by taking the inputs of the fuzzy control system and determining the degree of membership of their appropriate fuzzy sets. Every input set is a crisp numerical value of the associated input linguistic variable, and the output is a fuzzy degree of membership in the qualifying linguistic set. The value must lie in the fuzzy interval of 0 and 1. Input is then called "fuzzified set". A form that is required by the qualifying membership functions governed by fuzzy rules. This procedure is called "fuzzification" of the input, and mounts by either a table lookup query or by function evaluations.

3.2.3.2 Implication

The antecedents form the basis of implication method shapes. The consequent or the outcome of a particular rule comes from it. What to achieve, is to get the implication of applying the result of the antecedents constituting the *if*-part to the consequent in the *if-then* rule.

3.2.3.3 Aggregation

It is process of coming to decision based on "Rule Base". The process itself may consist of many rules. This way it basically "Aggregating "all the rules in to single fuzzy set. It is done per output variable once in the complete cycle of fuzzy calculations. The most commonly used aggregation method is used by the fuzzy logic OR operator, is the *max.* This process leads to selection of highest values for the said fuzzy set operation.

3.2.3.4 Defuzzification

Leekwijck W V(1999) defines that fuzzy set represents a degree of membership, a multi-value set. An appropriate decision need to be communicated and cannot be taken based on so many values. Single value that can represent the whole fuzzy set is chosen. The process of choosing this value out of output fuzzy set is called Defuzzification.

These values were computed for their membership and finally aggregated. The last step of the fuzzy reasoning process: Defuzzification, renovates the fuzzy reasoning output that is a fuzzy set is converted into a crisp value that represents the outcome of entire inference process.
There are various methods for Defuzzification studied by *Brokhoven E V (2006)*. One of the method is the *centroid* method. This method gives the center of area under the curve that is represented as the aggregated outcome or output fuzzy set. In present context of research we have used the Centroid method. This method is most widely employed because it displays operative attributes including: 1) The defuzzified output trend remains smooth around the output fuzzy region. 2) It is moderately easy to calculate.

3.3 Key Design Principles for building Rule Base

The design issues for building Fuzzy Rules for this research work are gathered as following:-

1. The Fuzzy Matrix covering all the possible traffic engineering constraints.
2. Developed Fuzzy rule do not contradict or invalidate each other.
3. Trivial and unnecessary rules are eliminated from the Rule Matrix.
4. Fuzzy rules have minimum computational overhead.

3.4 Components of Fuzzy Logic Controller

One of the superlative applications of Fuzzy Logic mathematics is to develop “Fuzzy Controllers”. It assists to control traffic or physical processes. The core tools of the typical fuzzy controller are as follows:

1. A fuzzy set of design variables (inputs), a fuzzy rule controller and performance (fuzzy output) variables of the system.
2. A set of *rules* consist of constructs, which tells the system how best it can be controlled mathematically. It encloses a fuzzy logic quantification of the linguistic narrative of how to attain the appropriate control. It contains *if-then-else* statements to define control operations of the system.
3. The *Fuzzy Inference Engine (FIE),* copies the expert’s decision creation is elucidation of knowledge about how to control the Fuzzy system. It evaluates which fuzzy control rules are highly relevant at the given time, and then decides to do with the inputs.
4. A *Fuzzification interface*, interprets controller’s inputs to functional information that the inference method is using for application of rules.
5. A *Defuzzification interface*, translates the conclusions attained by the inference mechanism into crisp input(s) for the system.

A fuzzy logic controller can be considered as an artificial decision creator that works in a loop. It collects the output data *y(t)*, then it compares to the input *r(t)*, and finally takes decision to control the system in such a manner that performance is improved in a closed loop. The input variables and output(s) variables are crisp in nature and are real numbers. The fuzzification module transforms the crisp input variables to the fuzzy sets. The inference mechanism utilized the fuzzy base rules to get the fuzzy implications and the Defuzzification module translates these fuzzy implications into crystal clear crisp output variable(s). The fuzzy controller of current work is explained in the Chapter 5.

3.5 Application of Fuzzy Logic in Networks

Traffic Controller based on Fuzzy Logic supports packet based IP/MPLS utility networks and provides greater flexibility as modern applications require any to any device communication flow.

1. Fuzzy Logic suits best for helping transition from legacy utility communications network to packet based IP networks to improve efficiency.
2. The Fuzzy Logic based Controller helps in emerging the IP and Operation Technology convergence.
3. The Fuzzy logic based controller helps in building capabilities of “Internet of Things” working with MPLS networks.
4. The Fuzzy logic based controller helps in reducing Latency issues, faster Provisioning and better link quality.
5. The Fuzzy Logic based MPLS controller spreads the network to service customers in effective and efficient expenses.
6. Fuzzy Logic is the best way to build DS-TE to suit network capabilities.

3.6 Current Status of Fuzzy Logic based TE Solutions

It is not surprising that many researchers have adopted the Fuzzy Logic to achieve higher level of performances. Especially, in the complexity of the *Asynchronous Transfer Mode* (ATM) networks. Typically, ATM networks have wide variety of traffic sources which operate at any given time. These traffic sources- Video, Data and Voice face difficulty in obtaining formal models for in-depth analysis. In such cases, fuzzy logic helps out as described by *Chen B(2003). Joaguim et al .(2004)* deployed fuzzy logic to build balancing scheme for MPLS networks.

Based on the successful implementations by *Khan J A(2003, 2004), Aboelela E (1997, 1998), Ghosh S (1998), Aminian M (2014)* published high impact papers based on Fuzzy Logic Controllers in Network. Lately, it has been observed that a surge of publications on employing Fuzzy Logic in various areas of the IP domain is done by *Ran G et al.(2010)* who applied FL on wireless sensor Networks. Thus, this procedure is much dependent on specific scenarios, and questions the choosing ranges to be pertinent in any active network traffic conditions. This advocates the necessity of choosing the right inputs and output. The dilemma of suitably selecting the right generic variables for high speed network traffic domain has been addressed by many more researchers.

3.7 Conclusion

The concept of mathematical fuzzy logic has been acknowledged as all encompassing formal method. The objective is to offer methods and tools for building a operative mathematical model. The scheming of fuzziness is based on the primer of degrees of truth, which form a special type of algebra. The main idea is to implement preparing the switches and router to perform like a “human companion” which understands in totality and follows the linguistic narratives of the network traffic control strategy. The methods employed in the context of current research have following conclusive ground:

1. The Traffic Engineering problems and decisive situations are well understandable by Fuzzy logic.
2. The strategy allows us to easily include non quantifiable information from the MPLS networks.
3. The degree of importance of each network performance metric is naturally included in the linguistic characterization.

Chapter 4

Network Simulator ns-3 for Fuzzy Logic System

4.1 Introduction

Deployment using Network Simulator is a process of creating artificial environment similar to the target environment. The purpose is to mimic the target process to understand the various aspects of the phenomena or predicted impact if variables change in the environment. The artificial environment is based on the mathematical models of the real phenomena. These models deterministic or stochastic in nature or based on Discrete Complex Event Models. The selection of simulation model depends on the nature of the real processes. For simulating high speed MPLS networks, ns-3 simulator discrete-event simulator (DES) is used. The Simulator imitates the MPLS network in the form of discrete events system.

The simulations are written in python as well as in C++ and is Unix command oriented. Its development is traced as shown in the Figure 4.1.

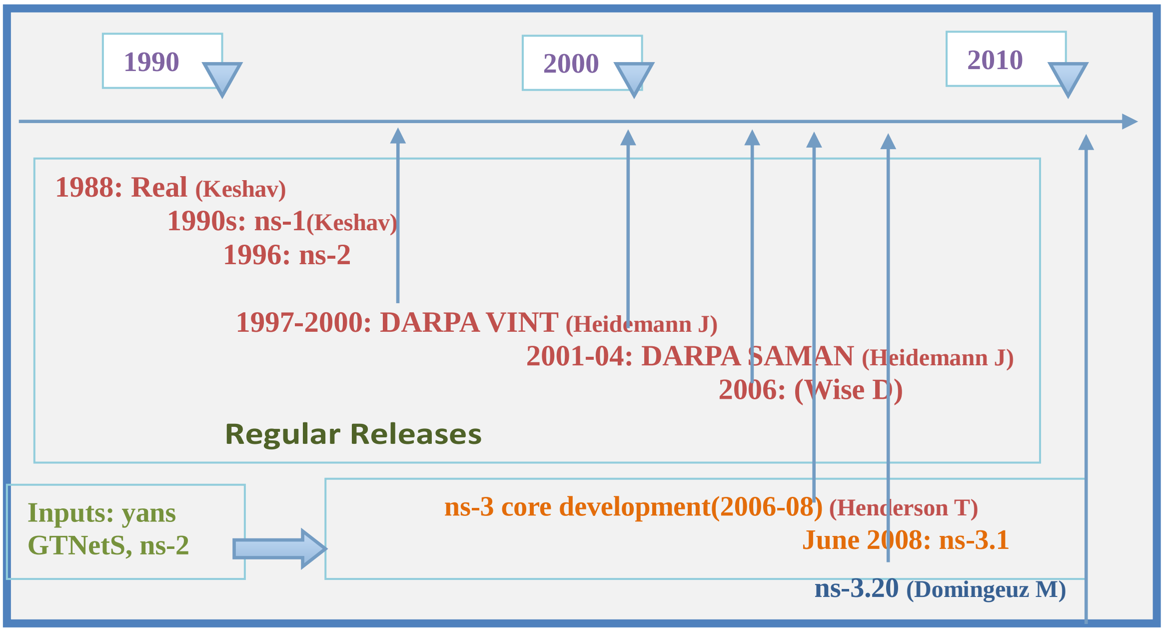

Figure 4.1: Development of ns releases

The progression of network simulators have became a very significant topic of research for analysis of novel approaches with existing or previous approaches. Simulation Modeling for high speed networks are studied by *Keshav S et al.(1988,1990), Heidermann J et al.(2000,2003),Wise D et al.(2006), Henderson T R et al.(2008)and Dominguez M et al.(2010,2011).* The regular releases are available for the researchers like *REAL*, computer network simulator developed by *Keshav S (1988).*

4.1.1 Working of ns-3

1. Simulation time advances in discrete jumps from one event to another event. The events that occur in MPLS network are as follows:-
   1.1. Arrival of Control Packet
   1.2. Arrival of Data Packet
   1.3. Prefixing of Packet with MPLS header
   1.4. Dispatch of Packets
   1.5. Table Look ups and Updates
   1.6. Addition of MPLS header to network layer header and link layer header
   1.7. Push operation from packet at Ingress.
   1.8. Pop operation from packet at Egress.
   1.9. Computation of metrics
   1.10. Selection of Paths
2. C++ functions schedule events that occur at specific simulation time.
3. The simulation scheduler orders the event execution.
4. Simulation stops at specific time when the events end.

ns-3 is written from scratch by the networking community to overcome the weaknesses of the old ns-2 simulator and it also facilitates the growth of new research projects as suggested by *Dominguez M et al. (2010, 2011).* The simulation working model of ns-3 is shown in Figure 4.2.

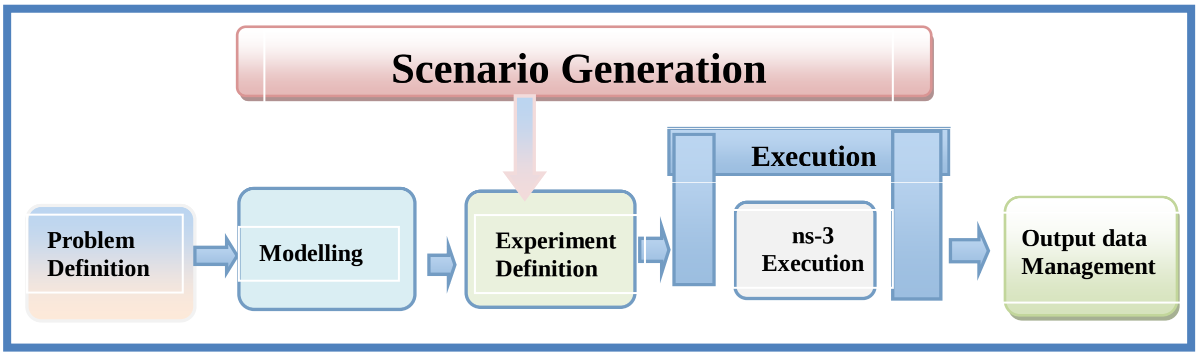

Figure 4.2: ns-3 simulation working model

The greater flexibility in developing and integrating new elements is appreciation to ns-3 modularity is advised by *Henderson T R (2006, 2008).* In contrast, ns-2 for the same goal usually requires changes to its core parts.

A lot of design choices for ns-3 have been made in the direction of having components more similar to the real counterparts (e.g. the routing stack offers to applications a socket-like API and consults to the net devices through a Linux-like packet socket interface).

An area where ns-3 is strong is simulation of IEEE 802.11 wireless networks, and many more models are still under development phase. Similar models are available in ns-2, but often in the form of external patches that need to be applied and sometimes generate conflicts with other patches. But, this problem is not in the ns-3 platform.

4.1.2 Suitability of the platform

After extensive survey of the available platforms for building MPLS network simulation. It was found that ns-3 simulator is best suited for present work. It has open source and a fair documentation is available for building network simulations as suggested by *Carneiro G (2009, 2011)*. The research work required the use of fuzzy logic mathematics, for which the need is to extend the ns-3 modules. *Avallone S (2013)* signifies that ns-3 is modular in nature and highly suitable for conducting network based simulation. The FLCS module cannot be simulated without MPLS module. Hence, both extensions have been deployed possible in ns-3. Finally, this platform allowed doing series of experimentations. The experiments described in this thesis, aims to demonstrate that FLCS approach is better and more robust against variations in the traffic payload in heterogeneous as well homogenous network links.

Clearly, higher the variance of the random variable used, higher is the disproportion between the amounts of flows entering at ingress. The numbers of experiments are differing according to the used pseudo-random number generator.

4.2 Key Characteristics of ns-3

It is one of the powerful integrated statistical platforms. The previous simulation tools were lacked in methodology documentation. The interpreting statistical tools are too complex. The usage of pointers creates a problem like dangling references. In spite of this, ns-3 provides low level functionality like tap devices and simulation core. The higher level of abstractions make switching, mixing of simulation topologies and testbeds easy. The description of experiment configuration regarding topology, application traffic, tracing configuration is very well provided. Deployment is easy and simple implementations as studied by researchers like *Nobre M (2015) and Nunez Martinez J (2015).*

Extraordinary features of ns-3 :

1. Memory Management is simple and uniform.
2. Reusability increases due to dynamic aggregation.

3. Path strings allow access to every object in simulation.
4. New modified attributes allow powerful and uniform configuration.
5. Trace sources allow arbitrary output file format.
6. Model closer to the real world makes validation easier.
7. Direct code execution is allowed.
8. Robust emulation for large scale and heterogeneous topologies are allowed.
9. It supports good software engineering due to single language architecture.
10. Error free operation due to proper Synchronization, Information sharing, Exception handling.

4.3 Motivation behind ns-3

Al-Ali A (2014) tailored following information about ns-3 *(1) It has a new core written in C++ and python. (2) It is extensible and is geared for mpls module technology stack. (3) It has an organized modular architecture that is expandable.(4) ns-3 code can be easily adapted to work in real devices like routers /switches.* Additionally, several more accurate extensions also be incorporated in the simulation scenarios. Thereby, reflecting the road layouts that actually exist. The contribution of Thesis is to fully realize first the MPLS extension for ns-3 that has the features explained in above and next sections. The discussion of the present network simulators, and their utility in implementing work for MPLS networks. The theory in adopting this simulator approach is an effort to reveal a nonlinear network. It works accurately and traces more evidence out of situations that seem completely unpredictable like packet traffic from different sources and destination in cloud data center. Therefore, a systematic survey of the existing simulators including (ns-2, ns-3, GloMoSim, QualNet, OMNET++,Mininet, NetKit) has been conducted. It has been found that, ns-3 and mininet simulator are most suitable for conducting series of observational expeditions on existing problem of traffic splitting and decongestion.

4.4 Module Organisation

The architectural design of planned ns-3 module extension is discussed in this section. The building block of the extension is followed by an explanation of the required modifications. MPLS extension for QoS and SLA support is extended to the capabilities of ns-3. The set of instructions for the framework and the default models provided by ns-3 is built as a set of libraries. User simulations are expected to be written as simple programs that make use of these ns-3 libraries. ns-3 is a free open source work. *Hood C L (2015)* signifies that the goal to build a discrete-event network simulator targeted for simulation research and education.

The abstract base classes with their methods which establish communication with interfaces are shown in ns-3 software organization architecture in Figure 4.3.

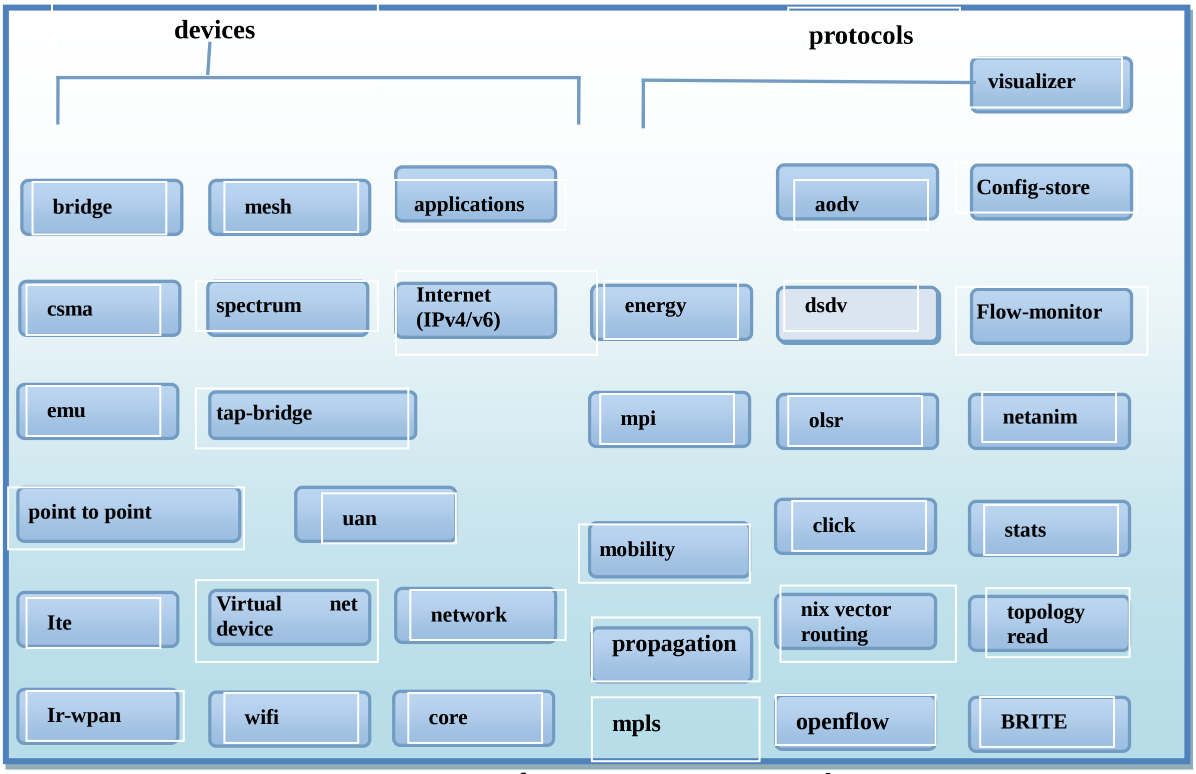

Figure 4.3 : ns-3 Software Organization Architecture

This is a collaborative project which facilitates researchers to add new functions and new algorithms by modifying the source files. It supports legacy routing methods and protocols. It also supports the ports of new open source routing enactments.

The overall routing architecture is shown in Figure 4.4. It is designed to support multiple routing algorithms, including policy-driven routing practical, on-demand and proactive routing protocols, and other undemanding routing protocols. The communication messages (SendOut, Receive) are depicted.

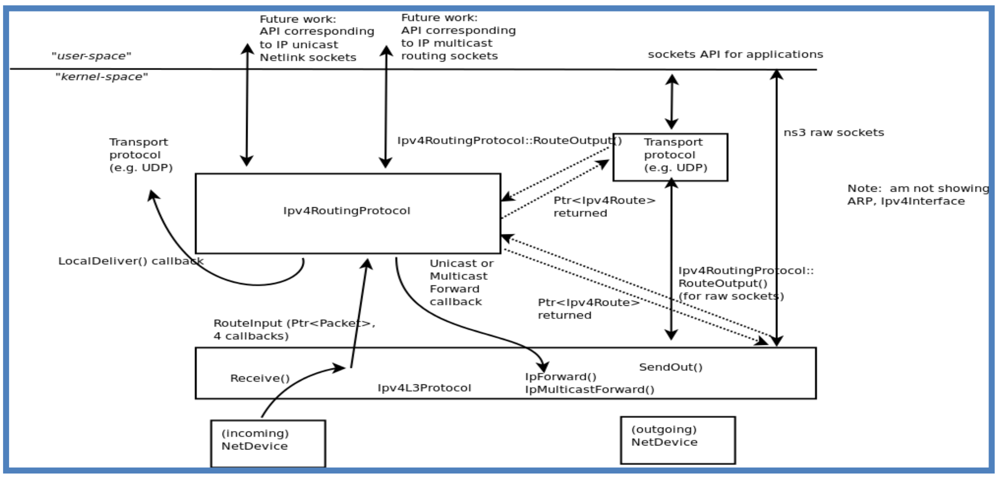

Figure 4.4: Routing Architecture

The structure of sample code written in ns-3 is shown in Figure 4.5. The syntax of creating the topology in framework is depicted with comments.

```
int main (int argc, char *argv[])
{
    // Set default attribute values
    // Parse command line arguments
    // Configure the topology; nodes, channels, devices, mobility
    // Add (Internet) stack to nodes
    // Configure IP addressing and routing
    // Add and configure applications
    // Configure tracing
    // Run simulation
}
```

Figure 4.5: Structure of ns-3 Code

The internet stack communication flow is depicted in Figure 4.6. The application of ns-3 as hybrid emulation model is depicted in Figure 4.7. This remarkable characteristic facilitates it to simulate complex network scenarios with ease.

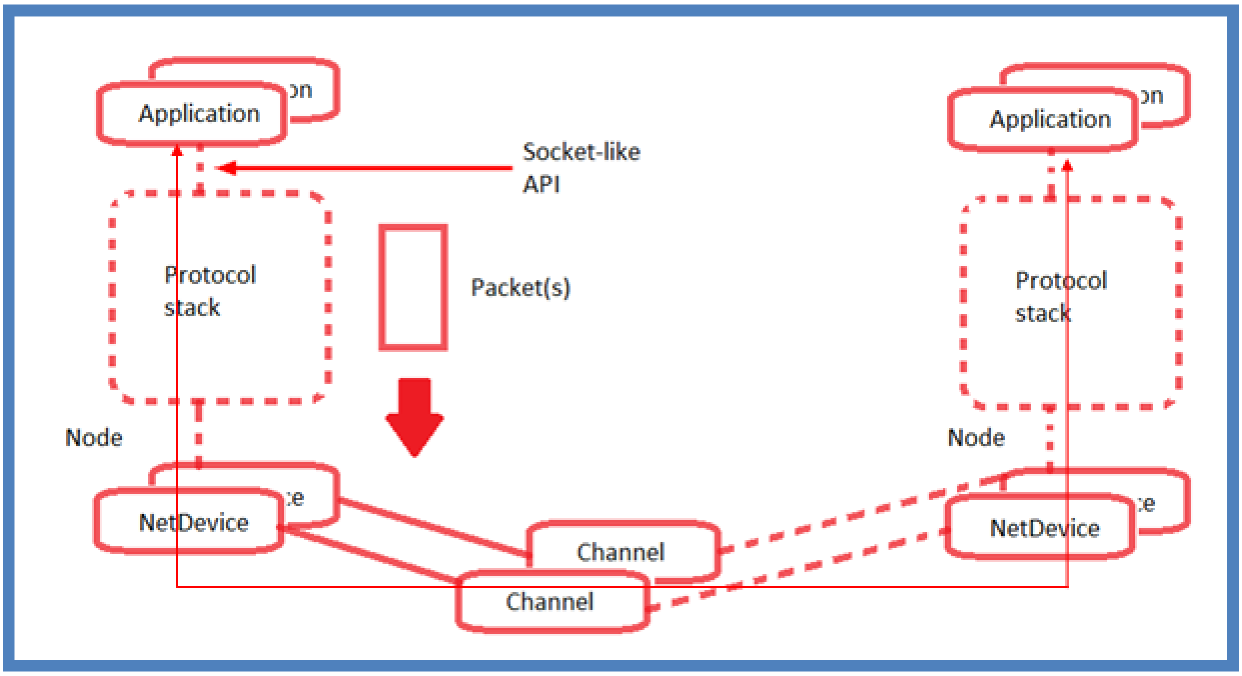

Figure 4.6: Basic Model Communication of Applications

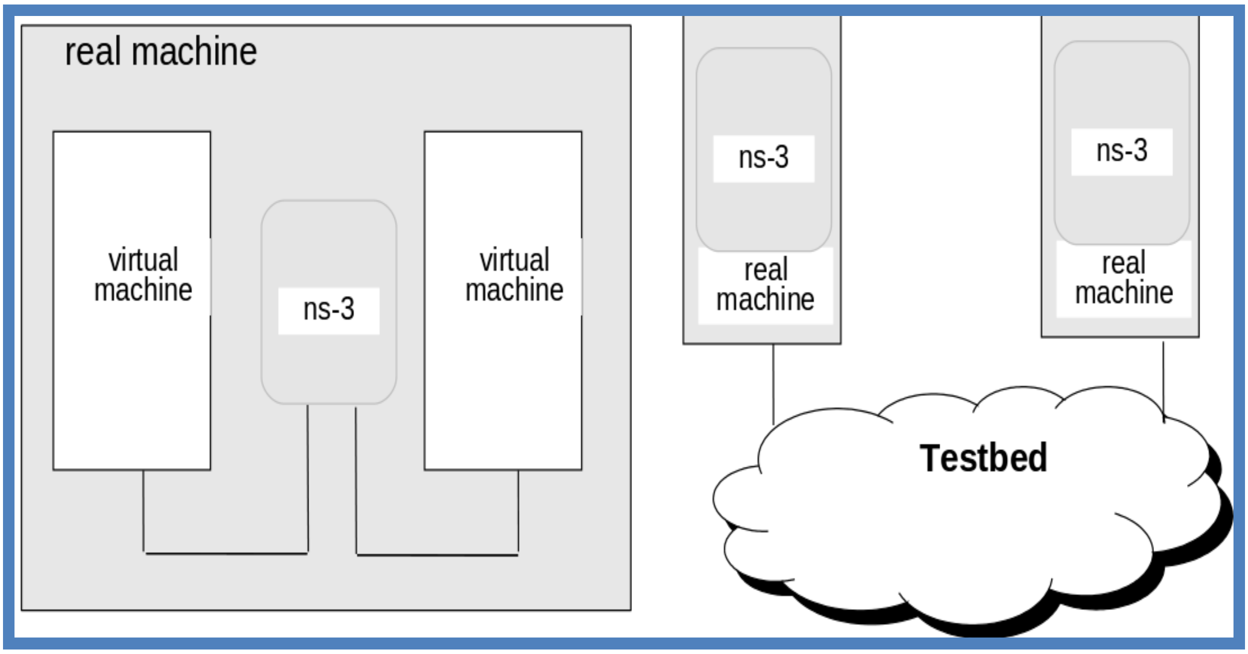

Figure 4.7: ns-3 Hybrid emulation model

Application Programming Interface (API) works among Application Protocol Stack, Net devices, Channel of all connected nodes of network.

