Sudan University of Science and Technology

College of Graduate Studies

School of Electronics Engineering

Implementing Nayan Seth’s Dynamic Load Balancing Algorithm in Software-Defined Networks: A case study

تنفيد خوارزمية نايان سيث لموازنة الحمل الديناميكية في الشبكات المعرفة برمجياً: دراسة حالة

A research submitted in partial fulfillment for the requirements of the M.Sc. degree in Computer and Network Engineering.

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بسم الله الرحمن الرحيم

قال تعالى:

﴿إِنْ أُرِيدُ إِلَّا الْإِصْلَاحَ مَا اسْتَطَعْتُ
وَمَا تَوْفِيقِي إِلَّا بِاللَّهِ عَلَيْهِ تَوَكَّلْتُ وَإِلَيْهِ أُنِيبُ﴾

صدق الله العظيم

سورة هود

الآية ٨٨

Dedication

To my PARENTS, TEACHERS, COLLEAGUES,

and of course to my BELOVED COUNTRY.

Acknowledgements

I would like to dedicate special thanks to my supervisor **Dr. Ahmed Abdullah** for sharing his expert knowledge within the domain and for his continuous help and support along the way. Thanks to him, not only for his help in general but also for his trust and guidance during the revision process.

I would also like to express my appreciation and gratitude to **Dr. Sami H. Salih** who, through his ideas, suggestions and advice improved this research.

My deepest thanks to all the staff in the School of Electronics Engineering and the College of Graduate Studies at Sudan University of Science and Technology, who, in many ways contributed in making this research a memorable and an enriching experience.

Finally, I thank my family, who constantly supported and encouraged me throughout the course of my studies.

Abstract

Traditional networking architectures have many significant limitations that must be overcome to meet modern IT requirements. To overcome these limitations; Software Defined Networking (SDN) is taking place as the new networking approach. One of the major issues of traditional networks is that they use static switches that cause poor utilization of the network resources. Another issue is the packet loss and delay in case of switch breakdown. This research proposes an implementation of a dynamic load balancing algorithm for SDN based data center network to overcome these issues. A test-bed has been implemented using Mininet software to emulate the network, and OpenDaylight platform (ODL) as SDN controller. Python programming language is used to define a fat-tree network topology and to write the load balancing algorithm program. Finally, iPerf is used to test network performance. The network was tested before and after running the load balancing algorithm. The testing focused on some of Quality of Service (QoS) parameters such as throughput, bandwidth, delay, jitter, and packet loss between two servers in the fat-tree network. The algorithm increased throughput with at least 32.3%, and improved network utilization. However, in large networks it increased mean jitter from 0.3736 ms to 3.2891 ms, and it increased packet loss by 4.9%.

المستخلص

تعاني بنية الشبكات التقليدية من محدودية وقصور يجب التغلب عليها لتلبية متطلبات تكنولوجيا المعلومات الحديثة. وللتغلب على هذه القيود أخذت تقنية الشبكات المعرفة برمجيا حيزا كبيرا من الإهتمام. أحد مشاكل الشبكات التقليدية أنها تستخدم المحولات الثابتة التي تؤدي لضعف استغلال موارد الشبكة، مشكلة أخرى هي فقدان وتأخر الحزم في حالة إنهيار المحول. يعرض هذا البحث تنفيذا لخوارزمية موازنة الحمل الديناميكية لشبكات مراكز البيانات المعرفة برمجيا، للتغلب على هذه المشاكل. تم إنشاء بيئة إختبار باستخدام برنامج المينينت لمحاكاة الشبكة، ومنصة أوبن ديلايت كمتحكم في الشبكة المعرفة برمجيا. استخدمت لغة بايثون في تعريف هيكل شبكة الشجرة المتفرعة ولكتابة برنامج خوارزمية موازنة الحمل الديناميكية. أخيرا استخدم برنامج ايبرف لإختبار أداء الشبكة. تم إختبار الشبكة قبل وبعد تطبيق خوارزمية موازنة الحمل. ركز الإختبار على بعض من عوامل جودة الخدمة مثل الإنتاجية، عرض النطاق، تأخر الحزم، تباين تأخر الحزم، وفقدان الحزم بين مخدمين في شبكة الشجرة المتفرعة. زادت الخوارزمية من الإنتاجية بنسبة لا تقل عن 32.3%، وحسنت من استغلال موارد الشبكة. ولكن في ما يتعلق بالشبكات الواسعة زادت الخوارزمية من متوسط تباين تأخر الحزم من 0.3736 ملي ثانية إلى 3.2891 ملي ثانية، كما زادت من فقدان الحزم بنسبة 4.9%.