The complete instruction of building the set of default libraries and the execution of example programs included in this package, are demonstrated in Table 4.1. This elaboration is for better understanding of the complete step by step procedure and simulation platform suggested by *Lopatka K(2012)*. There are two ways to incorporate any external libraries in ns-3. (1) Rewrite the complete source code as per ns-3 coding conventions and use it as a module in ns-3 build this is very tedious and time consuming. (2) Using the waf script to explicitly tell ns-3 program to use external libraries functionality by providing path to the header files, source files and library file.

Table 4.1: Steps of framing simulation platform

Steps performed for ns-3
Step1---installation UBUNTU
Open Terminal Ctrl+Alt+T
sudo apt-get update
sudo apt-get install build-essential
gcc...c++ compilers/other dependencies
Step 2----building of ns-3 framework
Open Terminal Ctrl+Alt+T
sudo apt-get install gcc g++ python
sudo apt-get install gcc g++ python python-dev
sudo apt-get install mercurial
sudo apt-get install bzr
sudo apt-get install gdb valgrind
sudo apt-get install gsl-bin libgsl0-dev libgsl0ldbl
sudo apt-get install flex bison libfl-dev
sudo apt-get install tcpdump
sudo apt-get install sqlite sqlite3 libsqlite3-dev
sudo apt-get install libxml2 libxml2-dev
sudo apt-get install libgtk2.0-0 libgtk2.0-dev
sudo apt-get install vtun lxc
sudo apt-get install uncrustify
sudo apt-get install doxygen graphviz imagemagick
sudo apt-get install texlive texlive-extra-utils texlive-latex-extra
sudo apt-get install python-sphinx dia
sudo apt-get install python-pygraphviz python-kiwi python-pygoocanvas libgoocanvas-dev
sudo apt-get install libboost-signals-dev libboost-filesystem-dev
Step 3--- Extraction
Copy ns-allinone-3.19.tar.gz in Documents
Right Click---> Extract Here
Open Terminal Ctrl+Alt+T
cd Documents/ns-allinone-3.19/ns-3.19
./waf distclean
./waf configure --enable-examples --enables-tests
./waf build

The snapshot of executing ns-3 platform is shown in Figure 4.8.

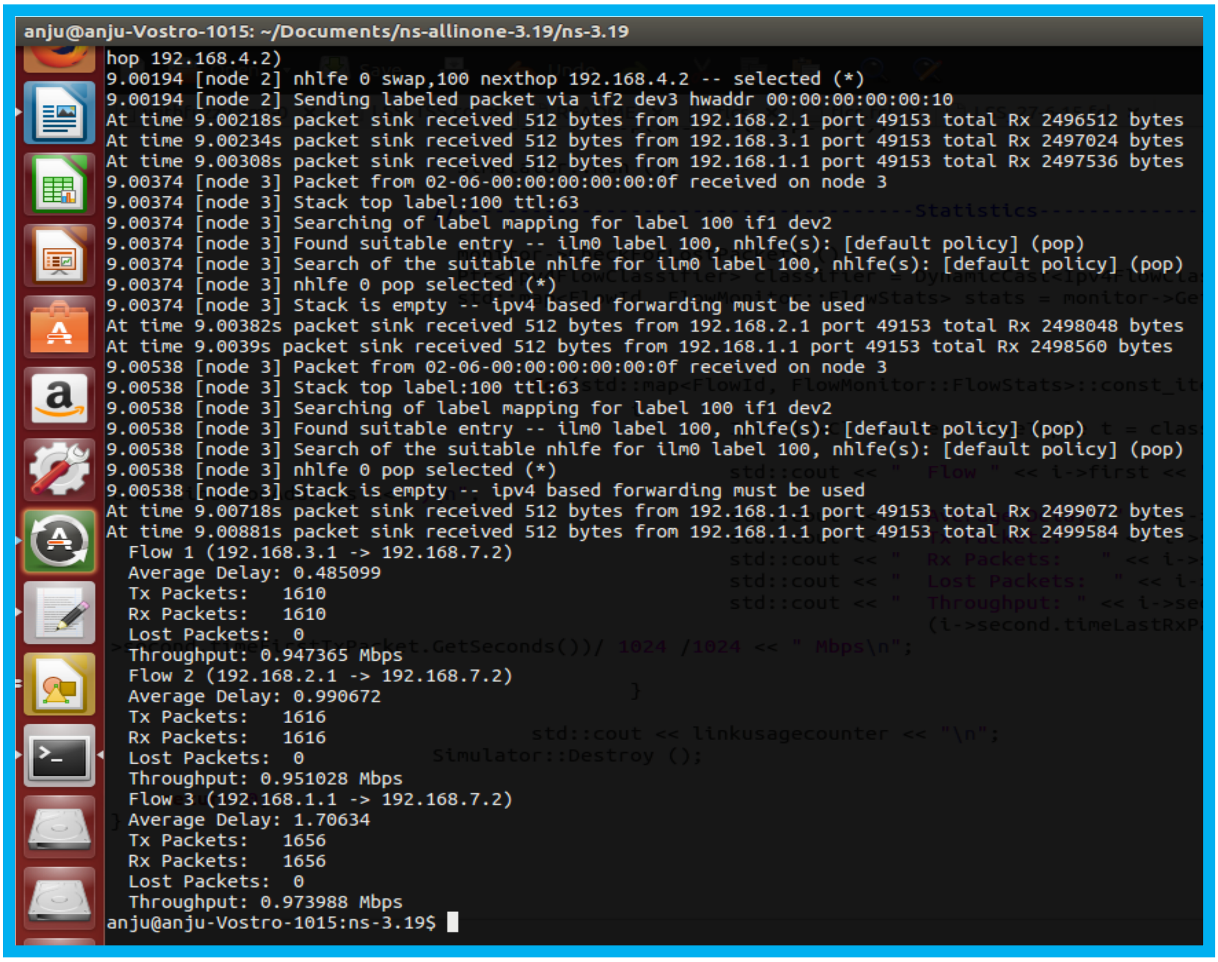

Figure 4.8: Execution of ns-3 platform

The implementation challenges faced during deployment are handling output files which is critical task. Running ns-3 under MPLS platform is difficult to implement. The parameters are modified for FLCS deployment model as per need.

4.5 Fuzzylite: Fuzzy Logic Control Library

Rada-Vilela J (2014) defines that Fuzzylite is a cross-platform and a free open-work fuzzy logic maths library authored in C++. Its implementation allows to easily create “fuzzy logic controllers” in a few steps with the use of object-oriented programming paradigm without requiring any other third-party libraries. The modular organisation of ns-3 as show in Figure 4.9. It allows incorporating external or third party libraries. For building the Fuzzy Controller for achieving the said objectives , Fuzzy-lite library was used and made part of ns-3 software organisation. *Lopatka K (2012)* employed on fuzzy logic to study the behavior of traffics.

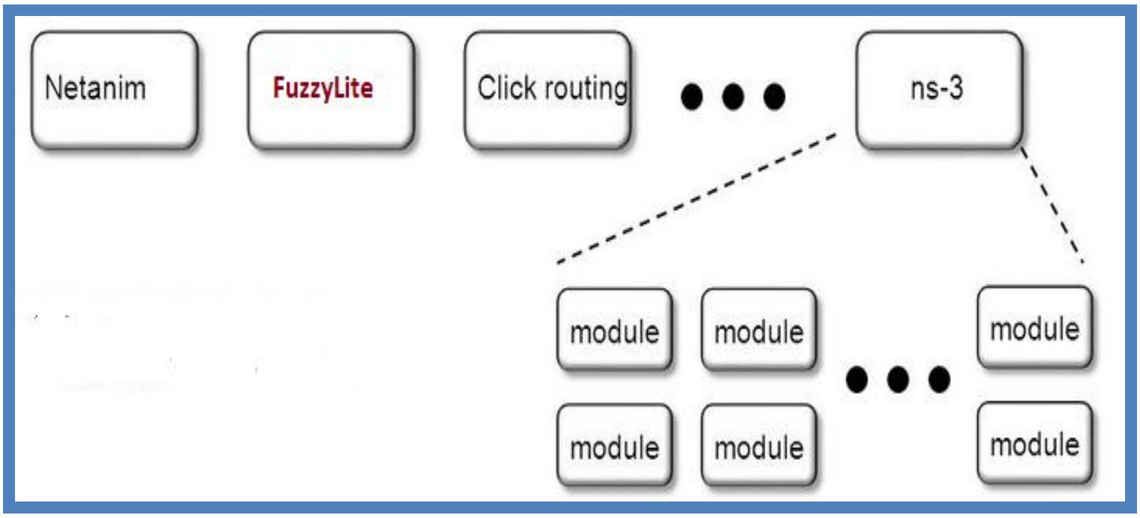

Figure 4.9: Support of integrating new modules

Most of these features were required to build the designed MPLS controller for traffic signaling purpose. It has been found that the most convenient way to incorporate the Fuzzy logic in the ns-3 was to add module of Fuzzylite. Fuzzylite is finally used for implementing the FLCS. The supporting features of fuzzylite as shown in Figure 4.10 includes following attributes:-

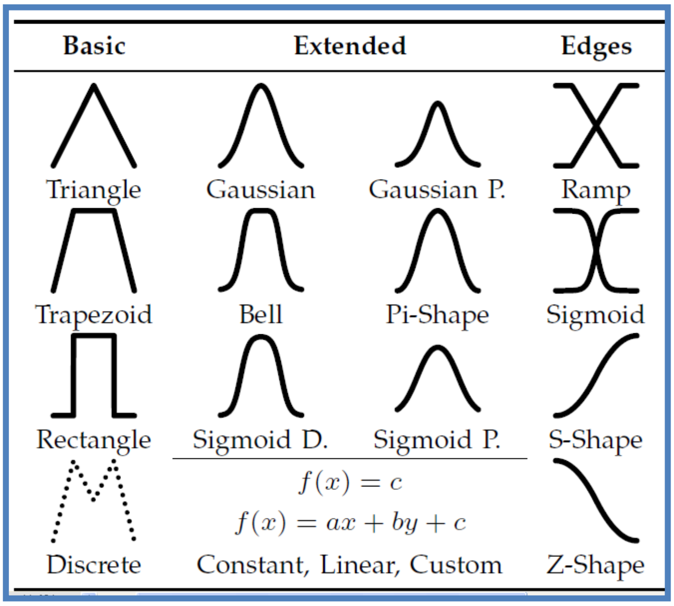

Figure 4.10: Supporting features of Fuzzylite

1. Basic terms as Triangle, Trapezoidal, Rectangle and Discrete
2. Extended terms as Guassian, Bell and many more.
3. Edge Ramp, Signoid and many more.

4.6 Conclusion

It is apparent from the research questions raised in introduction chapters and problems discussed that there is a need of in-depth experimentation to find efficacy of MPLS based networks using the default algorithms and Fuzzy Controller. It is necessary to find optimal solutions for high speed MPLS networks.

The existing work required an approach that emphasizes the methods in which the network bears a resemblance to a live ecosystem, convincing patterns as it grows, rather than a mechanical machine whose parts and operations have been planned out in progress. The most convenient way was to persuade this argument that knows the operations and parts of MPLS. The systems won't make us foresee all the complexity that will arise as, its hardware and software upgrades in terms of scalability. It is the experimentation under different conditions that needs to be checked. The most plausible solution for simulator is that the complex event of MPLS can be implemented without hardware and software investments. Some of the requirements of research work exceed the capabilities that other open-source tools could provide. Some are rejected due to non availability of proper documentation and some due to this fact they are not simple and user-friendly.

The most significant aspect of the research work was the use of formal fuzzy logic mathematics to solve network routing problems. For a logical assessment of such application, programming interfaces has explored various API including XFuzzy, jFuzzyLogic, Fuzzy4j, Matlab and Fuzzylite. Fuzzylite offers ease in designing the packet forwarding rules. It is based on imprecise or fuzzy input variables like load, delay, link capacity and utilization rate, etc. Implementation of the inference engine and support in terms of documentation from the Fuzzylite is good enough to understand and performing simulation. The outcomes obtained are depending upon the ns-3 simulator with fuzzy mathematics capability. The overhead was not much when its functions are called in the ns-3 simulation.

The use of Fuzzy mathematics in solving problems of imprecise system is not new. But, its application in controlling the high speed network traffic for decongestion at packet level is novel. There is a great scope in building approximation system for controlling the flow of packets. The Fuzzy Composite concepts have really made the outcomes of this research work applicable for telecom industry.

Chapter 5

Fuzzy Control Methodology and Implementation Results

5.1 Introduction

The Fuzzy Logic Control System (FLCS) is based on the Fuzzy Control Methodology. It classifies and arranges LSPs in preference order and then performs traffic splitting among them. The system is highly suitable for loaded conditions i.e. when communication links are going to be congested and it is not possible to maintain QoS. Fuzzy Logic is exceptionally efficient in numerous applications, such as intelligent control, decision building process as discussed in Chapter 3.

5.2 Formulation of Intelligent Controllers

In order to process the inputs of the fuzzy logic controllers for obtaining the output, the following steps have been adopted:-

1. Identification of the input variables and their fuzzy boundary properties for defining ranges.
2. Identification of the output variables and expected outcome with their boundaries.
3. Building of Rule Base that defines, How the system can be controlled?
4. Creation of the degree of fuzzy membership functions (e.g triangle) for each input fuzzy sets and output fuzzy sets.
5. Decided that, How the actions will be accomplished for each rule?
6. Aggregation of all the rules and finally defuzzification of the output.

The above procedure is applied on appropriate traffic parameters, resulting less complex routing system. The schematic flow diagram depicting the methodology applied is shown in Figure 5.1. The fuzzy controllers LsS and TSS with their specified rules and roles in the developed approach are shown in Figure 5.2 and Figure 5.3 respectively, indicating their inputs and output.

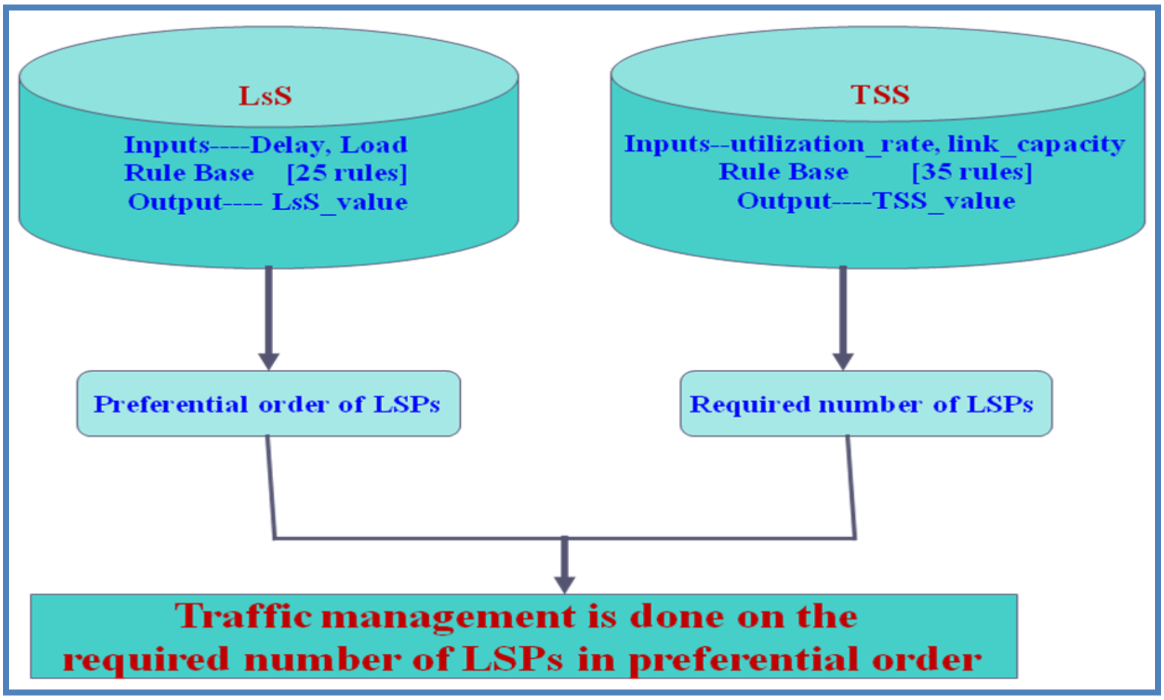

Figure 5.1:Traffic Management using Fuzzy Logic Control System

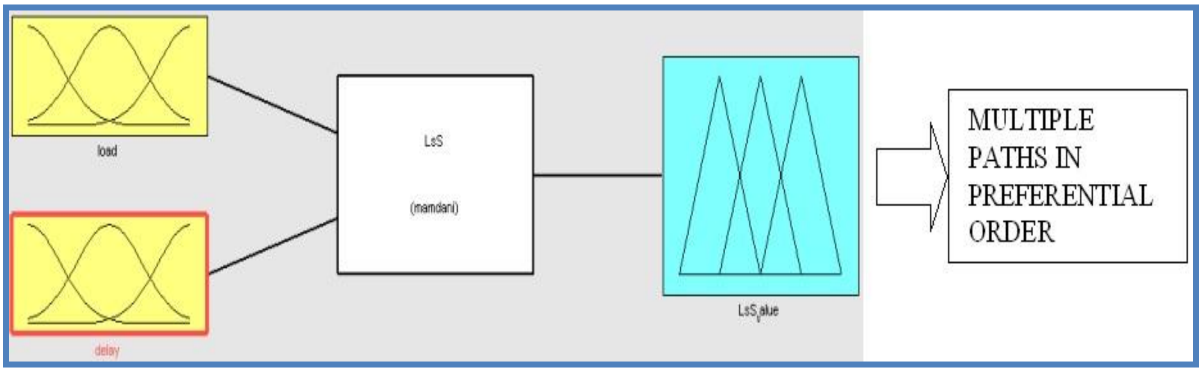

Figure 5.2: Input Parameters load and delay processed out giving LsS_value

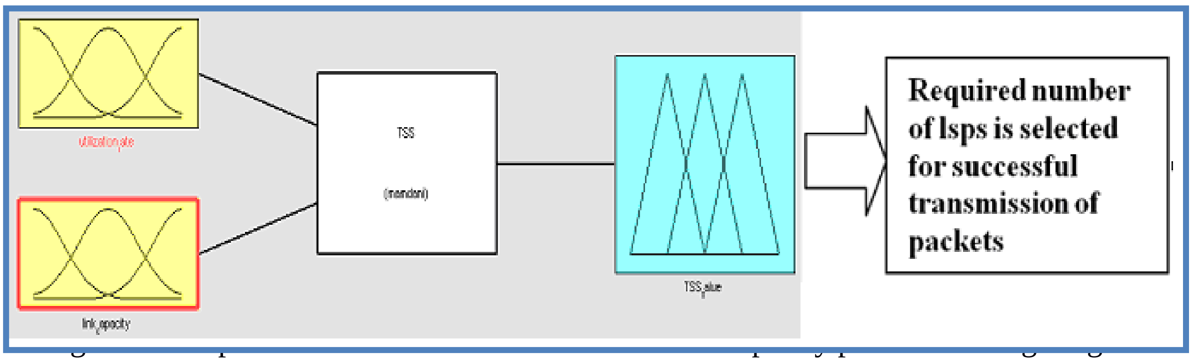

Figure 5.3: Input Parameters link capacity and utilization rate processed out giving TSS_value

5.3. Architecture of Traffic Regulator: Fuzzy Logic Control System

The Fuzzy logic Control System (FLCS) resides at the "incoming packet flow point" or ingress node. The FLCS has two sub fuzzy control systems viz. Label Switched Path setup System (LsS) and Traffic Splitting System (TSS) as presented in the Figure 5.4. It is holistic view of developed approach.

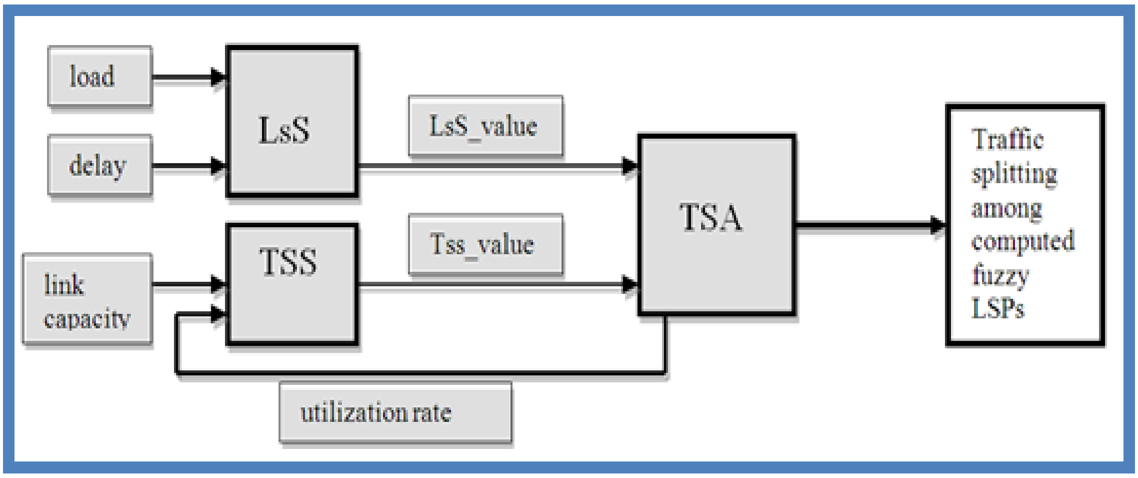

Figure 5.4: Holistic view of FLCS

LsS component selects LSPs on processing of two input fuzzy metrics (delay and load) and gives output fuzzy metric LsS_value. Load metric and Delay metric are most suitable QoS factors on which selection of suitable route depends as suggested by *Kurose and Ross (2008)*. The TSS component executes the traffic splitting among the computed paths, according to the two input fuzzy metrics (utilization rate and link capacity) and gives output fuzzy metric TSS_value. The snapshots of fuzzy controller LsS and TSS are presented in Figure 5.2 and Figure 5.3 respectively. A suitable decision of traffic splitting is build among the computed number of LSPs required by Traffic Splitting Algorithm (TSA). The computed fuzzy based LSPs for forwarding packets are obtained to avoid the situation of underutilization or over utilization of paths. None of the paths remains idle for longer time and proper utilization of resources takes place. Hence, it is better for congestion to be prevented rather than corrected. Implementation of FL using Mamdani Fuzzy Inference System designed by *Leekwijck W V (1999)* evaluates final decisions as LsS_value and TSS_value. The available number of rules in the Rule Base matrix LsS and TSS represents intermediate conditions or status and provides the control with a highly dynamic response.

LsS rule base is a set of inputs (delay (D), load(L)) with their five linguistic values (Very Low (VL), Low (L), Medium (M), High (H), Very High (VH)) and output LsS_value with their seven linguistic values (Zero (Z), Tiny (T), Very Small (VS), Small (S), Big (B), Very Big (VB), High (H)) forms at most 5*5 = 25 possible combinations. The matrix shown as Table 5.1 is referred as Fuzzy Rule Base Matrix-LsS with columns representing D and rows representing L. Hence, optimized decisions are made using developed 25 rules (R1, R2, R3…R25), which are maximum possible cases for the selection of LSPs under different situations.