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Abbreviations

ACL	Access Control List
API	Application program interface
BYOD	Bring Your Own Device
CAPEX	Capital Expenditure
CPU	Central Processing Unit
FSM	Finite State Machine
HPC	High-Performance Computing
ICMP	Internet Control Message Protocol
IP	Internet Protocol
IPv4	Internet Protocol version 4
IPv6	Internet Protocol version 6
IS-IS	Intermediate System to Intermediate System
IT	Information Technology
LAN	Local Area Network
LLB	Link Load Balancing
MAC	Media Access Control
MPLS	Multi-Protocol Label Switching
NE	Network Elements
ODL	OpenDaylight
ONF	Open Networking Foundation
OPEX	Operational Expenditure
OS	Operating System
OSPF	Open Shortest Path First
QoE	Quality Of Experience

QoS	Quality Of Service
SCTP	Stream Control Transmission Protocol
SDN	Software Defined Networking
TCL	Tool Command Language
TCP	Transmission Control Protocol
UDP	User Datagram Protocol

Chapter One

Introduction

Chapter One

Introduction

1.1. Preface

Traditional networking architectures have many significant limitations that must be overcome to meet modern IT requirements. To overcome these limitations; The Software Defined Networking (SDN) [1] is taking place as the new networking approach.

The traditional network system has the control plane and data plane together. Whereas the SDN approaches to build a computer network which separates and abstracts the network into control and data plane. The data plane does an operation of transferring the packets through the network. Unlike traditional networks, the underlying switches do not implement the control plane. The control plane with its intelligence are able to instruct the data planes over the network.

The control plane is a software or logical entity, which processes all the routing decisions taken by the data plane. Hence the network becomes directly programmable and agile [2].

OpenFlow is the most common protocol used in SDN networks which are used to communicate the controller with all the network elements (NE). It is an open standard that provides a standardized hook to allow researchers to run experiments, without requiring vendors to expose the internal workings of their network devices [2].

OpenFlow is often confused with the SDN concept itself, but they are different things. While SDN is the architecture dividing the layers, OpenFlow is just a protocol proposed to convey the messages from the control layer to the network elements. There is a bunch of OpenFlow based projects, including several controllers, virtualized switches and testing applications [2].

In order to increase available bandwidth, maximize throughput, and add redundancy; network load balancing must be used. Network load balancing is the ability to balance traffic across multiple Internet connections. This capability balances network sessions like Web, email, etc. over multiple connections in order to spread out the amount of bandwidth used by each LAN user, thus increasing the total amount of bandwidth available. Load balancing usually involves dedicated software or hardware, such as link load balancer.

Link load balancer, also called a link balancer, is a network appliance that distributes in-bound and out-bound traffic to and from multiple Internet links. Link load balancers are typically located between gateway routers and the firewall. Load balancing methods that are applicable to link load balancing (LLB) are round robin, destination IP hash, least bandwidth, and least packets.

1.2. Problem statement

There is a need for dynamic management of network resources for high performance and low latency of data transmission in a network.

Traditional networks use static switches. Issue with these networks is that each flow follows a single pre-defined path through the network. In case of switch breakdown, packets tend to drop until a different path is selected. Another issue is poor utilization of the network resources, where alternative links to the destination reside idle.

1.3. Proposed Solution

This research proposes a load balancer for SDN based data center networks. A dynamic load balancing algorithm is to be implemented in the SDN controller. The task of the algorithm is to distribute traffic of upcoming and incoming network flows in order to achieve the best possible resource utilization of each of the links present in a network.

1.4. Methodology

To assess the performance of the proposed scheme, the open-source OpenDaylight platform (ODL) is used as SDN controller, and the network is emulated using Mininet software. Objective measurement of throughput, delay and packet loss determines whether the chosen scheme provides better performance on the network.

1.5. Aims and Objectives

The aim of this research is to implement Nayan Seth's dynamic load balancing algorithm[19] in SDN-based data center networks in order to analyze the possibilities of achieving a better performance.

The objective of the research is to evaluate and validate the functionality of the proposed algorithm.

1.6. Thesis Outlines

The reminder of the document is organized in the following manner: Chapter Two provides background research relevant to SDN and Network Load Balancing. Chapter Three describes the methodology of the load balancing algorithms and presents the components used in this research to set the testbed. Chapter Four describes the proposed scenarios, and presents the results of the implementation. Chapter Five draw the conclusions and areas for future work.

Chapter Two

Literature Review

Chapter Two

Literature Review

2.1. Introduction

This chapter gives a general background and overview about the concept of Software Defined Networking, OpenFlow, Network Load Balancing, Interconnection networks, Dijkstra's algorithm; providing the information that must be taken into account in order to understand this research. Then is gives a brief summary about the literature review which have been taken into account in order to develop this research.

2.2. Traditional Networks Limitations

Traditional networking architectures have significant limitations that must be overcome to meet modern IT requirements. Today’s network must scale to accommodate increased workloads with greater agility, while also keeping costs at a minimum. Traditional approach has substantial limitations such as:

- **Complexity**: The abundance of networking protocols and features for specific use cases has greatly increased network complexity. Old technologies were often recycled as quick fixes to address new business requirements. Features tended to be vendor specific or were implemented through proprietary commands.
- **Inconsistent policies**: Security and quality-of-service (QoS) policies in current networks need to be manually configured or scripted across hundreds or thousands of network devices. This requirement makes policy changes extremely complicated for organizations to implement without

significant investment in scripting language skills or tools that can automate configuration changes. Manual configuration is prone to error and can lead to many hours of troubleshooting to discover which line of a security policy or access control list (ACL) was entered incorrectly on a given device. In addition, when applications were removed, it was almost impossible to remove all the associated policies from all the devices, further increasing complexity.

- **Inability to scale**: As application workloads change and demand for network bandwidth increases, the IT department either needs to be satisfied with an oversubscribed static network or needs to grow with the demands of the organization. Unfortunately, the majority of traditional networks are statically provisioned in such a way that increasing the number of endpoints, services, or bandwidth requires substantial planning and redesign of the network [3].

Traditional networking architectures are ill-suited to meet the requirements of today's enterprises, carriers, and end users. Thanks to a broad industry effort spearheaded by the Open Networking Foundation (ONF); SDN is transforming networking architecture [4].

2.3. Software-Defined Networking (SDN)

SDN is an emerging network architecture where network control is decoupled from forwarding and is directly programmable. This migration of control, formerly tightly bound in individual network devices, into accessible computing devices enables the underlying infrastructure to be abstracted for applications and network services, which can treat the network as a logical or virtual entity.

As a result, enterprises and carriers gain unprecedented programmability, automation, and network control, enabling them to build highly scalable, flexible networks that readily adapt to changing business needs [4].

SDN are controlled by software applications and SDN controllers rather than the traditional network management consoles and commands that required a lot of administrative overhead and could be tedious to manage on a large scale [3].

2.3.1. SDN Architecture

Network intelligence is (logically) centralized in software-based SDN controllers, which maintain a global view of the network. As a result, the network appears to the applications and policy engines as a single, logical switch. With SDN, enterprises and carriers gain vendor-independent control over the entire network from a single logical point, which greatly simplifies the network design and operation. SDN also greatly simplifies the network devices themselves, since they no longer need to understand and process thousands of protocol standards but merely accept instructions from the SDN controllers [4]. The figure 2-1 below depicts a logical view of the SDN architecture.