Table 5.1: Fuzzy Rule Base Matrix- LsS with inputs (load, delay)

delay / load	VL	L	M	H	VH
VL	**Z R1**	**T R2**	**VS R3**	**S R4**	**B R5**
L	**T R6**	**VS R7**	**S R8**	**B R9**	**B R10**
M	**T R11**	**VS R12**	**S R13**	**B R14**	**B R15**
H	**VS R16**	**S R17**	**B R18**	**VB R19**	**VB R20**
VH	**S R21**	**B R22**	**B R23**	**VB R24**	**H R25**

According to the QoS requirements of multimedia applications given by *Chen Y, Farley T and Ye N (2004).* Indeed, the International Telecommunications Union standard (ITU-recommendation 14), are defining boundaries of fuzzy sets of input parameters or linguistic terms of fuzzy controllers are as shown in Table 5.2. Linguistic values of L, D, LC and UR have been taken in such a way that the controllers are able to take decisions bringing best possible results with respect to vibrant traffic conditions.

This FMM (LsS-Fuzzy Rule Base Matrix) delivers large number of options to attain best routing options for taking decision. It provides competent alternate paths in preference order that support Traffic Engineering and Path Optimization objectives. The computed output response LsS_value identifies the paths as shown in Table 5.3. It demonstrates the classification of LSPs and also defines the fuzzy set boundaries. Paths lying in region Z, T, VS, S, B, VB, H are best, very good, good, satisfactory, just acceptable, not acceptable and rejected respectively.

Table 5.2: Linguistic values (Load, Delay, Utilization Rate and Link Capacity) with boundaries

Linguistic values with their boundaries							
Load	VL	L	M	H	VH		
	Below 0 to 250	0 to 500	250 to 750	500 to 1000	750 to above than 1000		
Delay	VL	L	M	H	VH		
	Below 0 to 0.25	0 to 5.0	2.5 to 7.5	5.0 to 10	7.5 to above than 10		
Utilization rate	Z	T	VS	S	B	VB	H
	Below 0 to 0.16	0 to 0.33	0.16 to 0.50	0.33 to 0.66	0.50 to 0.83	0.66 to 1	0.83 to above than 1
Link capacity	VL	L	M	H	VH		
	Below 0 to 250	0 to 500	250 to 750	500 to 1000	750 to above than 1000		

Table 5.3: Categorization of LSPs according to computed output value LsS_value

Paths falling in region	Category	Fuzzy set boundaries
Z	Best	Less than 0 to 0.16
T	Very Good	0 to 0.33
VS	Good	0.16 to 0.50
S	Satisfactory	0.33 to 0.66
B	Just Acceptable	0.50 to 0.83
VB	Not Acceptable	0.66 to 1
H	Rejected	0.83 to more than 1

Hence, in this way it arranges the paths in preferential order for the successful transmission of packets.

TSS rule base is a set of inputs (utilization rate (UR), link capacity (LC)), with their seven linguistic values of UR (Zero (Z), Tiny (T), Very Small (VS), Small (S), Big (B), Very Big (VB), High (H)) and five linguistic values of LC (Very Low (VL), Low (L) Medium (M), High (H), Very High (VH)) and output TSS_value with their five linguistic values (Very Low (VL), Low (L) Medium (M), High (H), Very High (VH)) forms at most 7*5 = 35 possible combinations. The matrix shown in Table 5.4 is referred as Fuzzy Rule Base Matrix- TSS with columns representing UR and rows representing LC. Hence, optimized decisions are made using developed rules 35 (R1, R2, R3… R35).

Table 5.4: Fuzzy Rule Base Matrix-TSS with inputs (link capacity, utilization rate)

utilization_rate / link capacity	Z	T	VS	S	B	VB	H
VL	**NC R1**	**NC R2**	**NC R3**	**NC R4**	**IO R5**	**IO R6**	**IW R7**
L	**NC R8**	**NC R9**	**NC R10**	**IO R11**	**IO R12**	**IW R13**	**IT R14**
M	**NC R15**	**NC R16**	**IO R17**	**IO R18**	**IW R19**	**IW R20**	**IT R21**
H	**NC R22**	**IO R23**	**IW R24**	**IW R25**	**IT R26**	**IT R27**	**A R28**
VH	**IW R29**	**IW R30**	**IT R31**	**IT R32**	**A R33**	**A R34**	**A R35**

At different values of Utilization Rate and Link Capacity, the values of linguistic variables are obtained as defined in Table 5.2, which indicates the boundaries of input fuzzy sets of TSS. This FMM (TSS-Fuzzy Rule Base Matrix) gives the information of the requirement of number of LSPs. Table 5.5 demonstrates the number of LSPs needed for the operation according to traffic scenario. If TSS_value lies in the region of NC, it is defined as no change or no need of additional LSP for congestion free transmission. Requirement of LSPs is obtained from TSS_value lies to check that in which region (NC, IO, IW, IT, A) values are lying.

Table 5.5: Traffic Splitting among LSPs according to output value TSS_value

Splitting requirement falling in Region	Requirement of LSPs	Fuzzy set boundaries
NC	No Change or no need of additional LSP	Below than 0 to 0.25
IO	Increase by one	0 to 0.50
IW	Increase by two	0.250 to 0.83
IT	Increase by three	0.50 to 1
A	All available LSPs	0.83 to more than 1

The requirement of number of LSPs depends upon the current dynamic status of the network in terms of highly loaded, loaded, equilibrium, lightly loaded, and least loaded. In highly loaded network - more number of paths is required and in lightly loaded- less number of paths is required. Hence, by applying Traffic Engineering (TE)/load balancing, objective of congestion free network is achieved.

The Triangular Membership Function (TMF) is applied to obtain the membership function of metrics as:-

$$triangle(x; a, b, c) = \max\left(\min\left(\left(\frac{x-a}{b-a}\right), \left(\frac{c-x}{c-b}\right)\right), 0\right) \qquad \ldots (5.1)$$

It is well-defined by three factors, where b designates the point on which, the membership function value is 1, a and c indicate the left and right limits of the definition domain of the membership function. On applying TMF as shown in equation (5.1), membership functions of input and output parameters are obtained as follows:-

$\mu_{load} = \{\mu_{VL}, \mu_{L}, \mu_{M}, \mu_{H}, \mu_{VH}\}$,

$\mu_{delay} = \{\mu_{VL}, \mu_{L}, \mu_{M}, \mu_{H}, \mu_{VH}\}$,

$\mu_{LsS\_value} = \{\mu_{Z}, \mu_{T}, \mu_{VS}, \mu_{S}, \mu_{B}, \mu_{VB}, \mu_{H}\}$,

$\mu_{utilization\_.rate} = \{\mu_{Z}, \mu_{T}, \mu_{VS}, \mu_{S}, \mu_{B}, \mu_{VB}, \mu_{H}\}$,

$\mu_{link\_capacity} = \{\mu_{VL}, \mu_{L}, \mu_{M}, \mu_{H}, \mu_{VH}\}$,

$\mu_{TSS\_value} = \{\mu_{NC}, \mu_{IO}, \mu_{IW}, \mu_{IT}, \mu_{A}\}$.

Routing decisions are build on the analysis of rules of the rule base and recognition of fired rules (activated rules). Minimum (MIN) operation is applied to find out the minimum or least value of parameters. The output responses LsS_value and TSS_value are obtained by applying logical product (AND) on fired rules. These fired rules combined to make an optimal decision. Composition merges the possessions of all applicable rules and gives the best-weighted influence of fired rules as shown in Table 5.6. Output linguistic terms are obtained as the combination of different rules. The execution of if then rules of fuzzy controllers is explained in section 5.6.1.

Table 5.6: Composition of rules of fuzzy controllers LsS and TSS

	Output linguistic variables
LsS	**Z = R1** **T = R2 + R6 + R11** **S = R3 + R7 + R12 + R16** **VS = R4 + R8 +R13 + R17 + R21** **B = R5 + R9 + R10 + R14 + R15 + R18 + R22 + R23** **VB = R19 + R20 + R24** **H = R25**
TSS	**NC = R1 + R2 + R3 + R4 + R8 + R9 + R10 + R15 + R16 + R22** **IO = R5 + R6 + R11 + R12 + R17+ R18 + R23** **IW = R7 + R13 + R19 + R24 + R25 + R29 + R30 + R20** **IT = R14 + R21 + R26 + R27 + R31 + R32** **A = R28 + R33 + R34 + R35**

Decision function is computed using as Center Average defuzzifier or discrete centroid method as follows:-

$$\mu_{CA} = \sum_{i-1}^{n} \mu_{xi} * X_{ci} / \sum_{i=1}^{n} \mu_{xi} \qquad \text{… (5.2)}$$

This is an approximation of Center of Area (COA) defuzzifier method. X_{ci} denotes center points of the output linguistic terms (*xi*), μ_{CA} is membership function of output linguistic term and μ_{xi} is membership function value of input linguistic term. On applying equation (5.2) on the linguistic terms and linguistic centers of control systems, LsS_value and TSS_value are obtained as shown in Table 5.7.

Table 5.7: Defuzzification of fuzzy controllers

	Linguistic term	Linguistic centre	
LsS	Z T VS S B VB H	Z_C T_C VS_C S_C Bc VBc H_C	LsS_value = (Z* Z_C +T* T_C +VS* VS_C +S* S_C +B* B_C +VB* VB_C +H* H_C)/ (Z+T+VS+S+B+VB+H)
TSS	NC IO IW IT A	NC_C IO_C IW_C IT_C A_C	TSS_value = (NC* NC_C +IO* IO_C +IW* IW_C +IT* IT_C +A* A_C)/ (NC+IO+IW+IT+A)

5.3.1 Decision maker: FLCS

FLCS algorithm implements and evaluates results of above mentioned system. It is composed of two parts; firstly determination and selection of multiple paths using LsS and secondly allocating network traffic among the required number of paths using TSS.

5.3.2 Determination and Selection of multiple paths using LsS

It uses two metrics L, D for the selection of LSPs. *L(i ,j), load* specifying number of packets to be sent on link (i, j) and *D(i , j), delay* specifying delay of link (i, j) during transmission. *D (i, j)* is evaluated using equation (5.3) as follows:-

$$D(i, j) = L(i, j)/ LC(i, j) \qquad \ldots(5.3)$$

LsS fuzzy inference system gives *LsS_value (i, j)*, which identifies links for the selection of LSPs. Link having minimum LsS_value is selected for the operation.

5.3.3 Allocating network traffic among paths

It uses two metrics LC and UR for finding the requirement of LSPs for successfully congestion free transmission. It is considered that link capacity of each link will remain same throughout the execution, but load, delay, utilization rate get changed. *LC (i, j), link_capacity* giving bandwidth value of link (i, j). *UR (i, j), utilization_rate* specifying utilization rate of link (i, j) computed as below equation (5.4) as follows:-

$$UR(i, j) = Freq(i, j)/NL(i). \quad \ldots(5.4)$$

Where *Freq (i, j)* is a frequency of link (i, j) and *NL(i)* gives a number of outgoing links from node i. TSS fuzzy inference system gives *TSS_value (i, j)* of each link used to compute number of paths required (Nlsps) for operation.

5.3.4 Pseudo codes of FLCS

Description of Data Structures and Variables used in building algorithm are as follows:-

NOTATION

Data Structure: FLCS

Link[i][j]	Link Matrix describing connectivity between two nodes. Link[i][j] = 1 if connectivity exists between nodes i and j otherwise 0.
LC[i][j]	Link capacity matrix giving bandwidth value of each link.
UR[i][j]	Utilization rate matrix specifying utilization rate of each link.
D[i][j]	Delay matrix specifying delay of each link.
L[i][j]	Load matrix specifying number of packets waiting to be sent on each link.
LsS[i][j]	LsS Value Matrix storing LsS_ value of each link used to identify paths.
TSS[i][j]	TSS Value Matrix storing TSS_ value of each link used to compute number of paths required for operation.
Freq[i][j]	Freq[i][j] storing the frequency of a particular link used.
FDlss[i][j]	Final decision of LsS as defuzzified values of LsS_value with respect to each link
FDtss[i][j]	Final decision TSS as defuzzified values of TSS_value with respect to each link.
Slsp[i]	gives the selected LSP for operation according to optimal LsS_value.
RLsS[i][j]	stores the rules of LsS
RTSS[i][j]	stores the rules of TSS

NOTATION

Variable: FLCS

Ingress	ingress to store the identifier of source node.
egress	to store the identifier of destination node.

n	number of nodes in the network.
L_{ak}, L_{bk}, L_{ck}	for storing the limits of linguistic terms of linguistic input variable Load of LsS.
D_{ak}, D_{bk}, D_{ck}	for storing the limits of linguistic terms of linguistic input variable Delay of LsS.
LsS_{ak}, LsS_{bk}, LsS_{ck}	for storing the limits of linguistic terms of linguistic output variable LsS_value of LsS.
UR_{ak}, UR_{bk}, UR_{ck}	for storing the limits of linguistic terms of linguistic input variable Utilization Rate of TSS.
LC_{ak}, LC_{bk}, LC_{ck}	for storing the limits of linguistic terms of linguistic input variable Link Capacity of TSS.
Nlsps	gives the number of required LSPs.
Tlsps	gives the total number of LSPs.
μ_{L}, μ_{D}, μ_{UR}, μ_{LC}, μ_{LsS}, μ_{TSS}	membership functions of load, delay, utilization rate, link capacity, LsS_value and TSS_value respectively.
μ_{Lk}, μ_{Dh}, μ_{URk}, μ_{LCk} μ_{LsSk}, μ_{TSSk}	membership functions of linguistic expressions of load, utilization rate, delay, link capacity, LsS and TSS respectively.
i, j, k, m, n	used for the loop control.

Algorithm: main module

Begin

Read n

Repeat

for i, j =1 **to** 8

Read Link[i][j]

Read L[i][j],D[i][j], UR[i][j] and LC[i][j]

1: Call LsS(D, L) = LsS_value

2: Initialize Freq[i][j] = 0.0

3: Call TSS(UR, LC) = Nlsps

Repeat

4: while(L[i][j]!=0)

5: for k=1 **to** Nlsps

6: min(LSS[i][j] **&&** Freq[i][j]) = Slsp[k]

7: Increment Freq[i][j] = Freq[i][j] + 1

end

Algorithm: Sub Module LsS (L, D)

Begin

Read

for k = 1 to 5

{(L_{ak}, L_{bk}, L_{ck}), (D_{ak}, D_{bk}, D_{ck})}

Read

for k = 1 to 7

{(LsS_{ak}, LsS_{bk}, LsS_{ck})}

Repeat steps 1 **to** 4

for i, j = 1 **to** 8

steps 1 **and** 2

for p=1 to 5

1: Evaluate DS L[i][j] and D[i][j]

$$\mu_L[p] = \sum_{k=1}^{5} \mu_{Lk}$$

$$\mu_D[p] = \sum_{k=1}^{5} \mu_{Dk}$$

2: Composition and aggregation

min(μ_L[p], μ_D[p]) = RLsS[i][j]

$$\mu_{LsS}[p] = \sum_{i,j=1}^{5} RLsS[i][j]$$

3: Defuzzification using centroid method

for h = 1 **to** 7

$$LsS[i][j] = \sum_{k=1}^{7} \mu_{UR_K}\ \mu_{LsS}[p]) * LsS_{bk}/\mu_{LsS}[h])$$

4: Applying TMF on LsS[i][j]

for m = 1 **to** 7

for n = 1 **to** 2

Return(Slsps[i] = **max**(FDlss[m][n]))

end

Algorithm: Sub Module TSS (UR, LC)

Begin

Read

for k = 1 **to** 7

$\{(TSS_{ak}, TSS_{bk}, TSS_{ck})\}$

Repeat steps 1 **to** 4

for i, j = 1 **to** 8,

steps 1 **and** 2

for p = 1 **to** 5 **and**

steps 1 **and** 2

for l = 1 **to** 5

1: Evaluate DS UR[i][j] and LC[i][j]

$$\mu_{UR}[p] = \sum_{k=1}^{5} \mu_{URk}$$

$$\mu_{LC}[p] = \sum_{k=1}^{5} \mu_{LCk}$$

2: Composition and aggregation

$$\mathbf{min}(\mu_{UR}[p], \mu_{LC}[l]) = RTSS[i][j]$$

$$\mu_{TSS}[l] = \sum_{i=1, j=1}^{5,7} RTSS[i][j]$$

3: Defuzzification using centroid method

$$TSS[i][j] = \sum_{l,k=1}^{7} \mu_{TSS[l]} * TSS_{bk}/\mu_{TSS}[l])$$

4: Applying TMF on TSS[i][j]

for m = 1 **to** 5

for n = 1 **to** 2,

Return(Nlsps = **max** (FDtss[m][n]))

end

FLCS (L, D, UR, LC)

Begin

1: LsS_value(i, j) = LsS(D, L)

/*Call LsS computes LsS_value to identify links for the selection of LSPs on processing inputs D and L */

2: TSS_value(i, j) = TSS(UR, LC)

Nlsps = TSS_value(i, j) /*Call TSS computes TSS_value to obtain the number of LSPs required for operation on processing input UR and LC */

3: while(L(i, j) ! = 0)

/*Transmission will be continue till load at node i=ingress is non zero*/

3.1: for k= 1 to Nlsps /*Traffic splitting takes place among the Nlsps */

Slsp[k] = min(LsS(i,j)) /*Generation of optimal LSPs (links having minimum */

3.2: Freq(i,j) = Freq(i,j) +1 /*Respective frequency of LSP is updated */

end

Step 1:-LsS computes the respective LsS_value of each link (i,j) of FLCS. *Step 2:*-TSS computes the respective TSS_value of each link (i,j) of FLCS, which gives the requirement of traffic splitting in network.*Step 3:*-Transmission goes continue till load at ingress is non zero. Traffic splitting takes place among the optimal Nlsps (LSP having minimum LsS_value). Respective frequency of each link (i,j) is augmented according to the number of times a particular link (i,j) is used. *Slsp* gives the optimal LSPs for operation.

5.4 An Illustrative example to realize Algorithm

For the realization of FLCS, the configuration of the network of 8 nodes shown in Figure 5.5 is assumed. The ingress of network is node 1 and egress is node 8.

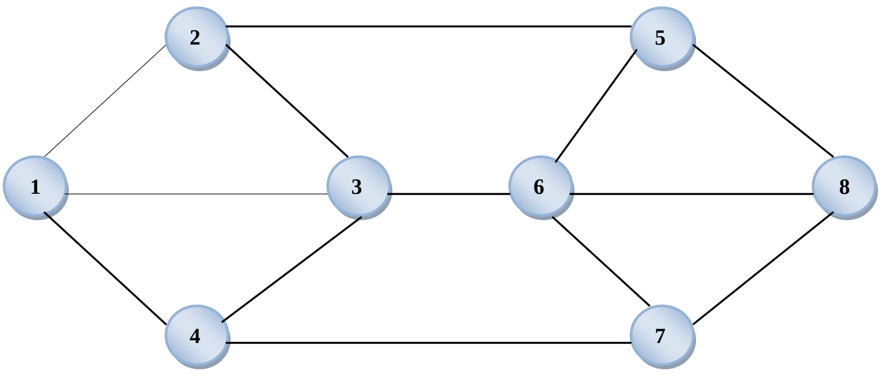

Figure 5.5: Network Model of 8 nodes

Assumed Matrixes are represented as:-

To obtain results of fuzzy controllers, steps of fuzzy logic have been performed. In order to deploy this task the values of all active variables are assumed. As there are 8 nodes so all these matrices are the orders of 8*8.

Values of LINK matrix LINK [8][8] are presented in Table 5.8(a), LINK CAPACITY matrix LC[8][8] is shown in Table 5.8 (b).

Table 5.8 (a): LINK Matrix

LINK	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	0	1	1	1	0	0	0	0
2	1	0	1	0	1	0	0	0
3	1	1	0	1	0	1	0	0
4	1	0	1	0	0	0	1	0
5	0	1	0	0	0	1	0	1
6	0	0	1	0	1	0	1	1
7	0	0	0	1	0	1	0	1
8	0	0	0	0	1	1	1	0

Table 5.8 (b): LINK CAPACITY Matrix

LC	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	0	90	348	916	0	0	0	0
2	90	0	916	0	90	0	0	0
3	348	916	0	348	0	916	0	0
4	916	0	348	0	0	0	90	0
5	0	90	0	0	0	90	0	348
6	0	0	916	0	90	0	916	90
7	0	0	0	90	0	916	0	90
8	0	0	0	0	348	90	90	0

DELAY matrix D[8][8] is presented in Table 5.8 (c), LOAD matrix L [8][8] is shown in Table 5.8 (d) and UTILIZATION RATE matrix UR[8][8] is depicted in Table 5.8(e)

Table 5.8 (c): DELAY Matrix

D	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	0	1	1.614	0.936	0	0	0	0
2	6.244	0	0.936	0	1	0	0	0
3	0.258	0.613	0	1.614	0	0.936	0	0
4	0.613	0	2.465	0	0	0	1	0
5	0	9.533	0	0	0	1	0	1.614
6	0	0	0.098	0	6.244	0	0.936	1
7	0	0	0	1	0	0.936	0	1
8	0	0	0	0	0.258	6.244	9.533	0

Table 5.8 (d): LOAD matrix

L	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	0	90	562	858	0	0	0	0
2	562	0	858	0	90	0	0	0
3	90	562	0	562	0	858	0	0
4	562	0	858	0	0	0	90	0
5	0	858	0	0	0	90	0	562
6	0	0	90	0	562	0	858	90
7	0	0	0	90	0	858	0	90
8	0	0	0	0	90	562	858	0

Table 5.8(e): UTILIZATION RATE Matrix

UR	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	0	0.66	1	0.33	0	0	0	0
2	0.66	0	0.33	0	1	0	0	0
3	0.75	0.27	0	0.50	0	1	0	0
4	0.33	0	0.66	0	0	0	1	0
5	0	1	0	0	0	0.66	0	0.33
6	0	0	1	0	0.50	0	0.25	0.75
7	0	0	0	1	0	0.33	0	0.66
8	0	0	0	0	0.33	1	0.66	0

After executing first iteration results are as follows:

Calculated values of LsS_value for each link (i, j) to obtain LsS[8][8]:

LsS Fuzzy controller computes the LsS_value of each link in order to identify LSPs in preferential order. The obtained results of LsS_value and TSS_value are shown in below Table 5.8(f) and Table 5.8(g) respectively.

Table 5.8 (f): LsS_value Matrix

LsS_value	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	0	0.263	0.390	0.775	0	0	0	0
2	0.662	0	0.526	0	0.315	0	0	0
3	0.263	0.662	0	0.390	0	0.526	0	0
4	0.36	0	0.775	0	0	0	0.263	0
5	0	0.526	0	0	0	0.315	0	0.662
6	0	0	0.263	0	0.360	0	0.775	0.315
7	0	0	0	0.315	0	0.775	0	0.263
8	0	0	0	0	0.559	0.36	0.574	0

Calculated values of TSS_value for each link (i, j) to obtain TSS [8][8]:

TSS computes the TSS_value of each path in order to compute the required number of LSPs.

Table 5.8 (g): TSS_value Matrix

TSS_value	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	0	0.250	0.750	0.65	0	0	0	0
2	0.250	0	0.650	0	0.597	0	0	0
3	0.375	0.528	0	0.250	0	0.912	0	0
4	0.650	0	0.353	0	0	0	0.597	0
5	0	0.597	0	0	0	0.250	0	0.202
6	0	0	0.912	0	0.196	0	0.528	0.357
7	0	0	0	0.597	0	0.65	0	0.250
8	0	0	0	0	0.202	0.597	0.250	0

Implementation is done using Mamdani Fuzzy Inference System of Fuzzy Logic Toolbox of Matlab. In the network each link (i, j) contains information as a set of 4 parameters (L, D, UR, LC). The algorithm presented in above section is executed for the assumed values of parameters shown as coordinates of links in Figure 5.6. Membership functions are obtained for all the set of values of links of assumed network using equation 5.1 and 5.2.

5.4.1 Realization of an algorithm

At a particular instance membership function value of input parameters L, D, UR, LC are implicit as L = 858Mb, D = 0.936s, UR = 0.33Mbps, LC = 916Mbps as described in section 5.4.2.2. The Stepwise execution of complete fuzzy methodology in deployed through Steps 1 to Step 4. The values of input Linguistic parameters and checked under the defined region of fuzzy controller and output parameters LsS_value and TSS_value at these above given respective input parameters are evaluated. The methodology applied here is very easy to understand and express. The other two sets of values or two more scenarios are also executed in same way as in next section 5.4.2.2. The results of these realizations are incorporated in Table 5.11.

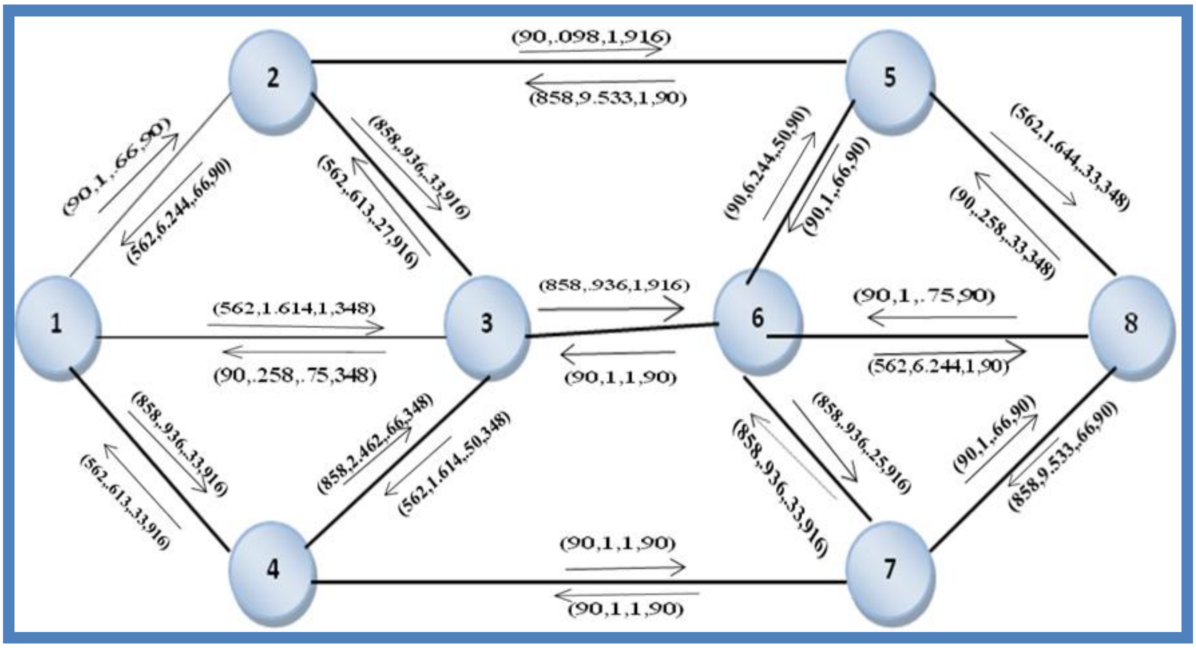

Figure 5.6: Input values of L, D, UR, and LC

5.4.2 Implementation with concluding results

5.4.2.1 Notations used in deployment of LsS

1. Computation of (FMM) to **find ordered LSPs**

   Let MF and Y is any value from the defined regions

   STEP 1 Put Y into MF system.