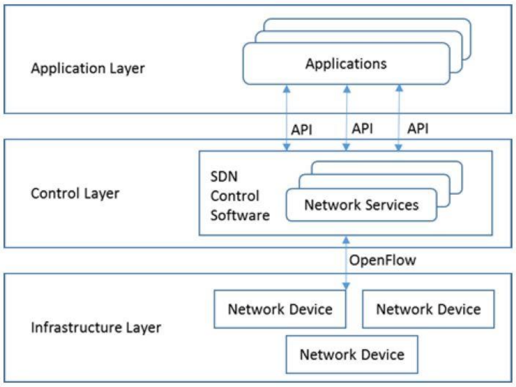


Figure 2-1: SDN Architecture.

SDN architectures support a set of APIs that make it possible to implement common network services, including routing, multicast, security, access control, bandwidth management, traffic engineering, quality of service, processor and storage optimization, energy usage, and all forms of policy management, custom tailored to meet business objectives. For example, an SDN architecture makes it easy to define and enforce consistent policies across both wired and wireless connections on a campus [4].

2.3.2. SDN Advantages

OpenFlow is the first standard interface designed specifically for SDN, providing high-performance, granular traffic control across multiple vendors' network devices. OpenFlow-based SDN is currently being rolled out in a variety of networking devices and software, delivering substantial benefits to both enterprises and carriers, including:

- Centralized management and control of networking devices from multiple vendors.
- Improved automation and management by using common APIs to abstract the underlying networking details from the orchestration and provisioning systems and applications.
- Rapid innovation through the ability to deliver new network capabilities and services without the need to configure individual devices or wait for vendor releases.
- Programmability by operators, enterprises, independent software vendors, and users (not just equipment manufacturers) using common programming

environments, which gives all parties new opportunities to drive revenue and differentiation.

- Increased network reliability and security as a result of centralized and automated management of network devices, uniform policy enforcement, and fewer configuration errors.
- More granular network control with the ability to apply comprehensive and wide-ranging policies at the session, user, device, and application levels.
- Better end-user experience as applications exploit centralized network state information to seamlessly adapt network behavior to user needs [4].

2.3.3. SDN Applications

To give an idea of how huge SDN is, the list below mentioned some of the applications which is related to.

- **Appliance Virtualization:** Firewalls, Load balancers, Content distribution, and Gateways.
- **Service Assurance:** Content-specific traffic routing for optimal Quality of Experience (QoE), Congestion control based on network conditions, Dynamic policy-based traffic engineering.
- **Service Differentiation:** Value-add service features, Bandwidth-on-demand features, BYOD across multiple networks, Service insertion/changing.
- **Service Velocity:** Virtual edge, distributed app testing environments, Application development workflows.

- **Traditional Control Plane:** Network discovery, Path computation, Optimization & maintenance, Protection & restoration.
- **Network Virtualization:** Virtual network control on shared infrastructure, Multi-tenant network automation & API.
- **Application Enhancement:** Specific SDN application, Reserved bandwidth for application needs, Geo-distributed applications, Intelligent network responses to app needs [2].

2.4. OpenFlow

OpenFlow is the first standard communications interface defined between the control and forwarding layers of an SDN architecture. OpenFlow allows direct access to and manipulation of the forwarding plane of network devices such as switches and routers, both physical and virtual (hypervisor-based). It is the absence of an open interface to the forwarding plane that has led to the characterization of today's networking devices as monolithic, closed, and mainframe-like. No other standard protocol does what OpenFlow does, and a protocol like OpenFlow is needed to move network control out of the networking switches to logically centralized control software [4].

OpenFlow was originally imagined and implemented as part of network research at Stanford University. Its original focus was to allow the creation of experimental protocols on campus networks that could be used for research and experimentation. Prior to that, universities had to create their own experimentation platforms from scratch. What evolved from this initial kernel of an idea was a view that OpenFlow could replace the functionality of layer 2 and layer 3 protocols completely in commercial switches and routers. This approach is commonly referred to as the clean slate proposition [1].

In 2011, a nonprofit consortium called the Open Networking Foundation (ONF) was formed by a group of service providers to commercialize, standardize, and promote the use of OpenFlow in production networks [1].

2.4.1. OpenFlow applications

There is a wide range of applications, where use of OpenFlow can improve overall system performance. The following list brings some of the experiments (performed at the Stanford University) [8].

- **Slicing the network:** The network infrastructure can be divided into logical slices (using e.g. FlowVisor software). Hence, different services can be mapped to different network slices, and the traffic could then be treated accordingly.
- **Load balancing:** The whole network can be viewed as one big software load balancing switch instead of deploying expensive load balancing hardware switches.
- **Packet and circuit network convergence:** OpenFlow provides a solution for merging packet and circuit networks into one, thus reducing CAPEX/OPEX spending of telecommunications companies.
- **Reduction of energy consumption:** The unused links can be switched off, so that less energy is needed to run e.g. a data center network.
- **Dynamic flow aggregation:** OpenFlow can help saving the resources (CPU, routing tables) or further ease management of the network.

- **Providing MPLS services:** OpenFlow can simplify deployment of new MPLS services (e.g. new tunnels including adjustments of their bandwidth reservation).

2.5. Network Load Balancing

Load balancing is very important in building high speed networks and also to ensure high performance in the network backbone.

The main idea of load balancing is to map the part of the traffic from the heavily loaded paths to some lightly loaded paths to avoid congestion in the shortest path route and to increase the network utilization and network throughput. Approached used for Load Balancing can be broadly classified in to following types [9]:

2.5.1. Round Robin forwarding.

Per packet round robin scheduling is advantageous only when all the paths are of equal cost. Otherwise packet disordering will take place which can be interpreted as false congestion signals. This would lead in unnecessary degradation in the throughput of the network leaving some links unutilized whereas at the same time leading to the overutilization of the other links.

2.5.2. Time dependent approach:

Balancing traffic on the basis of long time span as per the experience of the traffic.

Time dependent approach will vary the traffic on the basis of variations in the traffic over a long time span. These types of approaches are insensitive to the dynamic traffic variations.

2.5.3. Hashing based approaches.

Hashing based approaches are a stateless approach which applies the hash function on subset of five tuples (source address, destination address, source port, destination port and protocol id). This type of traffic splitting is fairly easy to compute. Though, it maintains the flow based traffic splitting yet by this method the traffic can- not be distributed unevenly. And more over as it does not maintain the state so dynamic traffic engineering is not applicable to these types of approaches.

2.5.4. Routing traffic as per the metrics calculated from the traffic.

Various authors have proposed traffic engineering with some calculated metrics like packet delay or/and packet loss etc. dynamically and applying them to split the traffic. This method is highly advantageous if the flow integrity is maintained and if the metrics calculation overhead is not considerable.

2.6. Interconnection networks

Interconnection networks were traditionally defined as networks that connect multiprocessors. However, interconnection networks evolved dramatically in the last 20 years and nowadays play a crucial role in areas like Data Centers or high performance computing (HPC) clusters.

Topologies for interconnection networks can be classified into four major groups: shared-bus networks, direct networks, indirect networks and hybrid networks. The choice of topology is one of the most important steps when constructing an interconnection network. The chosen topology combined with the routing algorithm and application’s workload determines the traffic distribution in the network [10].

2.6.1. Fat-Tree topology

The fat-tree topology is very popular for building medium and large system area networks [11]. It was invented by Charles E. Leiserson of the Massachusetts Institute of Technology in 1985 [12].

The fat-tree topology contains multiple paths among hosts so it can provide higher available bandwidth than a single-path tree with the same number of nodes. It is typically a 3-layer hierarchical tree that consists of switches on the core, aggregation and edge layers. The hosts connect to the switches on the Edge layer. The multipath feature of fat-tree networks enables chances to distribute data traffic on different network components.