   STEP 2 Check the region for both Linguistic terms**,** (L, D) that in which Y is lying. The detail list of values for Load and Delay are given below.

Linguistic term **L**

a. If entirely lying in **VL** region, then assign the computed DS to the fuzzy set **VL**.
b. If in the region **VL & L,** then calculate the DS and assign to both fuzzy sets.
c. If entirely lying in **L** region, then assign the calculated DS to the fuzzy set **L**.
d. If in the region **L & M,** then calculate the DS and assign to both fuzzy sets.
e. If precisely in **M** region, then assign the calculated DS to the fuzzy set **M**.
f. If in region **M & H,** then calculate the DS and assign the identical to both fuzzy sets.
g. If precisely in **H** region, then assign the calculated DS to the fuzzy set H.
h. If in region **H & VH,** then calculate the DS and assign the same to both fuzzy sets.
i. If in region **VH,** then assign the calculated DS to the fuzzy set **VH**.

Linguistic term **D**

a. If entirely lying in **VL** region, then assign the calculated DS to the fuzzy set **VL**.
b. If in the region **VL & L,** then calculate the DS and assign to both fuzzy sets.
c. If entirely lying in **L** region, then assign the calculated DS to the fuzzy set **L**.
d. If in the region **L & M,** then calculate the DS and assign to both fuzzy sets.
e. If precisely in **M** region, then assign the calculated DS to the fuzzy set **M**.
f. If in region **M & H,** then calculate the DS and assign the identical to both fuzzy sets.
g. If precisely in **H** region, then assign the calculated DS to the fuzzy set H.
h. If in region **H & VH,** then calculate the DS and assign the identical to both fuzzy sets.
i. If in region **VH,** then assign the calculated DS to the fuzzy set **VH**.

STEP 3 Applying the DS within the rule base obtained output Linguistic term LsS_value

a. If entirely lying in **Z** region, then assign the calculated DS to the fuzzy set **Z**.
b. If in the region **Z & T,** then calculate the DS and assign to both fuzzy sets.
c. If entirely lying in **T** region, then calculate the DS and assign to linguistic term **T**.
d. If in the region **T & VS,** then calculate the DS and assign to both fuzzy sets.
e. If in the region **VS,** then calculate the DS and assign to linguistic term **VS**.
f. If in the region **VS & S,** then calculate the DS and assign to both fuzzy sets.
g. If in **S** region, then assign the calculated DS to the fuzzy set **S**.
h. If in region **S & B,** then calculate the DS and assign the identical to both fuzzy sets.
i. If precisely in **B** region, then assign the calculated DS to the fuzzy set **B**.
j. If in region **B & VB,** then calculate the DS and assign the identical to both fuzzy sets.
k. If in region **VB,** then assign the calculated DS to the fuzzy set **VB**.
l. If in region **VB & H,** then calculate the DS and assign the identical to both fuzzy sets.
m. If in region **H,** then assign the calculated DS to the fuzzy set **H**.

STEP 4 Calculate the value of each rule using AND/MIN operation.

STEP 5 Apply SUM compositions to achieve the final DS for the output variables.

STEP 6 Stop

2. Formation of Information Base (IB) about **Selection of LSPs** for every node N in the network constructs an IB. The LsS_value of different paths recognizes the status of network. Computation of the **preferential order of the LSPs** to arrange all the set of nodes/ paths using an appropriate sorting technique to obtain preferential order of LSPs.

5.4.2.2 Notations used in deployment of TSS

1. Computation of Fuzzy Mixed metric (FMM) to **find requirement of no. of LSPs using TSS_value**.

Let MF and Y is any value from the available regions

STEP 1 Put Y into MF system.

STEP 2 Check the region for both Linguistic term (UR, LC) that in which Y is lying

The detail list of values for Linguistic terms (Utilization Rate and Link Capacity) is given below.

Linguistic term **UR**

a. If entirely lying in **Z** region, then assign the calculated DS to the fuzzy set **Z**.
b. If in the region **Z & T,** then calculate the DS and assign to both fuzzy sets.
c. If entirely lying in **T** region, then calculate the DS and assign to linguistic term **T**.
d. If in the region **T & VS,** then calculate the DS and assign to both fuzzy sets.
e. If in the region **VS,** then calculate the DS and assign to linguistic term **VS**.
f. If in the region **VS & S,** then calculate the DS and assign to both fuzzy sets.
g. If in **S** region, then assign the calculated DS to the fuzzy set **S**.
h. If in region **S & B,** then calculate the DS and assign the identical to both fuzzy sets.
i. If precisely in **B** region, then assign the calculated DS to the fuzzy set **B**.
j. If in region **B & VB,** then calculate the DS and assign the identical to both fuzzy sets.
k. If in region **VB,** then assign the calculated DS to the fuzzy set **VB**.
l. If in region **VB & H,** then calculate the DS and assign the identical to both fuzzy sets.
m. If in region **H,** then assign the calculated DS to the fuzzy set **H**.

Linguistic term **LC**

a. If entirely lying in **VL** region, then assign the calculated DS to the fuzzy set **VL**.
b. If in the region **VL & L,** then calculate the DS and assign to both fuzzy sets.
c. If entirely lying in **L** region, then assign the calculated DS to the fuzzy set **L**.
d. If in the region **L & M,** then calculate the DS and assign to both fuzzy sets.
e. If precisely in **M** region, then assign the calculated DS to the fuzzy set **M**.
f. If in region **M & H,** then calculate the DS and assign the identical to both fuzzy sets.
g. If precisely in **H** region, then assign the calculated DS to the fuzzy set H.
h. If in region **H & VH,** then calculate the DS and assign the identical to both fuzzy sets.
i. If in region **VH,** then assign the calculated DS to the fuzzy set **VH**.

STEP 3 Applying the DS within the rule base obtained Output Linguistic term **TSS_value**

a. If entirely lying in **NC** region, then assign the calculated DS to the fuzzy set **NC**.
b. If in the region **NC & IO,** then calculate the DS and assign to both fuzzy sets.
c. If entirely lying in **IO** region, then assign the calculated DS to the fuzzy set **IO**.
d. If in the region **IO & IW,** then calculate the DS and assign to both fuzzy sets.
e. If precisely in **IW** region, then assign the calculated DS to the fuzzy set **IW**.
f. If in region **IW & IT,** then calculate the DS and assign the identical to both fuzzy sets.
g. If precisely in **IT** region, then assign the calculated DS to the fuzzy set **IT**.
h. If in region **IT & ALL,** then calculate the DS and assign the identical to both fuzzy sets.
i. If in region **ALL,** then assign the calculated DS to the fuzzy set **ALL**.

STEP 4 Calculate the value of each rule using AND/MIN operation.

STEP 5 Apply SUM compositions to achieve the final DS for the output variables.

STEP 6 Stop

2. **Formation of Traffic Information Base (TIB) consists of information of Traffic splitting** for every LSP in the network. It contains information of status (utilization rate, link capacity) of paths. **Traffic splitting among calculated Fuzzy based LSPs is obtained according** to the output response (TSS_value) received.

5.4.2.3 Numerical illustration

LSPs Setup System (LsS)

load = 858

$\mu_{load} = \{\mu_{VL}, \mu_L, \mu_M, \mu_H, \mu_{VH}\}$

$= \{0, 0, 0, 0.62, 0.41\}$

delay = 0.936

$\mu_{delay} = \{\mu_{VL}, \mu_L, \mu_M, \mu_H, \mu_{VH}\}$

$= \{0.33, 0.17, 0, 0, 0, 0\}$

Activate rules, Substitute membership values and applying MIN operation

The evaluated values of TSS controller after applying the MIN operation are shown in Table 5.9.

Table 5.9: Activated rules of LsS

D \ L	**VL** **.33**	**L** **.17**	M	H	VH
VL	Z	T	VS	S	B
L	T	VS	S	B	B
M	T	VS	S	B	B
H **.62**	**VS** **.33**	**S** **.17**	B	VB	VB
VH **.41**	**S** **.33**	**B** **.17**	B	VB	H

Composition merges possessions of every possible applicable rules and provides the best weighted influence to all firing rules.

Z = Rule 1 = 0

T = Rules (2 + 6 + 11) = 0

VS = Rules (3 + 7 + 12 + 16) = 0 + 0 + 0 + 0.33 = 0.33

S = Rules (4 + 8 + 13 + 17 + 21) = 0 + 0 + 0 + 0.17 + 0.33 = 0 .50

B = Rules (5 + 9 + 10 + 14 + 15 + 18 + 22 + 23) = 0 + 0 + 0 + 0 + 0 + 0 + 0.17 + 0
= 0.17

VB = Rules (19 + 20 + 24) = 0

H = Rule 25 = 0

LsS_value

$\mu_{\mathbf{LsS\_value}} = \{\mu_Z, \mu_T, \mu_{VS}, \mu_S, \mu_B, \mu_{VB}, \mu_H\}$

= {0, 0, **0.33, 0.50, 0.17**, 0, 0}

Calculate decision functions (Centroid Method) and Fuzzified decisions

Output Center points

$Z_C = 0.0$

$T_C = 0.15$

$VS_C = 0.35$

$S_C = 0.50$

$B_C = 0.65$

$VB_C = 0 .85$

$H_C = 1.0$

Output = $(Z * Z_C + T * T_C + VS * VS_C + S * S_C + B * B_C + VB * VB_C + H * H_C)/ (Z+T+VS+S+B+VB+H)$

$= (0 * 0.0 + 0 * 0.15 + \mathbf{0.33 * 0.35 + 0.50 * 0.50 + 0.17 * 0.65} + 0 *.85 + 0 *1.0) / 1.0$

$= (0.0 + 0.0 + \mathbf{0.1155 + 0.25 + 0.1105} + 0.0 + 0.0) / 1.0$

$\mathbf{= 0.476/ 1.0 = 0.476}$

The final decision as LsS_value obtained indicates that the particular link is 86% in S and 14% in VS as displayed in Figure 5.7.

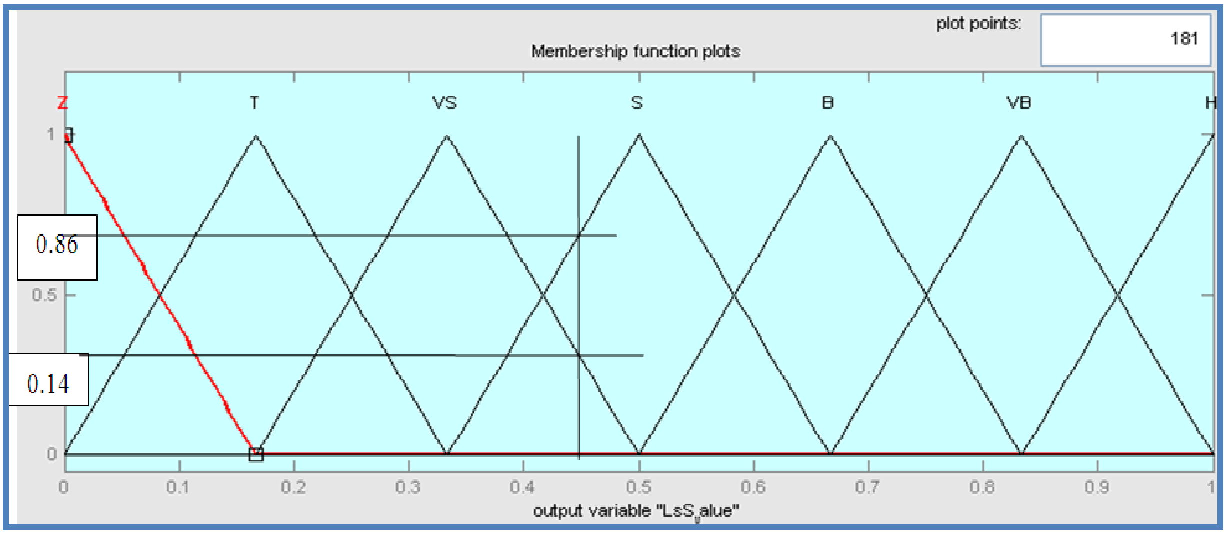

Figure 5.7: Fuzzified decision Output LsS_value indicates that link is 86% satisfactory and 14% good

Traffic splitting System (TSS)

utilization_rate = 0.33

$\mu_{utilization\_rate} = \{\mu_Z, \mu_T, \mu_{VS}, \mu_S, \mu_B, \mu_{VB}, \mu_H\}$

$= \{0, 0, 1, 0, 0, 0, 0\}$

link _capacity = 916

$\mu_{link\_capacity} = \{\mu_{VL}, \mu_L, \mu_M, \mu_H, \mu_{VH}\}$

$= \{0, 0, 0, 0.30, 0.66\}$

Activate rules, Substitute membership values and applying Min operation

The evaluated values of TSS controller after applying the MIN operation are shown in Table 5.10.

Table 5.10: Activated rules of TSS

UR / LC	**Z**	**T**	VS 1	S	B	VB	H
VL	NC	NC	NC	NC	IO	IO	IW
L	NC	NC	NC	IO	IO	IW	IT
M	NC	NC	IO	IO	IW	IW	IT
H 0.30	NC	IO	**IW 0.30**	IW	IT	IT	IK
VH 0.66	IW	IW	**IT 0.66**	IT	IK	IK	IK

Composition reflects the effects of all applicable rules and provides the best weighted influence to all firing rules as follows.

NC = Rules (1 + 2 + 3 + 4 + 8 + 9 + 10 +15+16) = 0 + 0 + 0 + 0 + 0 + 0 + 0 + 0 = 0

IO = Rules (5 + 6 + 11 + 12 + 17 + 18 + 23) = 0 + 0 + 0 + 0 + 0 + 0 + 0 + 0 = 0

IW = Rules (7 + 13 + 19 + 24 + 25 + 29 + 30 + 20) = 0 + 0 + 0 + 0.30 + 0 + 0 + 0 + 0 + 0 = 0.30

IT = Rules (14 + 21 + 26 + 27 + 31 + 32) = 0 + 0 + 0 + 0 + 0 + 0.66 + 0 = 0.66

A = Rules (28 + 33 + 34 + 35) = 0 + 0 + 0 + 0 + 0 + 0 + 0 = 0

TSS_value

$\mu_{TSS\_value} = \{\mu_{NC}, \mu_{IO}, \mu_{IW}, \mu_{IT}, \mu_{A}\}$

= {0, **0.30, 0.66**,0, 0}

Calculate decision functions (Centroid Method) and Fuzzified decisions

Output Center points

NC_C = 0.1

IO_C = 0.32

IW_C = 0.55

IT_C = 0.78

A_C = 1

Output = (NC * NC_C + IO * IO_C + IW * IW_C + IT * IT_C + A* A_C) / (NC+IO+IW+IT+A)

= 0 * 0.1 + 0 * 0.32 + **0.30 * 0.55 + 0.66 * 0.78** + 10 * 0/ 0.96

= 0 + 0 + **0.165 + 0.5148** + 0.0/ 0.96

= 0.67/ 0.96 =0.69

The final decision as TSS_value obtained indicates that according to the network status 32% increase of LSPs by two and 68% increase of LSPs by three are required VS as displayed in Figure 5.8.

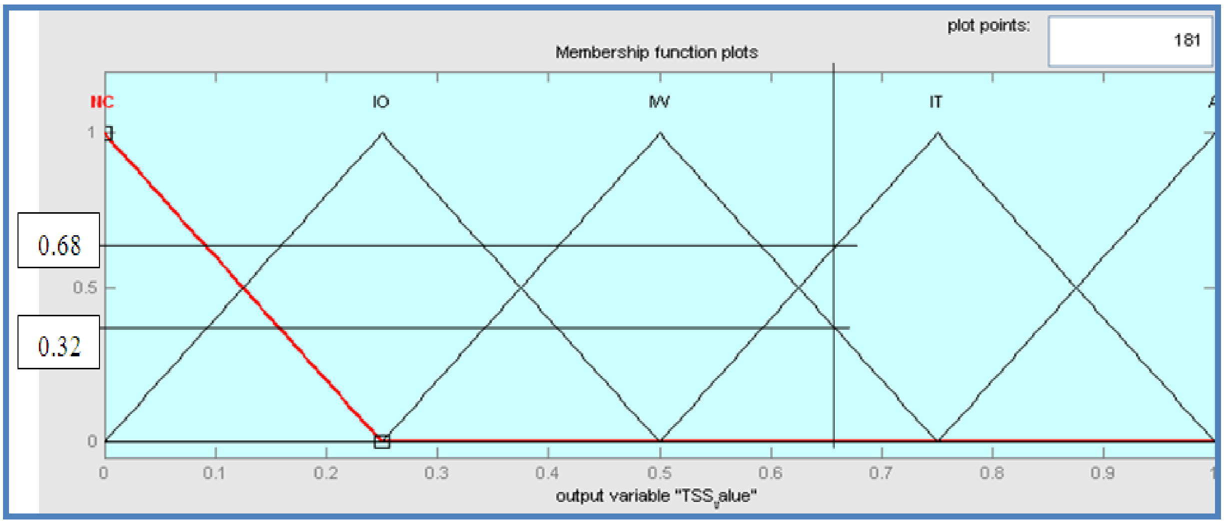

Figure 5.8: Fuzzified decision Output TSS_value indicates 68% increase of LSPs by and 32% increases of LSPs by 2

It concludes that the selected link needs 68% splitting of traffic by increasing LSPs by three. Throughout the simulation process, the updated information of all links is maintained according to which final decisions takes place. Hence, current algorithm has all the essential requirements into its account. The results are obtained from fuzzy controller (LsS, TSS) as matrix LsS_value and TSS_value.

5.4.2.4 Generation of LSPs in assumed scenario

The generation of LSPs takes place by the execution of FLCS algorithm as studied in above section. The step by step how LSPs get generated is predicted from Figure 5.9. In Figure 5.9(a), node 1 is coloured orange it indicates that it is a source. Node 1 is having neighbours as node 2, node3 and node 4. So, these are coloured red as shown in Figure 5.9(b) and the LsS_value of neighbours are compared. In Figure 5.9(c) node 2 is coloured orange which indicates that it is selected as it is having least LsS_value. Node 2 is having neighbours as node 3 and node 5 as shown in Figure 5.9(c) and the LsS_value of neighbours are compared.

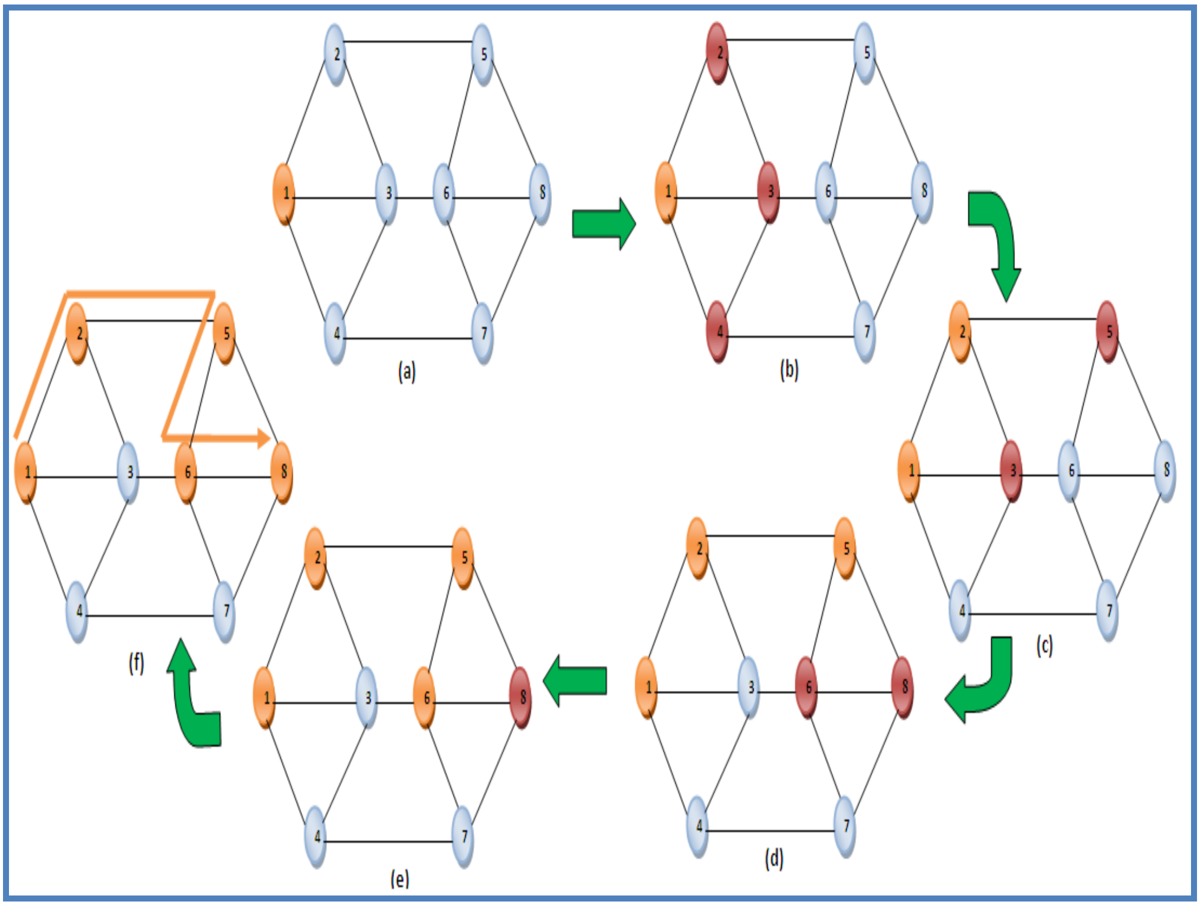

Figure 5.9: Generation of LSPs

Node 5 is coloured orange which indicates that it is selected as it is having least LsS_value shown in Figure 5.9 (d). Node 5 is having neighbours as node 6 and node 8 as shown in Fig.5.9 (d) and the LsS_value of neighbours are compared. Node 8 is coloured orange which indicates that it is selected as it is having least LsS_value shown in Figure 5.9 (e), which is final destination also. Hence, in this manner LSP is generated from node 1 to node 8 as shown in Figure 5.9 (f). Similarly other LSPs are generated; list of paths in preference order at different values of parameters is generated as shown in Table 5.10.

Values of parameters change the decision of selection of path. As, we have to use the optimal paths for the operation. Generated paths are optimal in terms of number of hops, in order to minimize the network cost. It has been observed that, when value of these parameters increases beyond the limit then path becomes unsuitable for future use. Dynamic status of network is studied and according to that suitable paths are selected. The FLCS is justifying the requirement specifications of MPLS algorithm as described and discussed in previous study too. The FLCS serves as online routing algorithm; computational expenses are low and work on the QoS metrics, which is the most desirable feature.

Table 5.11: Generation of LSPs in the network of 8 nodes

Node	Generated LSPs in preference order Ingress = 1 and Egress = 8			
1	1->2->5->6->8	1->3->4->7->8	1->4->7->8	
2	2->5->6->8	2->3->4->7->8	2->3->6->8	2->3->6->7->8
3	3->4->7->8	3->6->8	3->6->7->8	
4	4->7->8			
5	5->6->8	5->8	5->6->7->8	
6	6->8	6->7->8		
7	7->8			

For the better perceptive of approach, FLCS is executed with other two sets of different parametric values. The procedure described in 5.4.2.2 is applied on these values in the same way. The predictions of each link are computed for the selection of appropriate links and predictions of traffic splitting for all scenarios have been computed. The observations for three different scenarios are obtained presented in Table 5.12, which depicts that paths are best, good, very good, satisfactory, just acceptable, not acceptable and rejected according to the dynamic network. Hence, the algorithm has all the essential requirements into its account.