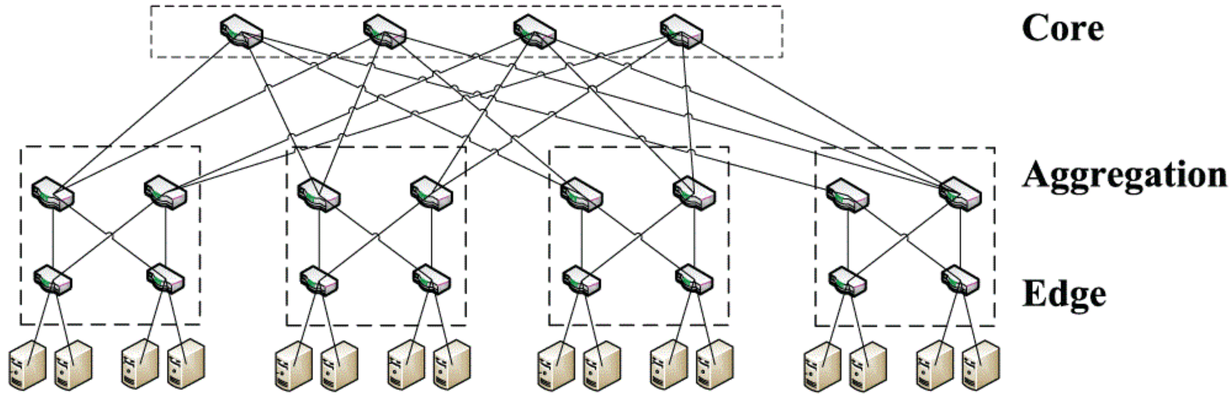


Figure 2-2: Fat-tree network topology.

There are three properties that make fat-trees the topology of choice for high performance interconnects [10]:

a) Deadlock freedom, the use of a tree structure makes it possible to route fat-trees without using virtual channels for deadlock avoidance.
b) Inherent fault-tolerance, the existence of multiple paths between individual source destination pairs makes it easier to handle network faults.
c) Full bisection bandwidth, the network can sustain full speed communication between the two halves of the network.

Although the fat-tree topology provides rich connectivity, having a fat-tree topology alone does not guarantee high network performance: the routing mechanism also plays a crucial role. Historically, adaptive routing, which dynamically builds the path for a packet based on the network condition, has been used with the fat-tree topology to achieve load balance in the network. However, the routing in the current major system area networking technology is deterministic. For a fat-tree based system area network with deterministic routing, it is important to employ an efficient load balance routing scheme in order to fully exploit the rich connectivity provided by the fat-tree topology [11].

2.7. Dijkstra's algorithm

Dijkstra's algorithm, conceived by Dutch computer scientist Edsger Dijkstra in 1956 and published in 1959 [13][14], is a graph search algorithm that solves the single-source shortest path problem for a graph with nonnegative edge path costs, producing a shortest path tree.

This algorithm is often used in routing and as a subroutine in other graph algorithms. For a given source vertex (node) in the graph, the algorithm finds the path with lowest cost (i.e. the shortest path) between that vertex and every other vertex.

It can also be used for finding costs of shortest paths from a single vertex to a single destination vertex by stopping the algorithm once the shortest path to the destination vertex has been determined. For example, if the vertices of the graph represent cities and edge path costs represent driving distances between pairs of cities connected by a direct road, Dijkstra's algorithm can be used to find the shortest route between one city and all other cities. As a result, the shortest path first is widely used in network routing protocols, most notably IS-IS and OSPF[15].

2.8. SDN Dynamic Load Balancing Algorithm

This research algorithm takes into account the advantages and features of SDN, which can sense the state of each of the elements on the network in order to act consequently.

In order to describe the algorithm, first it is needed to disclose the different data structures involved on it. Such structures characterize the different elements that have been taken in account in order to achieve an efficient load balancing, at the same time that to reduce as much as possible the computational cost and time [2].

The main data structures are explained bellow.

a) Flow

Since the algorithm provides load balancing based on flows, it is necessary to define a structure to describe each of the different flows with distinctive parameters.

Notice that for the goal of this research have been taking in account the IP sand Ports, but using OpenFlow it is possible to make a much more accurate identification of each flow with any of the header fields.