Table 5.12: Predictions of three Scenarios

Link	Prediction		
	Scenario I	Scenario II	Scenario III
1->2	70% VG, 30% G and requires 100% IO	4% B, 96% VG and requires 19% NC, 81% IO	84% just A, 18% S and requires 61% IW, 39% IT
1->3	6% VG, 94% G and requires 100% IT	32% VG, 68% G and requires 37% IW, 63% IT	89% S, 11% G and requires 35% IT, 65% A
1->4	89% S, 11% G and requires 37% IW, 63% IT	70% VG, 30% G and requires 61% IW, 39% IT	4% B, 96% VG and requires 19% NC, 81% IO
2->1	16% S, 84% JA and requires 100% IO	70% VG, 30% G and requires 100% IO	6% VG, 94% G and requires 37% IW, 63% IT
2->3	89% S, 11% G and requires 37% IW, 63% IT	32% VG, 68% G and requires 89% IW, 11% IT	4% B, 96% VG and requires 100% IT
2->5	70% VG, 30% G and requires 61% IW, 39% IT	6% VG, 94% G and requires 37% IW, 63% IT	32% VG, 68% G and requires 37% IW, 63% IT

3->1	4% B, 96% VG and requires 100% IT	90% VG, 10% B and requires 35% IT, 65% A	32% VG, 68% G and requires 37% IW, 63% IT
3->2	32% VG, 68% G and requires 89% IW, 11% IT	89% S, 11% G and requires 37% IW, 63% IT	70% VG, 30% G and requires 100% IO
3->4	6% VG, 94% G and requires 37% IW, 63% IT	4% B, 96% VG and requires 100% IT	32% VG, 68% G and requires 37% IW, 63% IT
3->6	89% S, 11% G and requires 35% IT, 65% A	57% S, 43% JA and requires 37% IW, 63% IT	4% B, 96% VG and requires 100% IT
4->1	32% VG, 68% G and requires 37% IW, 63% IT	16% S, 84% JA and requires 100% IO	6% VG, 94% G and requires 37% IW, 63% IT
4->3	57% S, 43% JA and requires 37% IW, 63% IT	32% VG, 68% G and requires 89% IW, 11% IT	6% VG, 94% G and requires 37% IW, 63% IT
4->7	70% VG, 30%G and requires 61% IW, 39% IT	32% VG, 68% G and requires 89% IW, 11% IT	4% B, 96% VG and requires 19% NC, 81% IO
5->2	89% NA, 11% R and requires 61% IW, 39% IT	6% VG, 94% G and requires 19% NC, 81% IO	32% VG, 68% G and requires 89% IW, 11% IT
5->6	70% VG, 30% G and requires 100% IO	57% S, 43% JA and requires 37% IW, 63% IT	32% VG, 68% G and requires 37% IW, 63% IT
5->8	6% VG, 94% G and requires 19% NC, 81% IO	70% VG, 30%G and requires 61% IW, 39% IT	70% VG, 30% G and requires 100% IO
6->3	90% VG, 10% B and requires 35% IT, 65% A	16% S, 84% JA and requires 100% IO	89% NA, 11% R and requires 61% IW, 39% IT
6->5	89% S, 11%G and requires 21% NC, 79% IO	70% VG, 30%G and requires 61% IW, 39% IT	6% VG, 94% G and requires 19% NC, 81% IO
6->7	89% S, 11%G and requires 89% IW, 11% IT	4% B, 96% VG and requires 100% IT	57% S, 43% JA and requires 37% IW, 63% IT
6->8	70% VG, 30%G and requires 57% IO, 43% IW	70% VG, 30%G and requires 100% IO	57% S, 43% JA and requires 37% IW, 63% IT
7->4	70% VG, 30%G and requires 61% IW, 39% IT	6% VG, 94% G and requires 19% NC, 81% IO	70% VG, 30% G and requires 100% IO
7->6	89% S, 11%G and requires 37% IW, 63% IT	70% VG, 30%G and requires 61% IW, 39% IT	89% not A, 11% R and requires 100% IO
7->8	70% VG, 30%G and requires 100% IO	84% just A, 18% S and requires 61% IW, 39% IT	4% B, 96% VG and requires 19% NC, 81% IO
8->5	4% B, 96% VG and requires 19% NC, 81% IO	70% VG, 30% G and requires 100% IO	89% S, 11%G and requires 37% IW, 63% IT
8->6	84% just A, 18% S and requires 61% IW, 39% IT	4% B, 96% VG and requires 100% IT	70% VG, 30% G and requires 100% IO
8->7	89% not A, 11% R and requires 100% IO	57% S, 43% JA and requires 37% IW, 63% IT	70% VG, 30%G and requires 61% IW, 39% IT

5.5. Likelihood of Fuzzy Logic Control Methodology

1. Computation Time

   At most 4 rules are fired from the rule base at an instance. Hence, 4-5 additions and multiplications are required to simplify computation.

2. Memory Requirements

   Only Edge router-s are required to be Fuzzy Inference Engine (FIE) capable. It needs few kilobytes of memory.

3. Ease of Implementation

   Due to simplicity of the methodology, it easily get adopted and implemented in the network.

5.6 Conclusions

In this chapter, a new fuzzy based approach for MPLS has been presented. The system consists of two fuzzy controllers viz., LsS and TSS. The fuzzy controller LsS basically selects the LSPs after the execution of component the two input fuzzy metrics Delay and Load and outcome LsS_value. The LsS_value identify the paths (best, very good, good, satisfactory, just acceptable, not acceptable and rejected). According to this value, preferential order of LSPs is generated. TSS performs the traffic splitting among the calculated paths as the dynamic link capacity and utilization rate and one output fuzzy metric TSS_value. Lesser the link capacity and utilization rate lesser the number of LSPs needed for the operation and vice-versa. The system keeps MPLS network congestion free to some extends.

Chapter 6

Simulation Analysis and Results

6.1 Introduction

This chapter confirms the outcomes obtained from the sequence of simulations carried out to evaluate the performance of FLCS. The subsequent sections also delineate the working of developed approach which likewise accomplishes to conquer the limitations of the past work done in context of MPLS based traffic congestion issues.

6.2 Selection of Simulation Parameters

The implementation of the research work is presented in following sections. The selection of the simulation parameters is done based on real life conditions and hypothesis. The simulation parameters for Discrete Event Model MPLS network suggested by *Chung J M (2001)* are shown in below Table 6.1. It includes Time interval, Number of events, Types of events, Entity and Packet Traffic Model.

Table 6.1: Basic Simulation parameters

S. No	Simulation Parameter	Description
1.	Time Interval(seconds)	Time after which a next event get fired.
2.	Number of Events	Frequency of events scheduled to occur in MPLS network.
3.	Types of Events	Events related control and routing of the packets (Appearance of Packet, Link Transmit Request, Proliferate packet through Sink, Arrival of Packet at Node, Arrival of Control Message, Refresh LSP States, Generate HELLO Message, Timeout Trigger, Initiate Traffic Generator, End Simulation).
4.	Entity	Routers, Switches, Queues, Packets, Links, Traffic Generator
5.	Packet Traffic Model	A stochastic model of the network flow in MPLS network.

6.3 Simulation Environment

As discussed in the Chapter 4, the simulator used for performance evaluation of research work is ns-3. The algorithm is tested and evaluated based on this simulation environment. *Seo et al. (2003),* studied that the ns-3 is a state-of-the-art platform that succeeds the popular ns-2 simulator. The ns-3 simulator is discrete event driven worked on time varying values.

6.3.1 Simulation Performance Indices

The network performance has been studied from the following statistical indices. These performance indicators have also been used by researchers *Kurose and Ross (2008)* and *Faucheur L (2005).* This selection covers the aspect of FLCS performance as it is based on Traffic Engineering and path selection decisions build mathematically by Fuzzy Logic. Table 6.2 presents the performance indices used in the simulation.

Table 6.2: Performance Indices of Simulation

S. No	Performance Indices	Impact on Traffic Engineering during Simulation
1.	Descriptive Statistics of Mean Delay in Seconds $\overline{delay} = \frac{delaysum}{rpackets}$, *delaysum* is the total delay occurred and *rpackets* denotes received packets.	Delay reflects the state of Network; whether packets in queue or in collision.
2.	Descriptive Statistics of Mean Packet Loss rate in Percentage $\overline{PLR} = \frac{lpackets}{rpackets + lpackets}$, where *lpackets* denotes lost packets and *rpackets* denotes received packets.	Mean Packet Loss reflect that packets are getting dropped due to collision or timeouts.
3.	Descriptive Statistics of Throughput in Mbps $T = \frac{8\alpha}{0.5*10^6}$, where T is throughput, α is the number of bytes received, the unit is Mbps.	Number of packets reaches at their destination finally.

Descriptive analysis forms the basis of quantitative data analysis and helps in reviewing the variable behavior. The observation of the Mean Delay, (MAXIMUM (MAX), MINIMUM (MIN) and STANDARD DEVIATION (STDEV)) of Mean Delay have concluded the performance of the algorithm. The observations of throughput have revealed that the overall resources are utilized. The observations related to the MIN, MAX, STDEV of Mean Packet Loss Rate concludes the behavior of the network links in terms of capacity utilization and scaling up due to the congestion.

6.3.2 Study of Simulation Topology

The heterogeneous network topology has been implemented for simulation of the proposed algorithm. The parameters used to select the simulation factors are given in the Table 6.3. It includes traffic updates, traffic load, types of traffic and diverse characteristic of communication links.

Table 6.3: Selection of Simulation factors

S. No	Factor	Description
1.	Traffic updates	The changes in packet arrival model with time impacts the overall performance of network.
2.	Traffic load factor	The payload or the volume of the network impacts the working of network.
3.	Heterogeneous Propagation Delays	Due to the geographic distribution of network users, there will be different classes of delays. Assessing that impact is the objective.
4.	Heterogeneous Link Capacities	Assessing the effect of different link capacities on performance of a MPLS network.
5.	Data Streams, Video and Voice traffic	Change in data stream type leads to change in packet size. How does this change impact the network performance is the objective of this study.

The analysis of three traffic scenarios has been carried out. Three committed servers, one each for VoIP, Video streaming and Data application traffic have been considered. This assures proper validation of solutions of congestion control using traffic splitting. A comparison between classical approach OSPF and proposed FLCS has been conducted. *Katz D (2003)* defines in *RFC 3630* about the OSPF. The scenario composed of MPLS-TE together with constant bit rate (CBR). The dynamic route selection is done by FLCS approach. This arrangement of soft components demonstrates the improvements by using

FLCS for LSP selection. The decisions are taken by FLCS, which works in ingress node as demonstrated in chapter 1. The incoming request follows an exponential distribution and the requested bandwidth is uniformly distributed between ranges [0~10] (Mbps), [10~100] (Mbps), [100~1000] (Mbps) to model Voice, Data and Video Traffic respectively as described by *Adas A (1997)* and *Park K (2000)*. IPV4 network stack has been used and packets are generated using a hypothetical ON/OFF model with the Drop Tail Queue. Holding time is randomly distributed with a mean of 300 seconds (ON = 0.325 OFF = 0.64). It means that the system executes for every 0.325 seconds and then takes pause of 0.64 seconds and again restarts and continuously works so on.

Different traffic types are used in simulations. The data traffic has been simulated for File Transfer Protocol (FTP) over Transport Control Protocol (TCP). Voice and video traffic have been simulated over the User Datagram Protocol (UDP). The packet size of the UDP is 512 byte and 1024 byte for the TCP. The statistical comparison MAX, MIN and STDEV of FLCS and OSPF is depicted in next sections.

6.4 Simulation Framework for Three Scenarios

The Table 6.4 below shows the various combinations of parameters that make up the definition of the three scenarios. Table 6.4 depicts the information of topology for the Scenario I, II and III. Here, the impact of having diverse kinds of bandwidths Link Capacities and Propagation delay is intended to be investigated. The fuzzy intelligent algorithm evaluates large number of overlapping condition between the values of bandwidth and propagation delay, the bound of both variables for this case follows an expected curve.

Table 6.4: Simulation setup for three Scenarios

Scenario	Description of Scenario	Parameters used in Scenario
I	Heterogeneous Network link capacities in terms of High Bandwidth and Low Propagation delay	a) 10 Mbps, 3ms (Red) b) 100 Mbps, 2 ms (Green) c) 1000 Mbps, 1ms (Black)
II	Heterogeneous Network link capacities in terms of Lower Bandwidth and Higher Propagation delay	b) 10 Mbps, 10ms (Red) b) 100 Mbps, 5ms (Green) c) 500 Mbps, 3ms (Black)
III	Heterogeneous Network link capacities in terms of higher Bandwidth and Higher Propagation delay	a) 15 Mbps, 5ms (Red) b) 200 Mbps, 3 ms (Green) c) 1000 Mbps, 1ms (Black)

Following are the details obtained by running series of the experiments from the scenario I, II and III.

6.4.1 Scenario I

In this scenario, a topology with Heterogeneous Network link capacities in terms of High Bandwidth and Low Propagation delay has been deployed as shown in Figure 6.1. The traffic flow analysis from traffic sources to destination has been studied. The topology composed of 2 LERs (ingress, egress) and 6 LSRs with three different communication links. The Mean Delay and Mean Loss Rate of Video, Data and Voice traffic has been computed by varying traffic for 300 seconds. The delay values are accumulative in nature. This value typically depends on the interface/ hardware type, e.g. it is lower for Ethernet but higher for Serial interfaces. But, routing algorithm governing the network makes the real difference. The delay influences path selection keeping the bandwidth value constant. In this research work, the actual metric value for a prefix is derived from the sum of the delay values in the path and the lowest bandwidth value along the route. This is yet another reason to use this as a more predictive approach. The topology for this scenario as shown in Figure 6.1, Link capacities and propagation delays a) 10 Mbps, 3ms (Red) b) 100 Mbps, 2 ms (Green) c) 1000 Mbps, 1ms (Black)

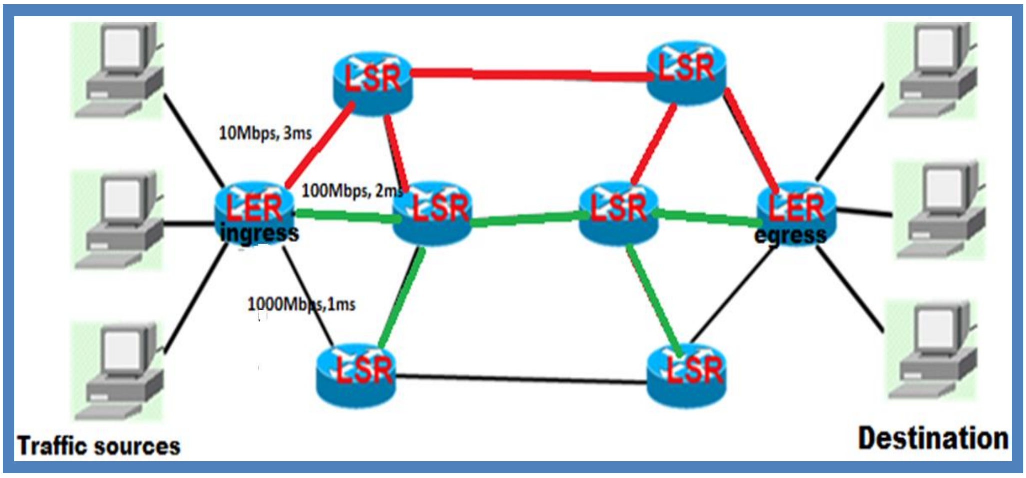

Figure 6.1: Link capacities and propagation delays for scenario I

Figure 6.2 (a), 6.2 (b) and 6.2(c) presents the results of Mean Delay for Video Traffic, Data Traffic and Voice Traffic respectively. From Figure 6.2 (a, b, c), it is comprehensible that FLCS has the contracted range of mean delay as compared to OSPF, which is an evidence that FLCS is numerically stable. The OSPF algorithm exhibits series of fluctuations with high amplitude that inevitably deteriorates performance of the network. It is apparent from the figures that, OSPF is making the network slower as its delay value is more. The value of OSPF and FLCS has difference in performance with respect to the delay. The variation of the values is lowest in case of FLCS; this has been attributed to the fact that it is steadier as compared to OSPF as it remains range bound with lowest standard deviation. The three types of traffic has been generated in topology, it is reflected that all packet types cannot be treated same as they produce different delay characterizations. It makes sense to implement simple Round Robin algorithm if there are equal cost path. But, normally this case is now not applicable as different links are having different qualities. As network has multiple types of packets flowing through it, so every packet would be considered separately. In case of data packets, the mean accumulated delay values are lower than the video packets and it seems that it is due to the smaller packet size. But, OSPF is making the network slower and FLCS has lower delay value under similar conditions.

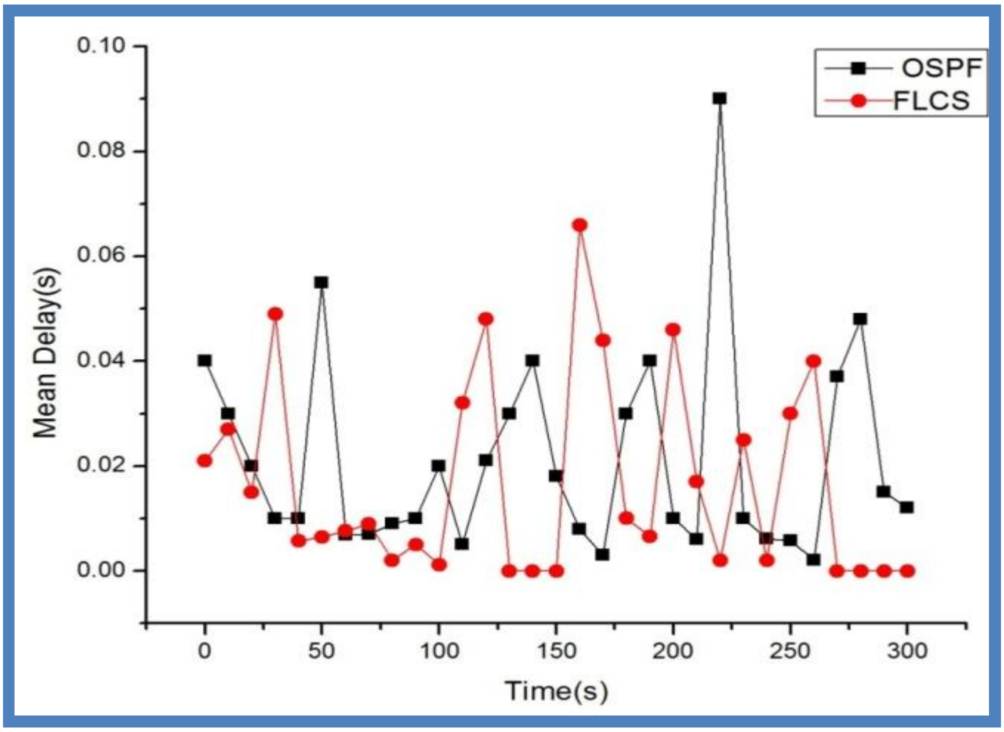

Figure 6.2(a): Variation of Mean delay(s) for Video Traffic with respect to time

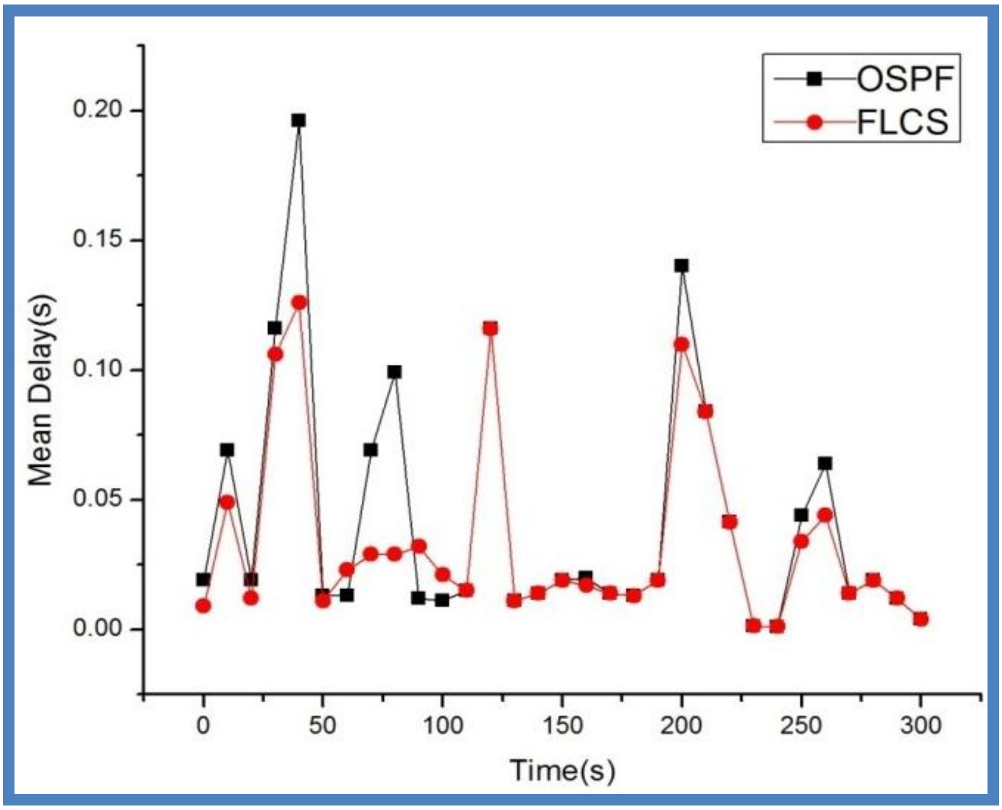

Figure 6.2(b): Variation of Mean delay(s) for Data Traffic with respect to time

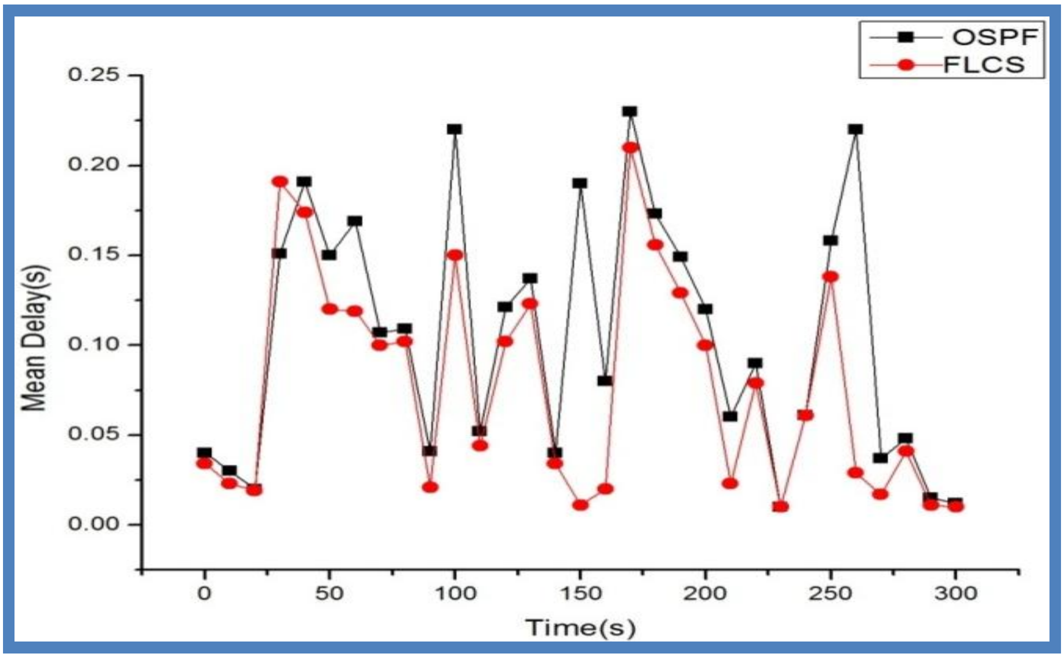

Figure 6.2(c): Variation of Mean delay(s) for Voice Traffic with respect to time

In case of voice packet based traffic, the trend continues to be similar to Video. OSPF has higher values of accumulated mean delay in successive 10 sessions. The overall observation indicates that, the FLCS compete with each other in terms of delay for all the cases. It is inferred that FLCS has been be commercially implemented and most extensively used in industry.

The Mean Loss Rate variation is studied and observed. It is reflected from the Figure 6.2 that FLCS acquires a superior performance with low packet loss rate. The results of Mean Loss Rate for different Traffic have been depicted in Figure 6.2 (d), 6.2 (e) and 6.2 (f) for traffic types Video, Data and Voice respectively.

It is clear from the graph depicted in Figure 6.2 (d) of Video Traffic, that the maximum Mean Loss occurs in OSPF. Implementation of the routing algorithm is appeared to be in narrow bound range in terms of variation. There is a greater degree of deviation in OSPF in terms of Mean Loss rate, this attributed to the fact that the Link Quality from various possible paths is unequal. It has been inferred that bigger size of packets makes the algorithm more sensitive towards changes. Hence, there is more variation. In case of data packet, the loss is highest in case of OSPF algorithm implementation. At same time, when the mean loss value of the OSPF is also comparable and is in close range to FLCS.

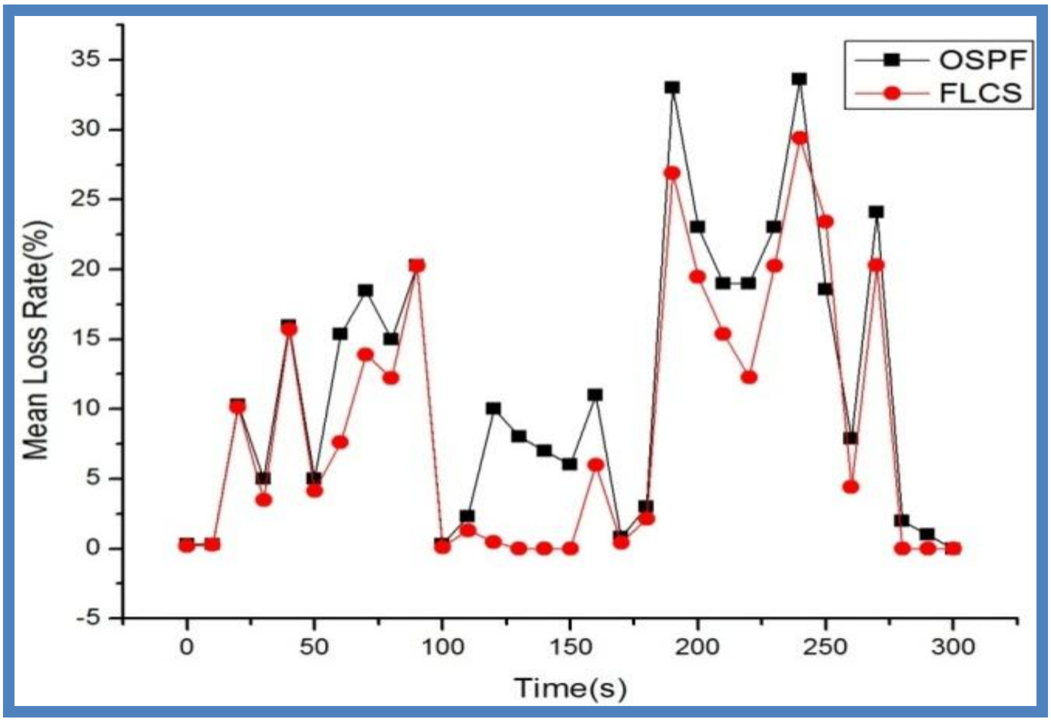

Figure 6.2(d): Variation of Mean Loss Rate (%) for Video Traffic with respect to time

Although it has been observed that the variation of two algorithms seems to be nearly same but the FLCS brings overall low loss of packets.

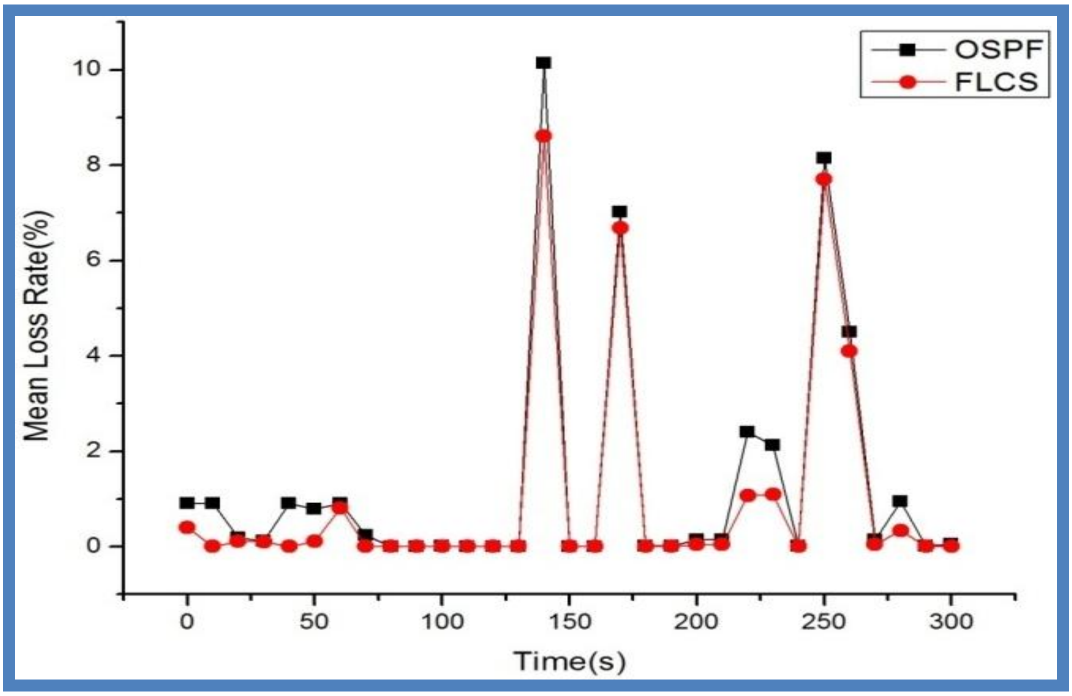

Figure 6.2(e): Variation of Mean Loss Rate (%) for Data Traffic with respect to time

The Mean Loss Rate (MLR) for Data and Voice Traffic is negligible at maximum instants as observed from figure 6.2(e) and 6.2(f).

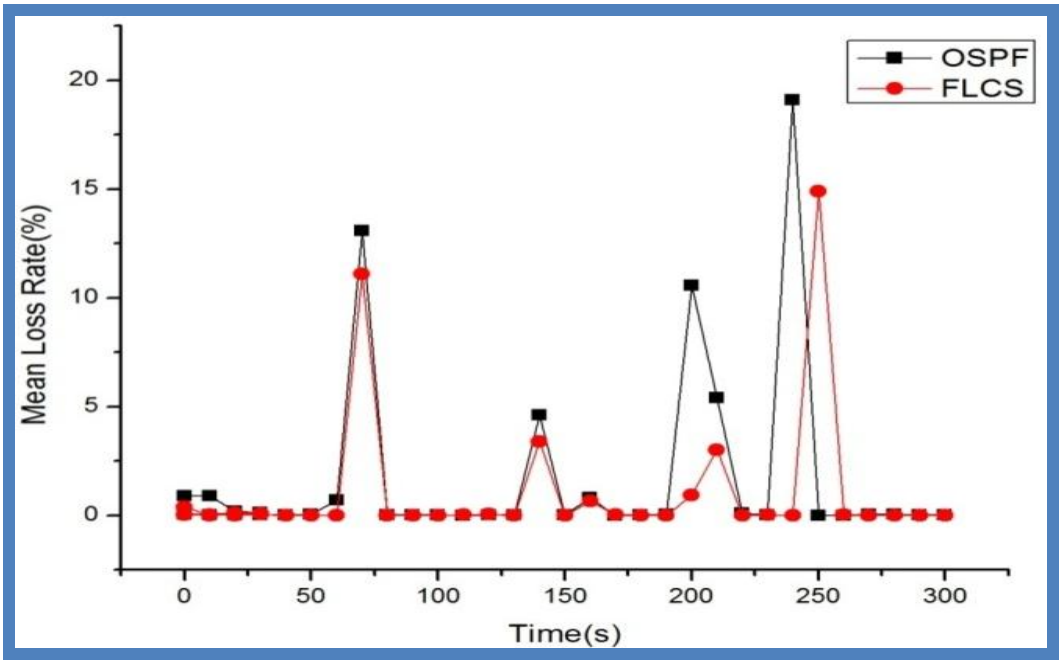

Figure 6.2(f): Variation of Mean Loss Rate (%) for Voice Traffic with respect to time

The FLCS encompasses better throughput and lower loss percentage and minor delay variations in TCP and UDP traffic as shown in Figure 6.3(a) and 6.3(b) respectively.

As compared to the results of OSPF and FLCS algorithm, OSPF shows more oscillations that result in degraded throughput and high variance of delays. Thus, it has revealed that this approach is based on shortest path due to which it gradually susceptible to the variations. Therefore, this aspect has been explored through simulation. FLCS achieves the highest utilization with small or no losses and lowest mean loss variation. The OSPF reflects poor performance as under traffic variation. It is attaining much lower throughput and larger delays. This has been be attributed to the fact that the developed intelligent algorithm FLCS is able to utilize the attributes of link/LSP of the network to build optimum routing decisions.

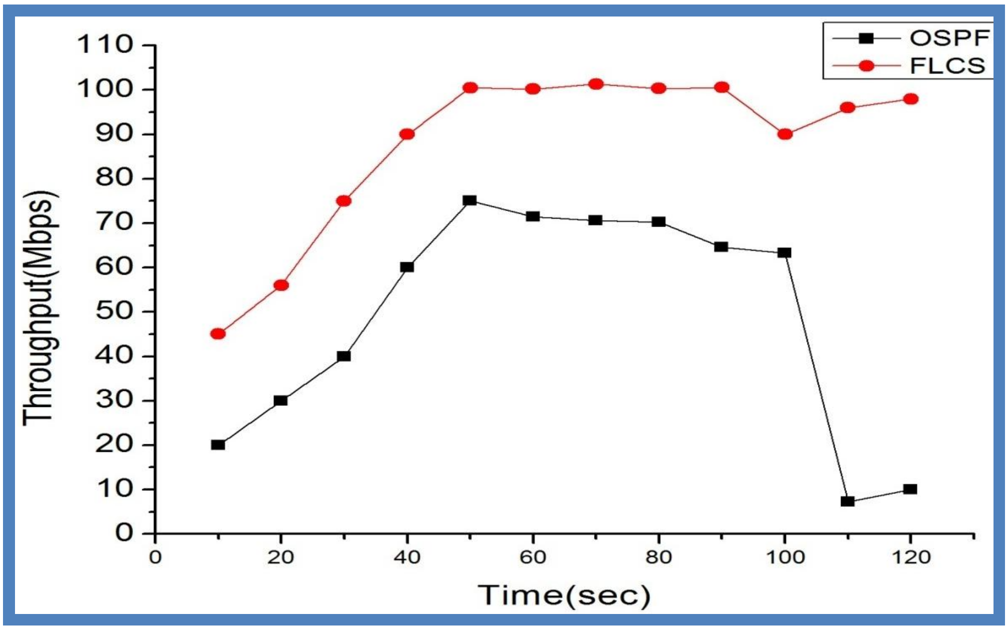

Figure 6.3(a): Variation of Throughput with TCP traffic

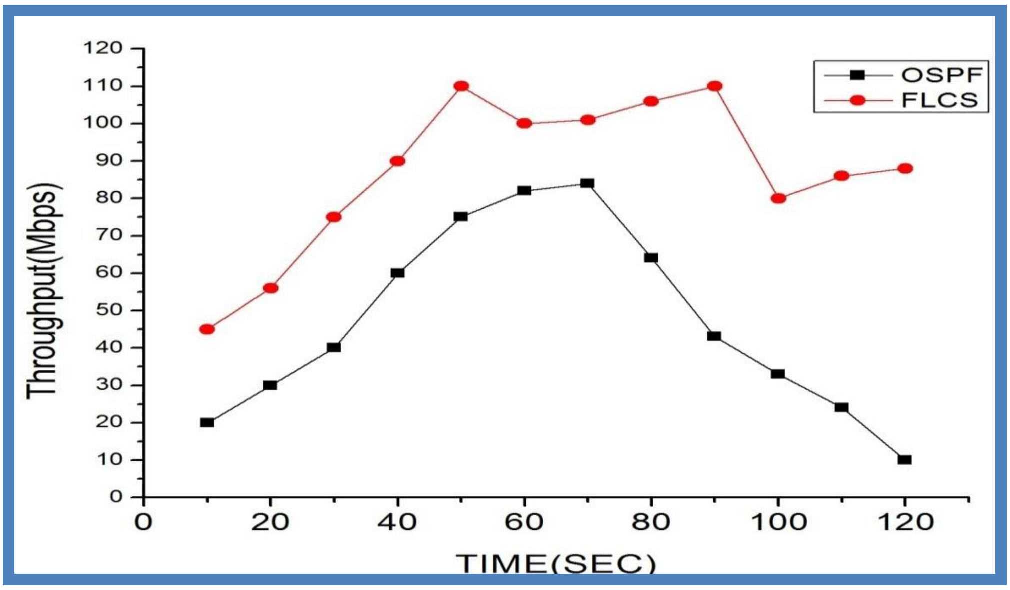

Figure 6.3(b): Variation of Throughput with UDP traffic

6.4.2 Interpretation and Results of Scenario I

The Table 6.5 presents the values of performance indicators (Mean Delay, Mean Loss Rate) for the scenario I. The two protocols, the existing OSPF and developed FLCS have been evaluated in terms of statistical analyzers MAX, MIN and STDEV of the values of performance parameters.

Table 6.5: Scenario I: Descriptive Statistical Analysis

Traffic Types		Video Traffic		Data Traffic		Voice Traffic	
Performance Parameter		**Mean Loss Rate**		**Mean Loss Rate**		**Mean Loss Rate**	
Protocol		**OSPF**	**FLCS**	**OSPF**	**FLCS**	**OSPF**	**FLCS**
Statistical Analyzers	MAX	**33.61001**	**29.41090**	**16.70110**	**8.60410**	**19.10010**	**14.90010**
	MIN	**0**	**0**	**0.00110**	**0.00110**	**0**	**0**
	STDEV	**9.66351**	**8.98499**	**2.95828**	**3.46701**	**4.50338**	**5.41680**
Performance Parameter		**Mean Delay**		**Mean Delay**		**Mean Delay**	
Protocol		**OSPF**	**FLCS**	**OSPF**	**FLCS**	**OSPF**	**FLCS**
Statistical Analyzers	MAX	**0.96660**	**0.40044**	**0**	**0.12610**	**0.25101**	**0.21091**
	MIN	**0**	**0**	**0.00010**	**0**	**0**	**0**
	STDEV	**0.019397**	**0.01888**	**0.04777**	**0.399**	**0.07077**	**0.82869**

The table contains descriptive statistical analysis of all these performance factors. It is apparent from these values that FLCS, as an intelligent system is a better choice for MPLS based network. The concluded results of the scenario I from Table 6.5 are as follows:-

The FLCS exhibits improvements in the terms of mean delay (42.0%) and mean loss rate (2.4%) for Video Traffic, mean delay (5.4 %) and mean loss rate (3.4%) for Data Traffic and mean delay (44.9 %) and Mean Loss Rate (4.1 %) for Voice Traffic. Moreover, 42 %, 15.4 % and 44.4 % of Video packets, Data packets and Voice packets respectively are crashed due to buffer overflow at the congested node when using OSPF. The FLCS algorithm on the other hand maintains the traffic delivery performance. This is achieved by distributing the traffic over suitable preferable paths and maintaining low queue lengths, all the packets are successfully delivered.

6.4.3 Scenario II

In this scenario, a topology with Heterogeneous Network link capacities in terms of Lower Bandwidth and Higher Propagation delay has been implemented. The range of propagation of delay and bandwidth reflect the vibrant conditions in which the medium values of bandwidth and mid-range values of propagation delay are investigated. Video, Data and Voice traffic are based on the normal distribution.

The Mean Delay and Mean Loss Rate of Video, Data and Voice traffic is displayed, which is obtained by varying traffic for 300 seconds. The topology for this scenario as shown in Figure 6.4. Link capacities and propagation delays are (a) 10 Mbps, 10ms (Red) (b) 100 Mbps, 5 ms (Green) (c) 500 Mbps, 3ms (Black).

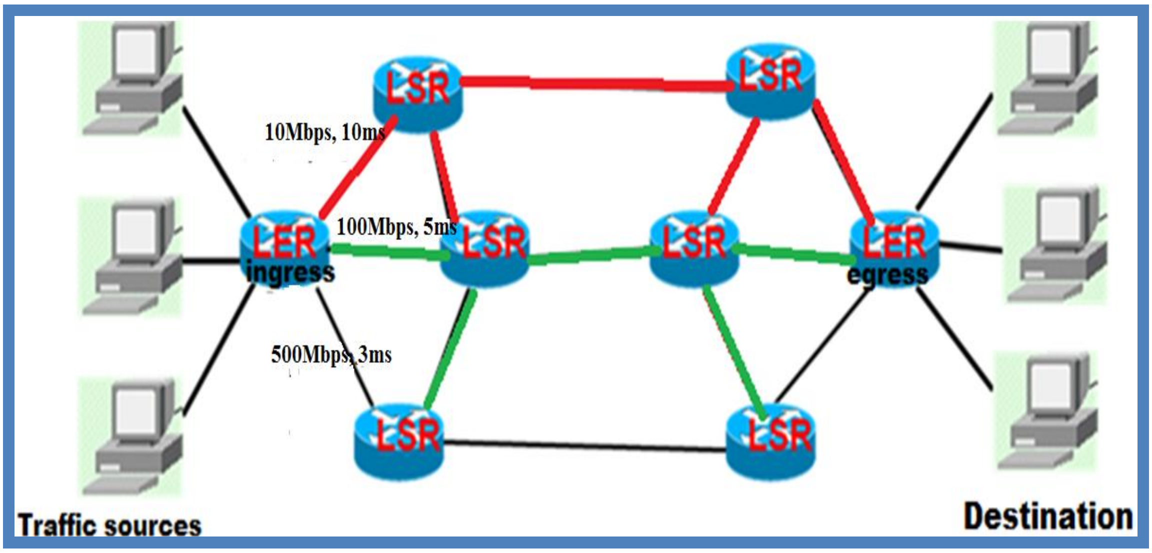

Figure 6.4: Link capacities and propagation delays for scenario II

This has been endorsed from Figure 6.5 (a, b, c), that it is apparent about FLCS that it has a fine range of Mean delay as compared to OSPF. But, at very few instances it has been observed that Mean Delay of FLCS is rising but it falls sharply when the intelligent controller performs its task of congestion control by selecting appropriate paths with less delay and lower utilization rate. The maximum value of mean delay for this scenario is 0.19 second, it is observed in the case of data traffic on the working of OSPF algorithm. The variation is less due to the fact, that OSPF is the protocol that uses the concept of Single Autonomous Units to reduce the overhead in communication. It uses the link state information to take routing decisions based on the Shortest Path First (SPF). It uses different types of packets to get information on the link, which include the link – state request, update Acknowledgement and Advertisement for the communication over the network.

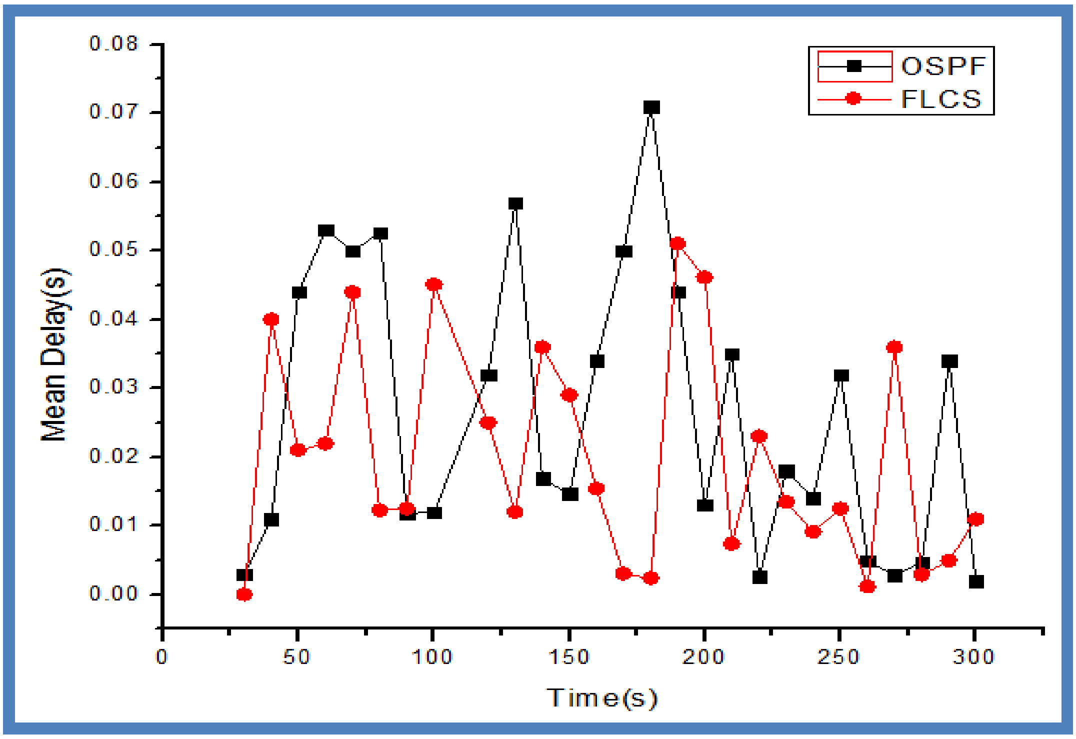

Figure 6.5(a): Variation of Mean delay(s) for Video Traffic with respect to time

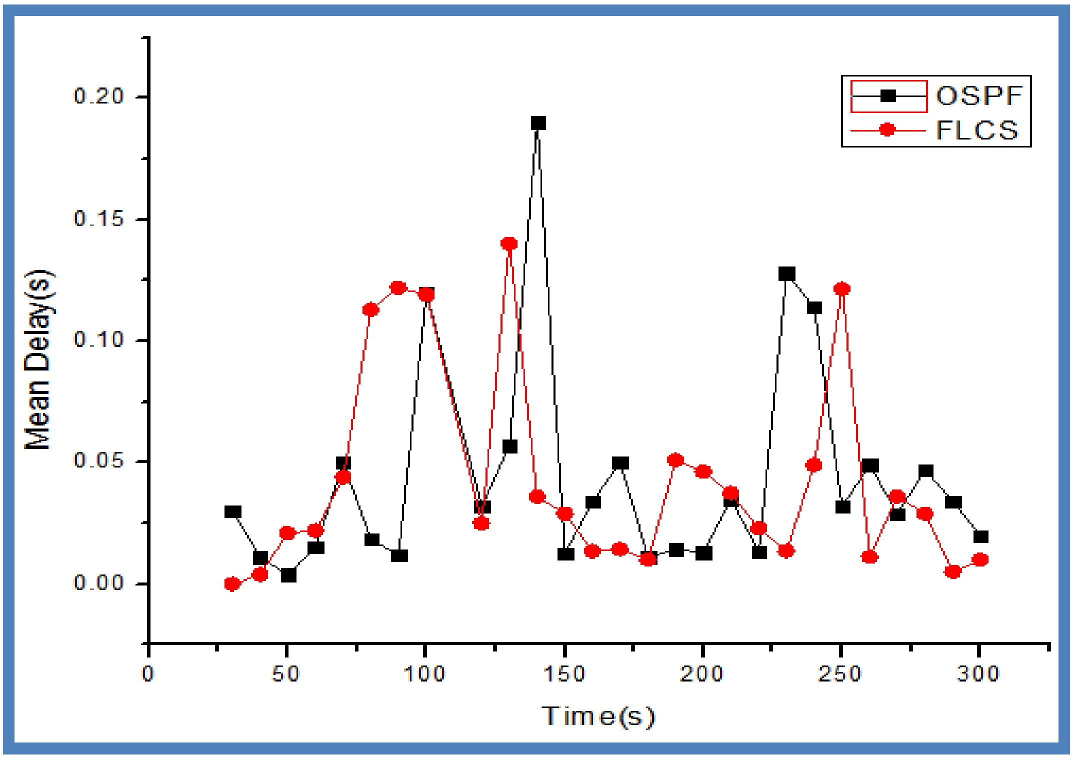

Figure 6.5(b): Variation of Mean delay(s) for Data Traffic with respect to time

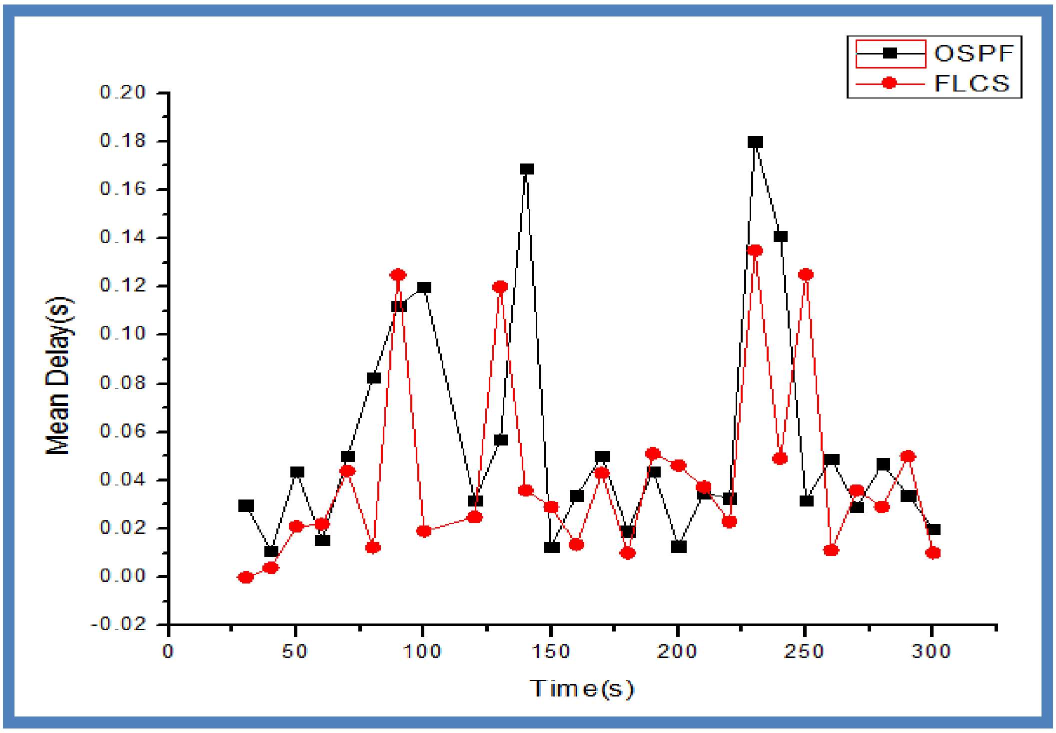

Figure 6.5(c): Variation of Mean delay(s) for Voice Traffic with respect to time

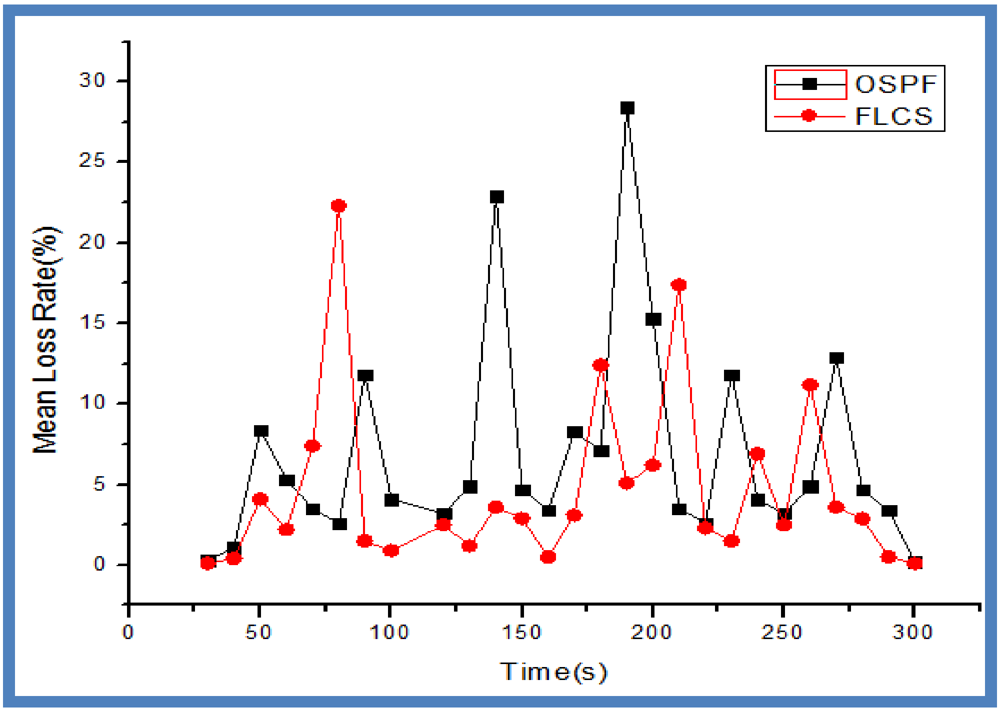

Figure 6.5(d): Variation of Mean Loss Rate (%) for Video Traffic with respect to time

The results of Mean Loss Rate for different traffic types are shown in Figure 6.5 (d, e, f). It has been observed that a better performance of FLCS with firmness is reflected in these figures are irrespective of the boost of traffic fluctuations. It has been revealed that it is due to fuzzy intelligent approach that causes maximum resource utilization of existing network.

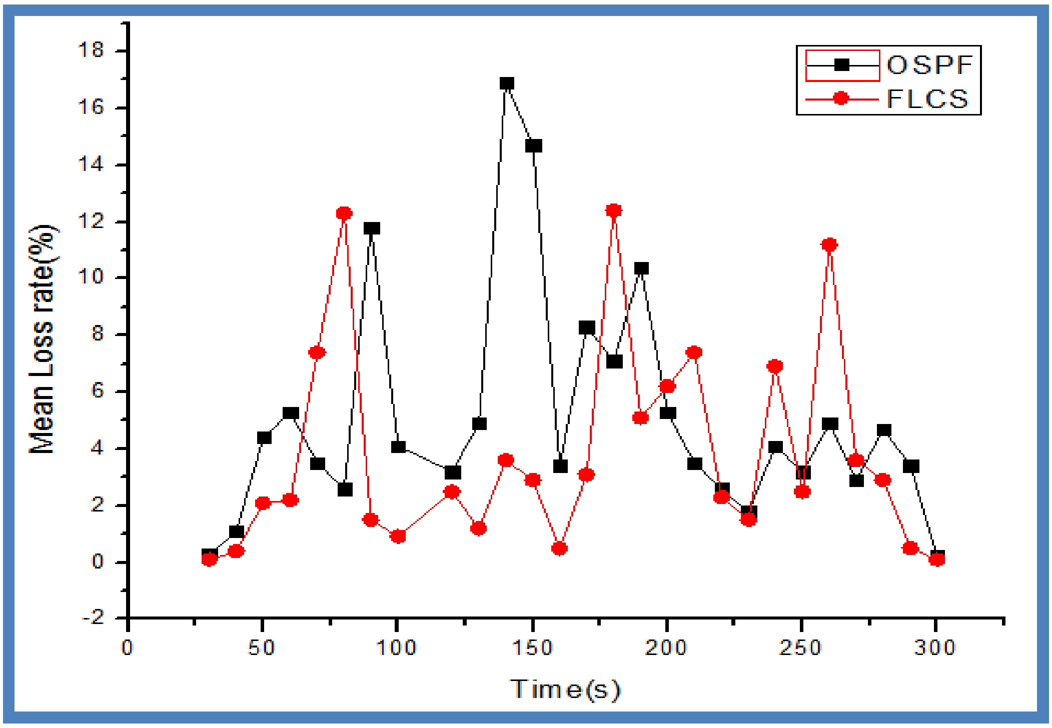

Figure 6.5(e): Variation of Mean Loss Rate (%) for Data Traffic with respect to time

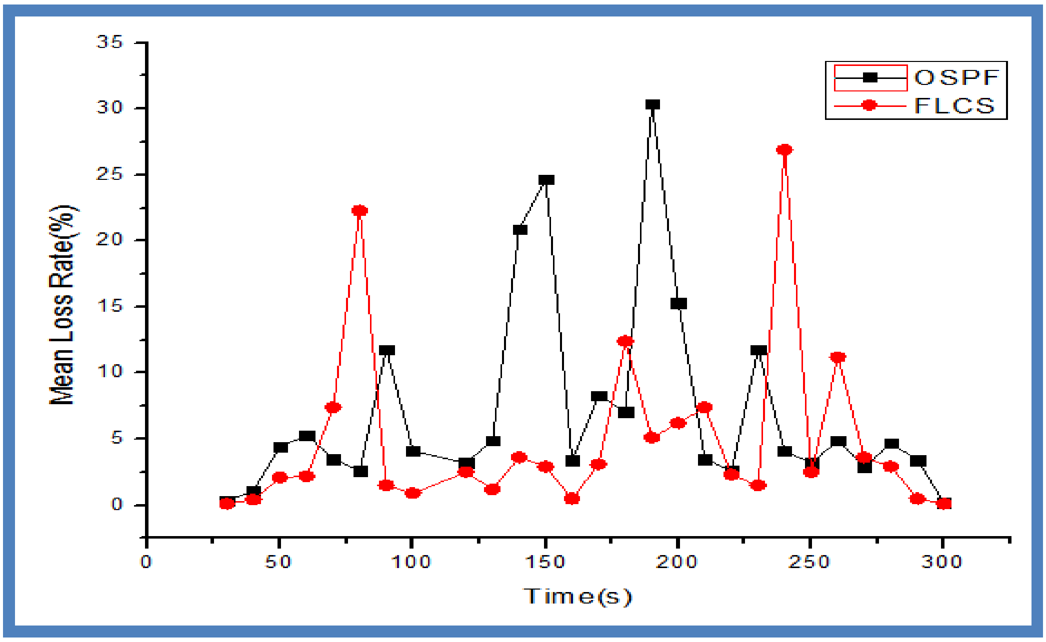

Figure 6.5(f): Variation of Mean Loss Rate (%) for Voice Traffic with respect to time

Following figure 6.6 (a) and figure 6.6 (b) are presenting the throughput for UDP and TCP traffic respectively. This aspect has been studied to analyze the effect in variant traffics.

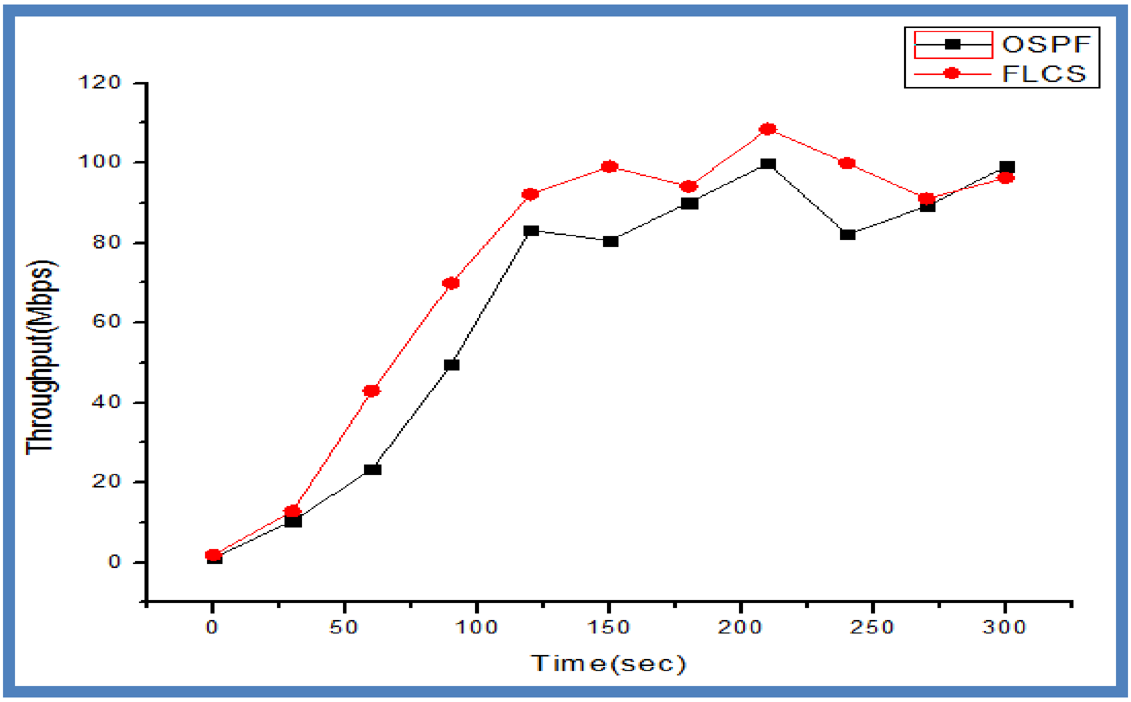

Figure 6.6(a): Variation of Throughput with UDP traffic

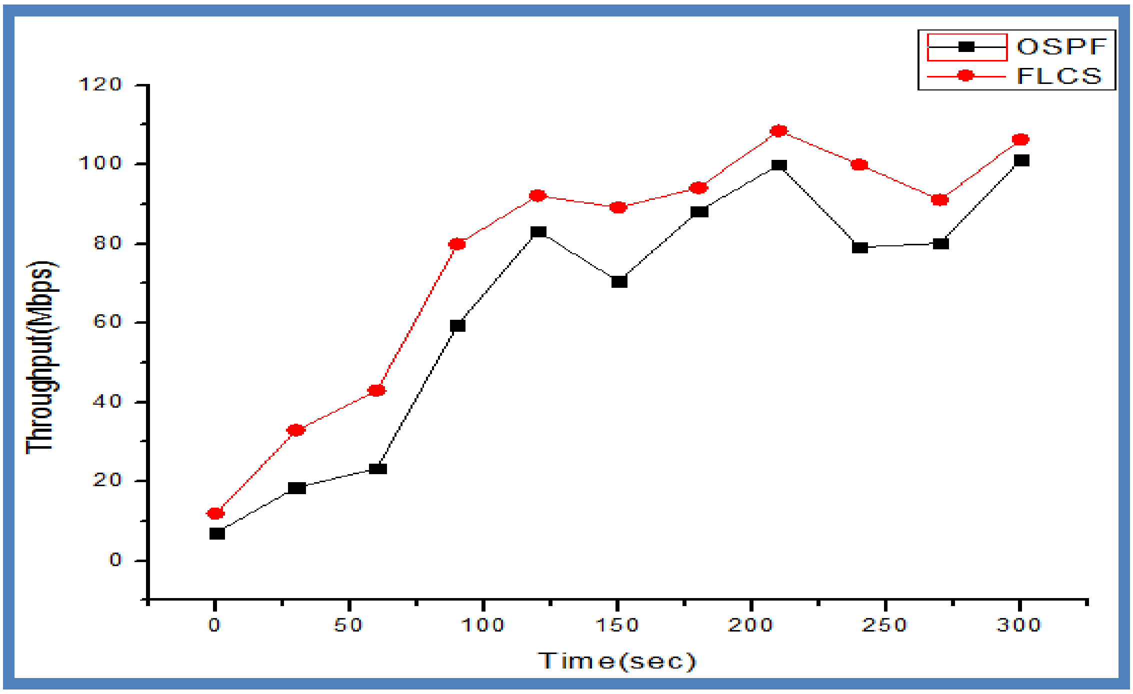

Figure 6.6(b): Variation of Throughput with UDP traffic

FLCS has the higher throughput with lower loss percentage and smaller delay variations. The OSPF algorithm shows vast fluctuations which leads to ruined throughput and high variance of delays.

6.4.4 Interpretation and Results of scenario II

The Table 6.6 presents the values of performance indicators (Mean Delay, Mean Loss Rate) for the scenario II. It is apparent from these values that FLCS is a better option for MPLS based network. FLCS achieves the highest utilization with small or no losses and lowest mean loss variation. The OSPF reflects poor performance under traffic variation. It is achieving much lower throughput and larger delays.

Table 6.6: Scenario II: Descriptive Statistical Analysis

Traffic Types		Video Traffic		Data Traffic		Voice Traffic	
Performance Parameter		Mean Loss Rate		Mean Loss Rate		Mean Loss Rate	
Protocol		OSPF	FLCS	OSPF	FLCS	OSPF	FLCS
Statistical Analyzers	MAX	28.40012	22.30031	16.9	11.20091	28.20345	26.20230
	MIN	0.20001	0.10054	0.01006	0.01004	0.50001	0.10120
	STDEV	6.642134	5.419996	4.49900	3.63732	8.10830	6.61505
Performance Parameter		Mean Delay		Mean Delay		Mean Delay	
Protocol		OSPF	FLCS	OSPF	FLCS	OSPF	FLCS
Statistical Analyzers	MAX	0.071010	0.051001	0.19021	0.14012	0.18031	0.19101
	MIN	0.00301	0	0.00405	0	0.01102	0
	STDEV	0.017668	0.02044	0.044267	0.041761	0.04738	0.04500

As shown in the above Table 6.6, the descriptive results in terms of MAX, MIN, STDEV of performances parameters have been computed. The FLCS in the terms of Mean Delay reduced by (0.002 %) and Mean Loss Rate improved by (6.1 %) for Video Traffic is improved. Mean Delay by (5.4 %) and Mean Loss Rate by (5.7 %) for Data Traffic. Mean delay increased by (0.001 %) and Mean Loss Rate improved by (2.0 %) for Voice Traffic. However, the FLCS algorithm performs very well in terms of Mean Loss Rate but for few instants it causes a small bit of delay. But, it is not much significant and packets are successfully delivered. For few seconds in these scenarios, the algorithm OSPF outperforms due to low queuing delay. Even though FLCS utilizes multiple paths and it leads to less delay for the said congested path.

6.4.5 Scenario III

In the scenario III, a topology with Heterogeneous Network link capacities in terms of higher Bandwidth and Higher Propagation delay has also been deployed, as shown in Figure 6.7. The range of propagation of delay and bandwidth reflect the fuzzy condition in which the lower values of bandwidth and high range values of propagation delay are investigated. In this case also, Video Data and Voice traffic with traffic shape based on the normal distribution has been considered. Link capacities and propagation delays a) 15 Mbps, 5ms (Red) b) 200 Mbps, 3ms (Green) c) 1000 Mbps, 1ms (Black)

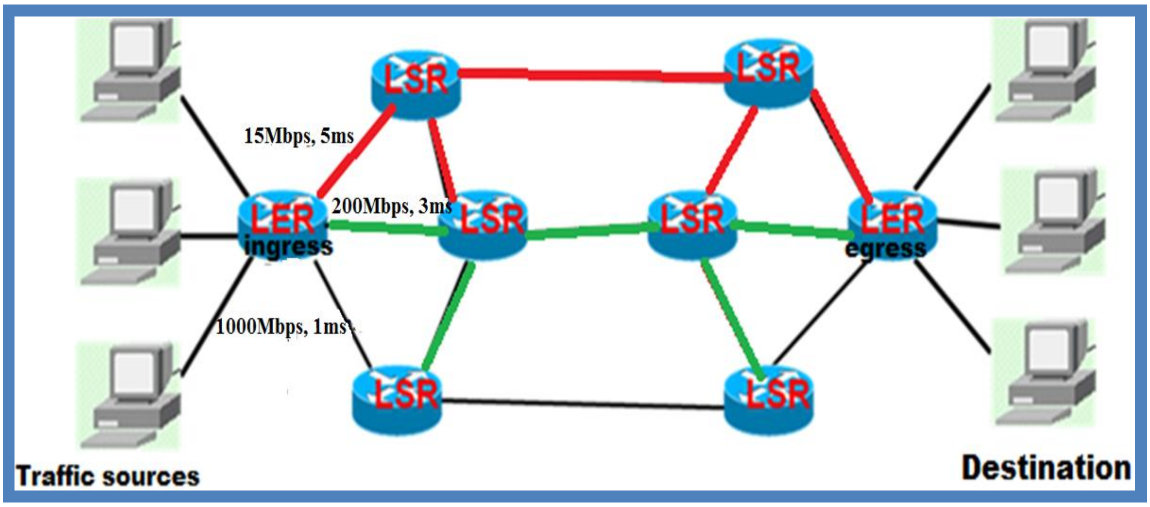

Figure 6.7: Link capacities and propagation delays for scenario III

This is attributed to the fact that the proposed algorithm reflects the true strength of the network links. If the average delay for a particular path is coming high, the delay factor impacts the routing path calculations. Figure 6.8(a, b, c) exhibits the Mean Delay variation for different traffic types Video, Data and Voice respectively. Figure 6.8 (d, e, f) displays the Mean Loss Rate variation for traffic types Video, Data and Voice respectively. The mean delay of OSPF at maximum instants is higher than FLCS.

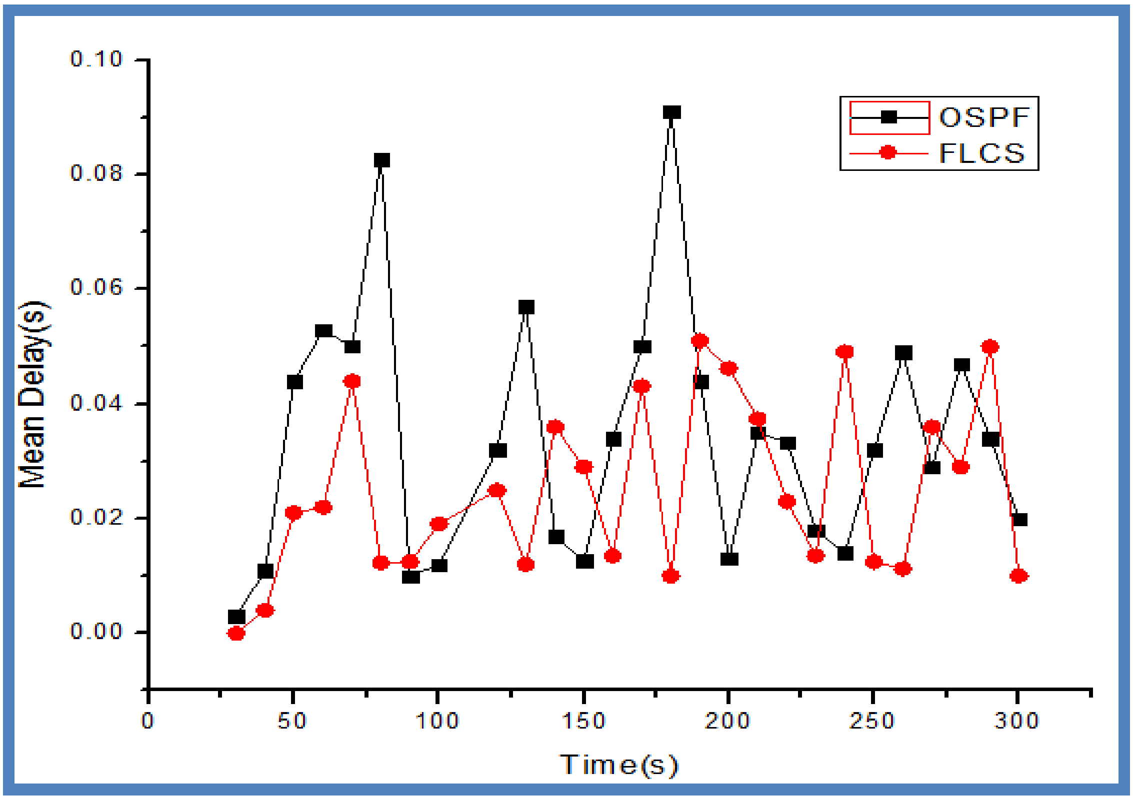

Figure 6.8(a): Mean delay(s) for Video Traffic with respect to time

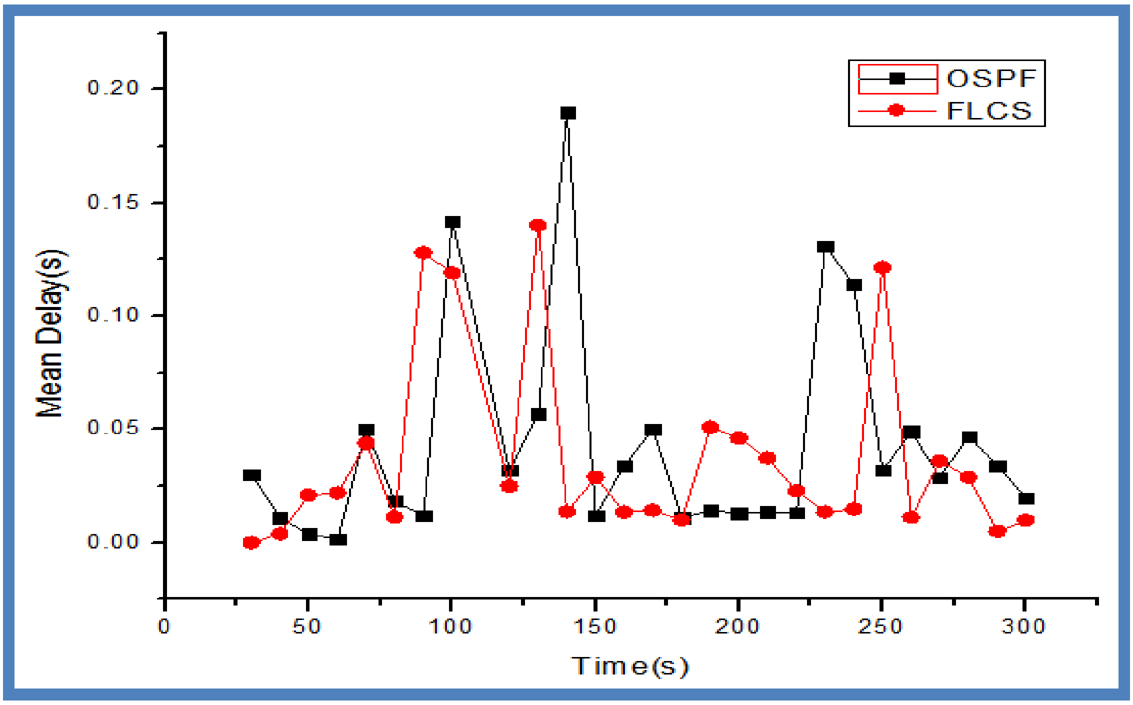

Figure 6.8(b): Mean delay(s) for Data Traffic with respect to time

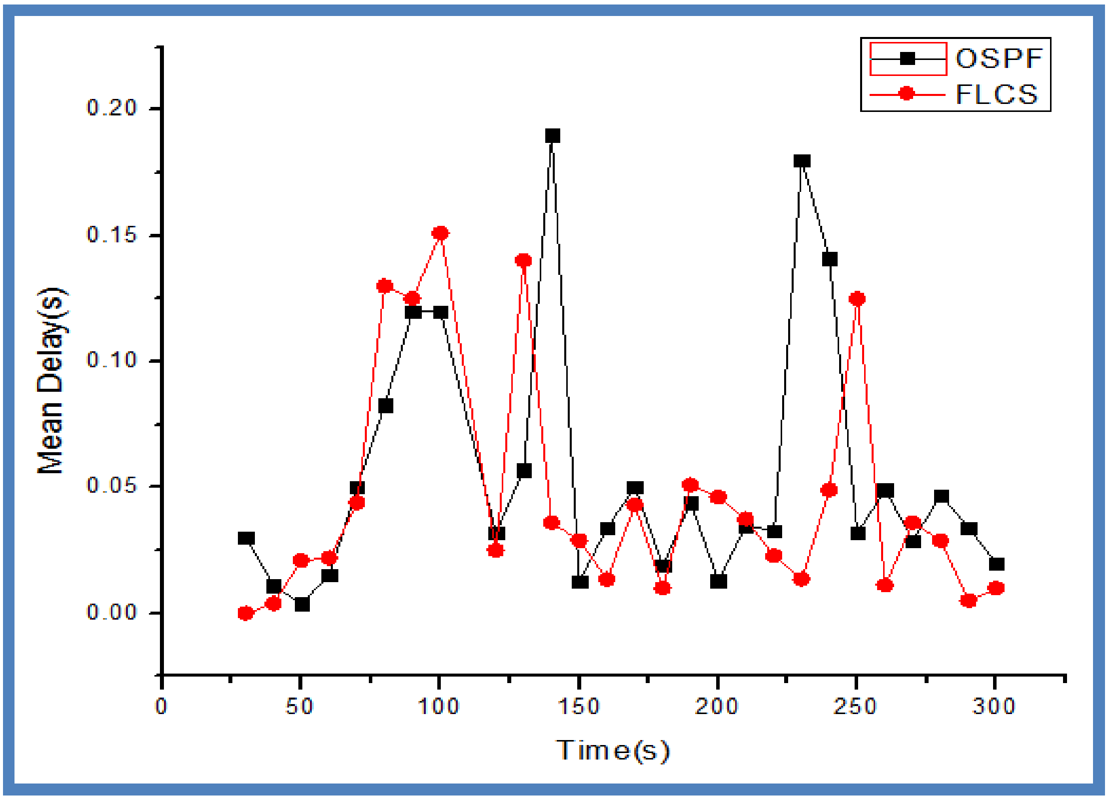

Figure 6.8(c): Mean delay(s) for Voice Traffic with respect to time

It is obvious that FLCS has the weak range of variance delay as compared to OSPF. It due to excessive traffic fluctuations the mean delay seems to be higher than OSPF at some particular instances. Well, it does not deteriorate performance of the network. But, in the case of OSPF it effects for a certain interval. Since, the simulator is discrete event driven, experimented with time varying values. The results of Mean Loss Rate for different traffic types are shown in Figure 6.8 (d, e, f).

In case of voice traffic, again the highest percentage of loss is in OSPF. Hence, looking at all the cases and metric value of Mean Loss Rate and Mean Delay, it is concluded that the performance of OSPF algorithm is not suitable. It infers that a link with the highest load may not be the link with the lowest capacity and vice versa. The quality of network link is therefore, critical to the performance of the network. Therefore, there might be packet drop due to queue overflow or might be underutilized link. For few seconds in this scenario, the algorithm OSPF outperforms due to low queuing delay. Even though FLCS utilizes multiple paths and it leads to less delay for the said congested path.

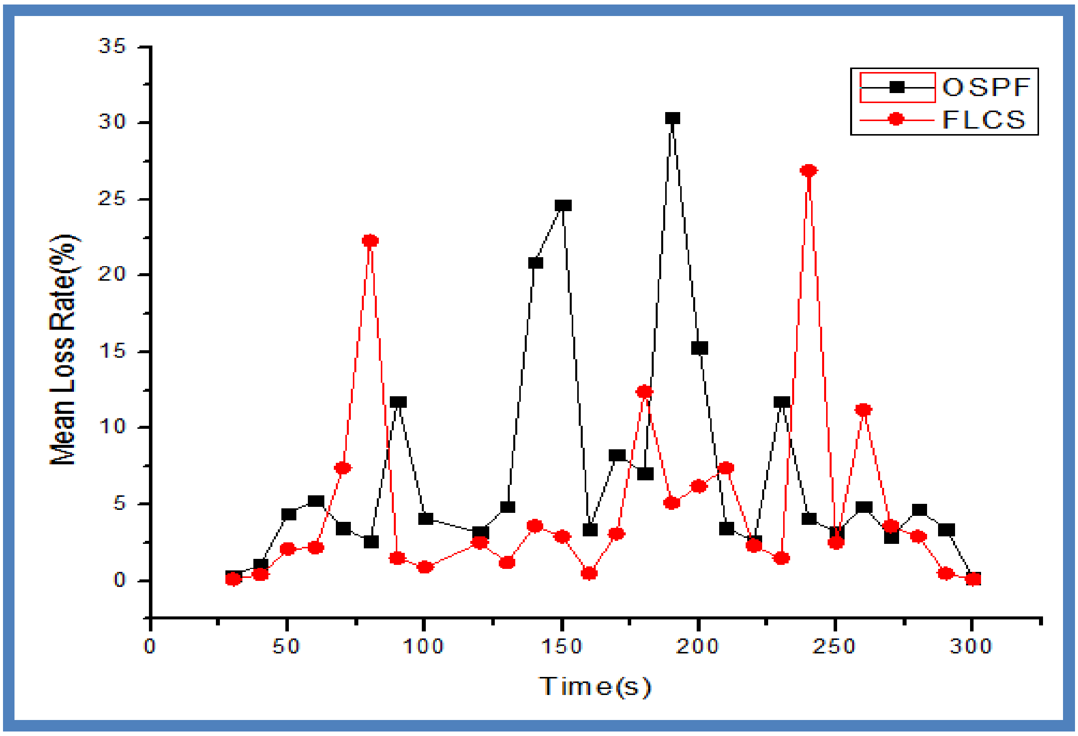

Figure 6.8(d): Mean Loss Rate (%) for Video Traffic with respect to time

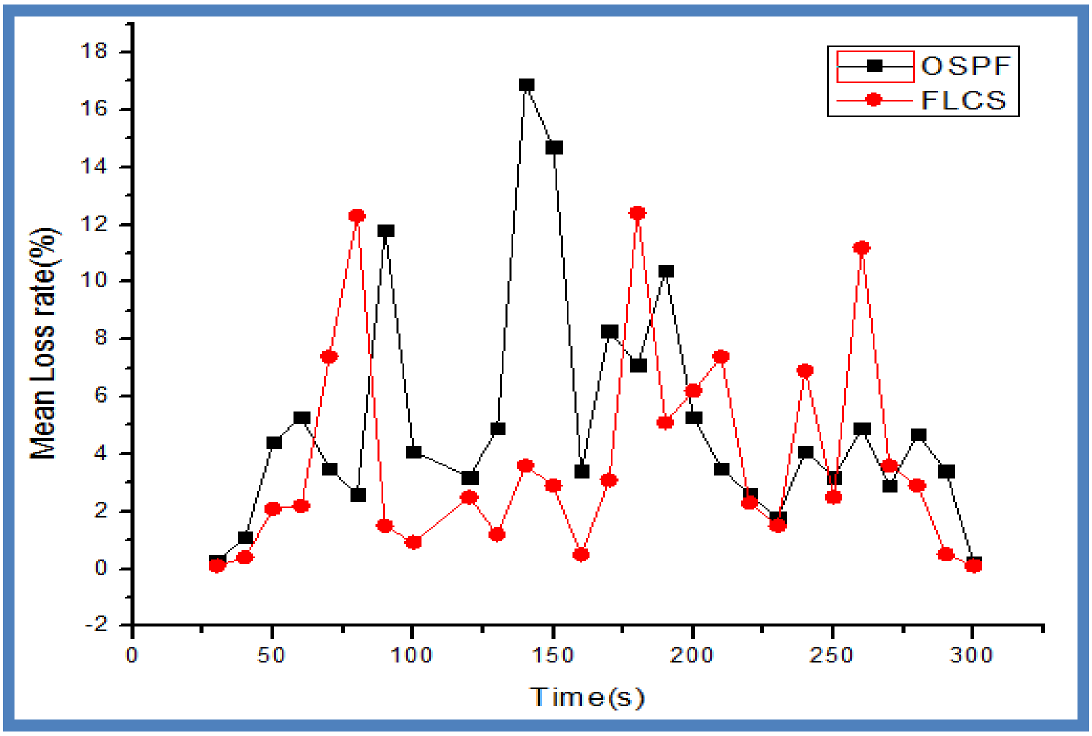

Figure 6.8(e): Mean Loss Rate (%) for Data Traffic with respect to time

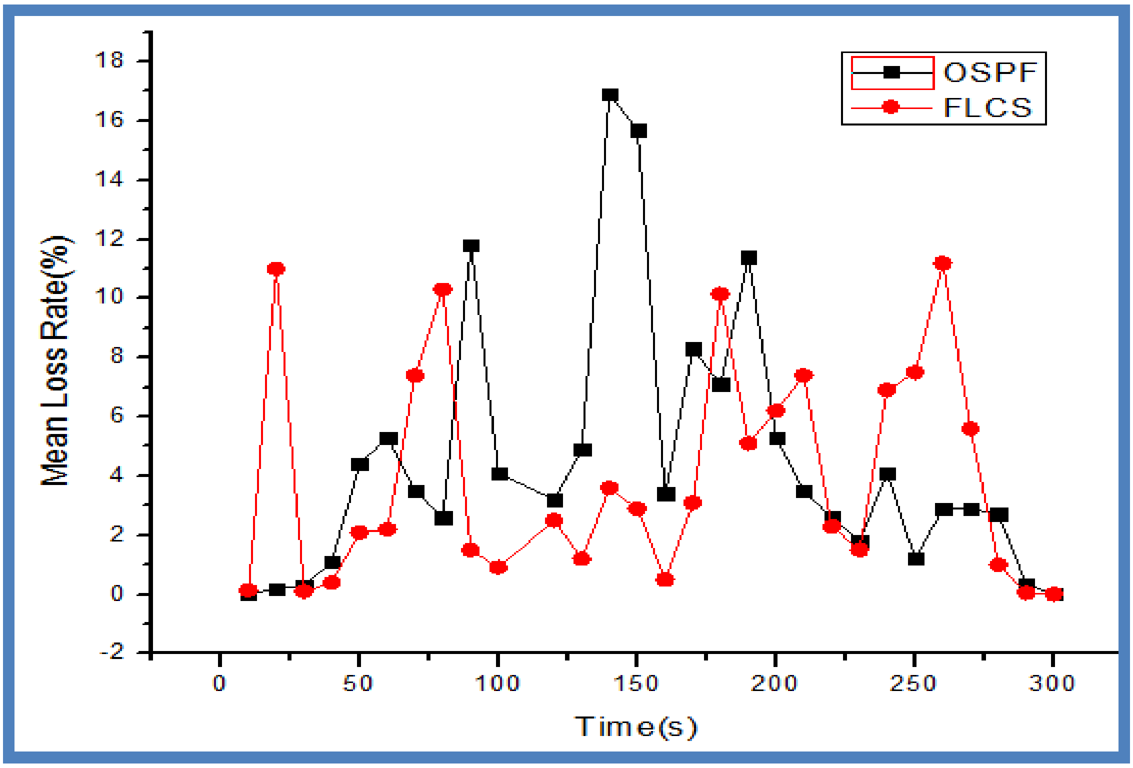

Figure 6.8(f): Mean Loss Rate (%) for Voice Traffic with respect to time

It has been observed that a superior performance of FLCS with stability is reflected from above these graphs depicted in Figure 6.8. The algorithm FLCS has the higher throughput as shown in Figure 6.9(a) for TCP Traffic and Figure 6.9 (b) for UDP Traffic. This is due to lower loss percentage and smaller delay variations during transmission.

During the traffic flow each protocol adds some extra information in the packets to address routing and controlling decisions. In this way the processing of packets cause additional overheads. Hence, there is always a need for correct throughput calculations to take such configurations into account. Following are the observations from the below Figure 6.9.

1. It is clear that in TCP flow, OSPF is helping in getting the higher level of capacity in terms of throughput.
2. A similar case arises when UDP is considered. It is clear that throughput is highest in case of UDP.
3. This metric basically depends on the Maximum Transmission Unit (MTU) size and Packet Loss Rate (PLR). The OSPF could not perform due to the fact that it has highest packet loss.

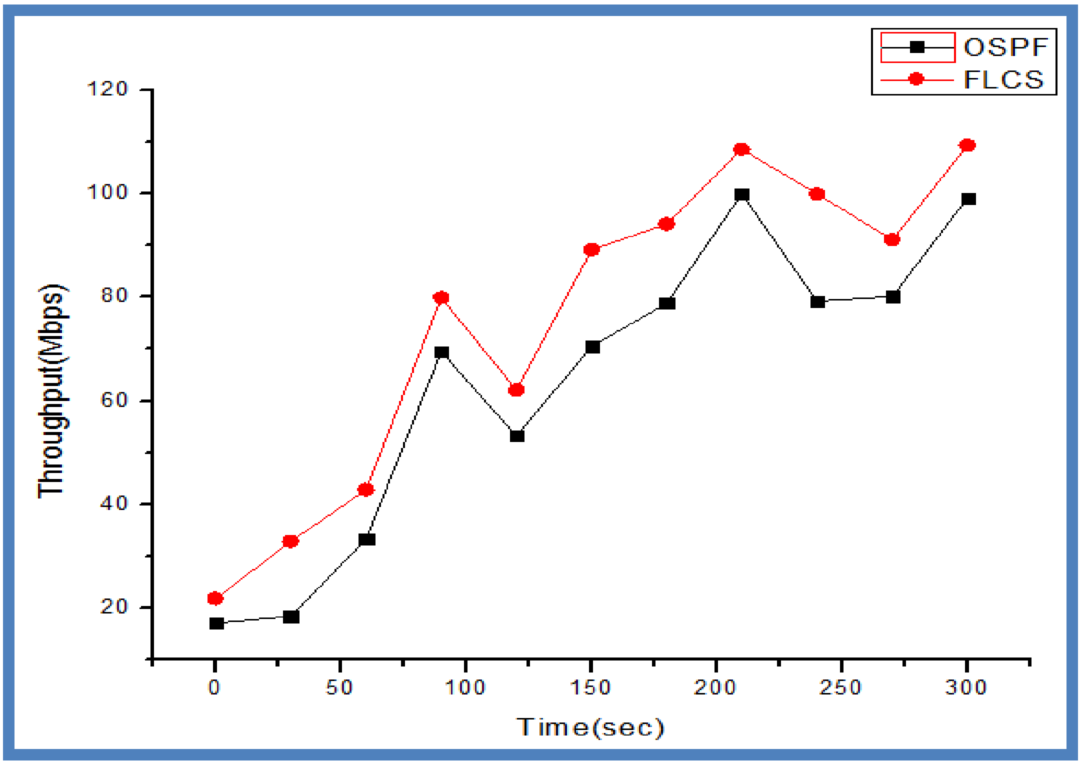

Figure 6.9(a): Variation of Throughput with TCP traffic

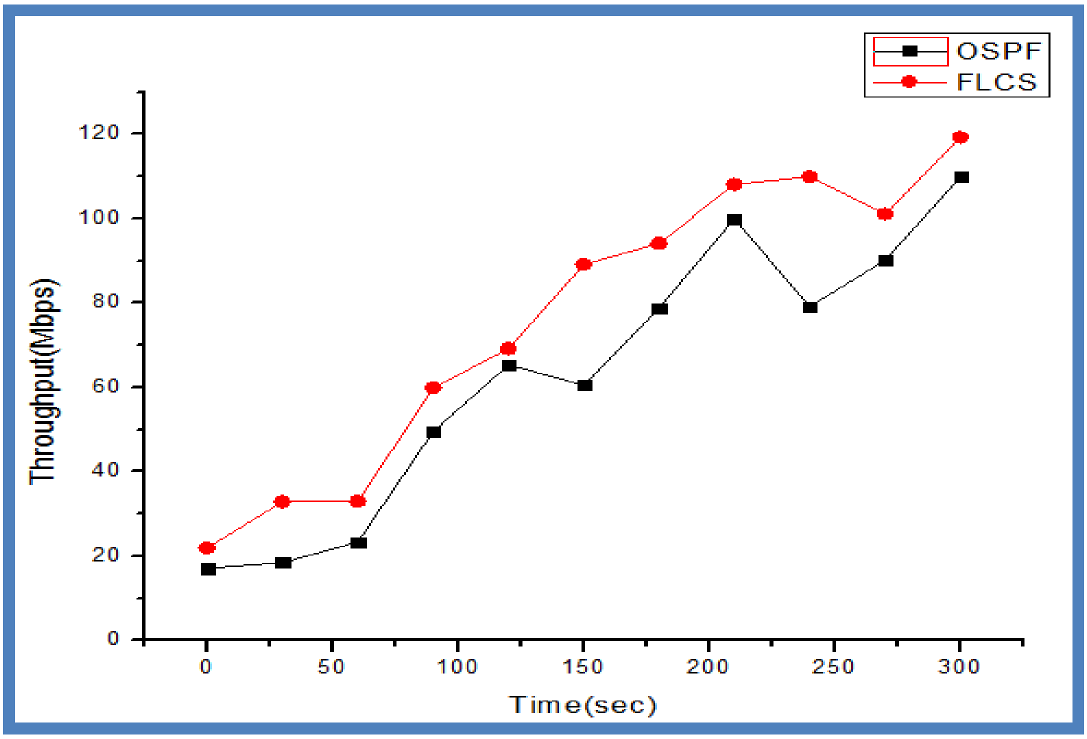

Figure 6.9(b): Variation of Throughput with UDP traffic

6.4.6 Interpretation and Results of Scenario III

The Table 6.7 holds the values of performance indicators (Mean Delay, Mean Loss Rate) for the scenario III. The table contains descriptive statistical analysis of all these performance factors. It is apparent from these values that FLCS is a better option for MPLS based network. FLCS achieves the highest utilization with small or no losses and lowest mean loss variation. The OSPF reflects poor performance under traffic variation. OSPF is achieving much lower throughput and larger delays.

Table 6.7: Scenario III: Descriptive Statistical Analysis

Traffic Types		**Video Traffic**		**Data Traffic**		**Voice Traffic**	
Performance Parameter		**Mean Loss Rate**		**Mean Loss Rate**		**Mean Loss Rate**	
Protocol		**OSPF**	**FLCS**	**OSPF**	**FLCS**	**OSPF**	**FLCS**
Statistical Analyzer	MAX	**30.40012**	**26.91001**	**12.70012**	**11.20012**	**16.90021**	**12.00012**
	MIN	**0.20010**	**0.10002**	**0.01000**	**0.01002**	**0.20001**	**0**
	STDEV	**7.52320**	**6.51001**	**3.54500**	**3.58838**	**4.50338**	**5.41680**
Performance Parameter		**Mean Delay**		**Mean Delay**		**Mean Delay**	
Protocol		**OSPF**	**FLCS**	**OSPF**	**FLCS**	**OSPF**	**FLCS**
Statistical Analyzer	MAX	**0.91001**	**0.051**	**0.19002**	**0.14001**	**0.19021**	**0.15101**
	MIN	**0.00300**	**0**	**0.00152**	**0**	**0.00400**	**0**
	STDEV	**0.02161**	**0.01530**	**0.04600**	**0.04001**	**0.05000**	**0.82869**

The FLCS exhibits improvements in the terms of Mean Delay by (0.859 %) and Mean Loss rate (3.49%) for Video Traffic. The Mean Delay by (0.05 %) and Mean Loss Rate by (1.5%) for Data Traffic are improved. Mean Delay is lowered by (0.039 %) but Mean Loss Rate by (4.9%) for Voice Traffic get improved. The FLCS algorithm maintains the traffic delivery performance. This is achieved by distributing the traffic over suitable preferable paths and maintaining low queue lengths, all the packets are successfully delivered.

6.5 Conclusion

It is concluded that fuzzy controller is able to map the real life traffic scenarios better as compared to the OSPF. This is advantageous due to Fuzzy mathematics. The FLCS algorithm outperforms due to the fact that it is able to find the membership of the fuzzy set of variables more accurately even when the conditions may have some overlapping or disjoint set values of the network traffic. The efficiency of algorithm, path selection mechanism is reflected in the mean packet loss percentage, which remain low as compared to the algorithm OSPF. FLCS has processed bounded Mean Delay, Mean Packet Loss with capability of working successfully in highly variable and uncertain traffic network. In nutshell, it is concluded that FLCS achieves improved robustness then OSPF. This has been attributed to the fact that FLCS is more receptive to the changes occurring in the network. The FLCS offers significant improvements in concession controlled by intelligent LSPs under varying operating conditions it is worth pointing out that the Inference Engine remains unchanged throughout. The maximum delay found in case of data packet traffic scenario is 0.19 seconds and minimum delay is 0 seconds, the maximum value belongs to OSPF and minimum to FLCS algorithm. The maximum delay found in case of voice packet traffic scenario is 0.25 seconds and minimum delay is 0 seconds. This is due to the fact that the basic logic of the OSPF is characterizing a route by a restrictive cost and an additive cost derived from the network link costs of the component links of the route or simply it is a routing algorithm that finds and stores all the possible optimal routes from said source node to all other nodes in the network. The packets in queue, have the lowest constructing cost metric value that is less than or equal to the maximum limiting cost acceptable by the network link and having the lowest additive cost. The maximum delay in case of video packet traffic scenario is 0.91 seconds and minimum delay is 0 seconds. The maximum value belongs to OSPF and minimum to FLCS algorithm. The basic idea is to route a request along the path that causes least "interference" to the next request for some other pair of ingress egress. If the link belongs to “minimum usage”, then the pair is marked as appropriate. The least weight is selected for establishing LSPs. The obtained results of simulation experiments are displayed in Table 6.5, 6.6, 6.7 and Figure 6.2, 6.3, 6.5, 6.6, 6.8 and 6.9 that give a better understanding of parameters investigated. These findings show that the fuzzy logic based traffic monitor is more efficient solution and constitutes a good alternative than other conventional methods of traffic engineering based on complex event optimization.

Chapter 7
Conclusion and Future Scope

7.1 Conclusion

Today, the variability of the data streams is high. So, there is a need for highly scalable infrastructure having high availability. This is not possible without inbuilt fault tolerance algorithms and highly effective traffic management components of the networks. The basic TE operand in MPLS consists of building E2E tunnels between the ingress and egress of the network. The use of dynamic load balancing methods to provide congestion free routing is also in practice. However, it has been empirically found that the next generation speed requirement is above 100 Gbps. The network metric computations become vague due to some basic problems. At higher speed the numerical computations of various metrics become numerically unstable. It refers to how a malformed input affects the execution of an algorithm.

The main aim of this research work is to analyze the behavior of MPLS network having a fuzzy traffic controller. This behavior analysis is followed by demonstrating an approach that is modeled in ns-3 simulator, estimating the capabilities of fuzzy controller. Analysis is carried out while focusing on the network strategies; delay, throughput and packet loss for their traffic classes Video, Data and Voice. The proposed strategy is suggesting multiple optimal mutually exclusive paths. This developed approach serves dual purpose. First, it recognizes multiple paths. Second, the traffic is distributed equally among those selected LSPs. TE regulates over multiple optimal links without much overhead. The novel strategy of fuzzy logic has been applied to execute traffic amongst the multiple LSPs arranged in the order of preference. In this respect, the work has been implemented by using combination of theoretical research and empirical experimentation stated by the review of the current state quo on MPLS and associated technologies. It has been examined that proposed MPLS network algorithm, FLCS supports traffic engineering. FLCS consists of two fuzzy controllers Label Switched Path System (LsS) and Traffic Splitting System (TSS). The validation of the fuzzy logic controller for checking the correctness of proposed scheme has been done by conducting simulated scenarios from real life indices solicited from industry and secondary literature sources. The solution provided in this work has proved that the system provides well organized Voice, Video packet flow transmission, traffic splitting, consistency in path selection and high degree of head to tail controlled connectivity. The proposed strategy is most suitable for packet switched networks. The strategy is adaptive and guarantees loop free routing as it is highly supported by the described routing algorithm. The system can smoothly run multiple logical traffic flows in the network, where heterogeneous physical links are present in terms of bandwidth, delay and demand from the user.

7.2 Future Scope

The MPLS technology is providing the platform for Software Defined Network (SDN) and Network Function Virtualization (NFV). Service Providers are using MPLS for the successful deploying of Cloud Computing. It is evident from industry resources that most of the companies are in process of adopting cloud or have already incorporated cloud based technology which primarily works on advantages of SDN. The proposed FLCS implemented in this research work supports similar level of real-time dynamics. On using SDN, the network services are no longer static in nature. The SDN controller dynamically optimizes network resource utilization, allocation and service placement.

Following are future directions that can enrich the current work:

1. The proposed Fuzzy Logic Controller work is based on the triangular shaped membership functions. A traffic composition having discrete intervals can also be represented by trapezoidal shape of membership. It would be more sensitive to the variations and offers more stable calculations for higher levels of Link Capacities. Computation related to jitter and Queuing delay also be conducted in future.
2. Other real world scenario, which consists of mix bag of old and new routers having legacy protocols and new network protocol stack need to be investigated for backward capability issues.
3. In present work, the scenarios having diverse classes of traffic running concurrently have been discussed. It would be interesting to note the findings of such network where the traffic classifier is not present.
4. The descriptive statistics method has been used to verify how the available resources can be optimized in order to guarantee service using fuzzy logic. For future research work, it is suggested that verification method also includes the finding of the correlation between the variables that impact the traffic conditions.

List of Publications by the Author

1. Anju Bhandari and V. P. Singh, "Proposal and Implementation of MPLS Fuzzy Traffic Monitor", International Journal of Advanced Computer Science and Applications (IJACSA), vol. 7(1), pp. 565-564, January, 2016.

   Journal's First volume was published in the year 2006. Impact factor-1.505.

   Indexed in (16):- "Thomson Reuters Emerging Sources Citation Index (2015)", ICI Journals Master List " INSPEC (IET)", "Directory of Open Access Journals (DOAJ)".

2. Anju Bhandari and V. P. Singh, "Congestion Control using Fuzzy Based LSPs in Multiprotocol Label Switching Networks", International Journal in Foundations of Computer Science & Technology (IJFCST), Academy and Industrial Research Collaboration Centre (AIRCC), ISSN:1839-7662, Vol. 6 (2), pp. 1-21, March, 2016.

   Journal's First volume was published in June 2010.

   Indexed in (13):- "CSEB", "EBSCO host databases", "getCITED", "ProQuest", "Google scholar", "ULRICHSWEB" , "PubZone", "Pubget", "WorldCat" ,"CiteSeer^x" , "Scribd", ".docstoc", "CNKI Scholar- SciencePG journals".

3. Anju Bhandari and V.P. Singh, "Design of Fuzzy-based Traffic Provisioning in Software Defined Network", International Journal of Information Technology and Computer Science (IJITCS), MECS Publisher, ISSN: 2074-9015, Vol. 8 (9), pp. 49-61, September, 2016.

   Journal's First online volume was published in June 2009, Global impact factor-0.716.

   Indexed in (17):- "CrossRef", "EBSCO host databases", "ProQuest", "Google scholar", "WorldCat", "CNKI Scholar- SciencePG journals", " INSPEC (IET)", "Directory of Open Access Journals(DOAJ)", "Index Copernicus (IC)", "Journal Seek", "ULRICHSWEB", "Scirus", "Academic Journals Database".

4. Anju Bhandari and V.P. Singh "Applicability of Multi protocol switching Networks: survey" in International Conference on "Emerging Technologies" organized at NCCE, Israna, Vol. 1, pp- 399-408, 2014.

5. Anju Bhandari and V.P. Singh, "Proposal of Fuzzy-based Traffic Administration in Software Defined Network". (Communicated in Wireless Personal Communications, Springer).

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