A Flow structure specifies a specific traffic flow from one host to another one. The structure is as follows:

Flow = {<FlowID>, <SrcIP>, <DstIP>, <SrcPort>, <DstPort>,<UsedBandwidth>}

FlowID: identify each flow with a unique ID.

SrcIP: this field contains the IPv4 of the source host who initialized a flow.

DstIP: IPv4 of the destination host.

SrcPort: port number of the source.

DstPort: port number of the destination.

UsedBandwidth: transmission speed of a specific flow, in Mbps.

b) Flows Collection

Groups of flows are put together in collections, which contain a number of flows with common characteristic (e.g. flows that goes through a same link).

FlowsCollection={< Flow 1 >,< Flow2 > ... < Flow n >}

c) Path

Keeping information about each parallel route between each pair of hosts it is crucial to be able to redirect the flows according to the current network conditions. To accomplish that tracking, a data structure representing each of the possible paths has been designed.

A Path structure contains the information about a precise path between two hosts, and it is composed as shown below:

Path={<PathID>,<Hops>,<Links>,<Ingress>,<Egress>,<Capacity>,< Flows>,
<UsedBandwidth>, <FreeCapacity>}

PathID: identify each single possible path with a unique ID.

Hops: contains a identifier of each of the switches within the path.

Links: list of all the links involved in the path. Each of the links is composed by a pair of Switch-Port identifiers.

Ingress: identifier of the switch with the source host is connected to.

Egress: identifier of the switch with the destination host is connected to.

Capacity: specify the maximum capacity of the path. Which corresponds to the capacity of the link with smallest capacity along the path.

Flows: list of flows which are routed through this path.

Used Bandwidth: sum of the traffic of all the flows that are using this path, in Mbps.

Free Capacity: capacity available in this path. It's the minimum capacity free of the Links that shape the path.

d) Paths Collection

Path Collection contains a list of all the possible paths of the hosts that have initiated a communication between them, and information about each of the paths [2].

PathsCollection={< Path 1 >,< Path2 > ... < Path n >}

2.9. Literature Review

In 2014, Yuanhao Zhou, Li Ruan, Limin Xiao andRui Liu published the paper "A Method for Load Balancing based on Software-Defined Network". The paper presented a method for load balancing based on SDN. It implemented load balancing according to PyResonance controller. PyResonance is Resonance implemented with Pyretic. Resonance is an SDN control platform that advocates event-driven network control. It preserves a Finite State Machine (FSM) model to define a network policy. The paper showed that traffic can be distributed more efficiently and easily with the aid of the proposed solution [5].

In May 2015, Senthil Ganesh N and Ranjani S. published the paper “Dynamic Load Balancing using Software Defined Networks”. In this paper a Software-Defined Network using OpenFlow protocol was implemented to improve the efficiency of load balancing in enterprise networks. By using this technique, the network becomes directly programmable and agile. Here the http requests from different clients will be directed to different pre-defined http servers based on Round-Robin scheduling. Round-Robin scheduling is easy to implement and are good to be used in geographically distributed web servers [6].

In June 2015, Smriti Bhandarkar and Kotla Amjath Khan published the paper “Load Balancing in Software-defined Network (SDN) Based on Traffic Volume”. The paper showed that the key limitations are statically configured forwarding plane and uneven load balancing among the controllers in the network. It proposed The dynamic load balancer which dynamically shifts the load to the other shortest path when it is greater than the bandwidth of the link. By experimental analysis, the paper concluded that the proposed approach gives better results in terms of responses/sec and efficiency as compared with the existing Round-Robin load balancing algorithm [7].

Chapter Three

Methodology

Chapter Three

Methodology

3.1. Introduction

This chapter describes the algorithm designed to accomplish a dynamic load balancing system, and presents the components and software tools used in this research to set the testbed.

3.2. Algorithm Description

As explained formerly, the task of the Nayan Seth's algorithm[19] is to distribute traffic of upcoming and incoming network flows in order to achieve the best possible resource utilization of each of the links present in a network. In order to achieve such aim, it is necessary to keep track of the current state of the network. Figure 3-1 illustrates the steps of the load balancing algorithm.

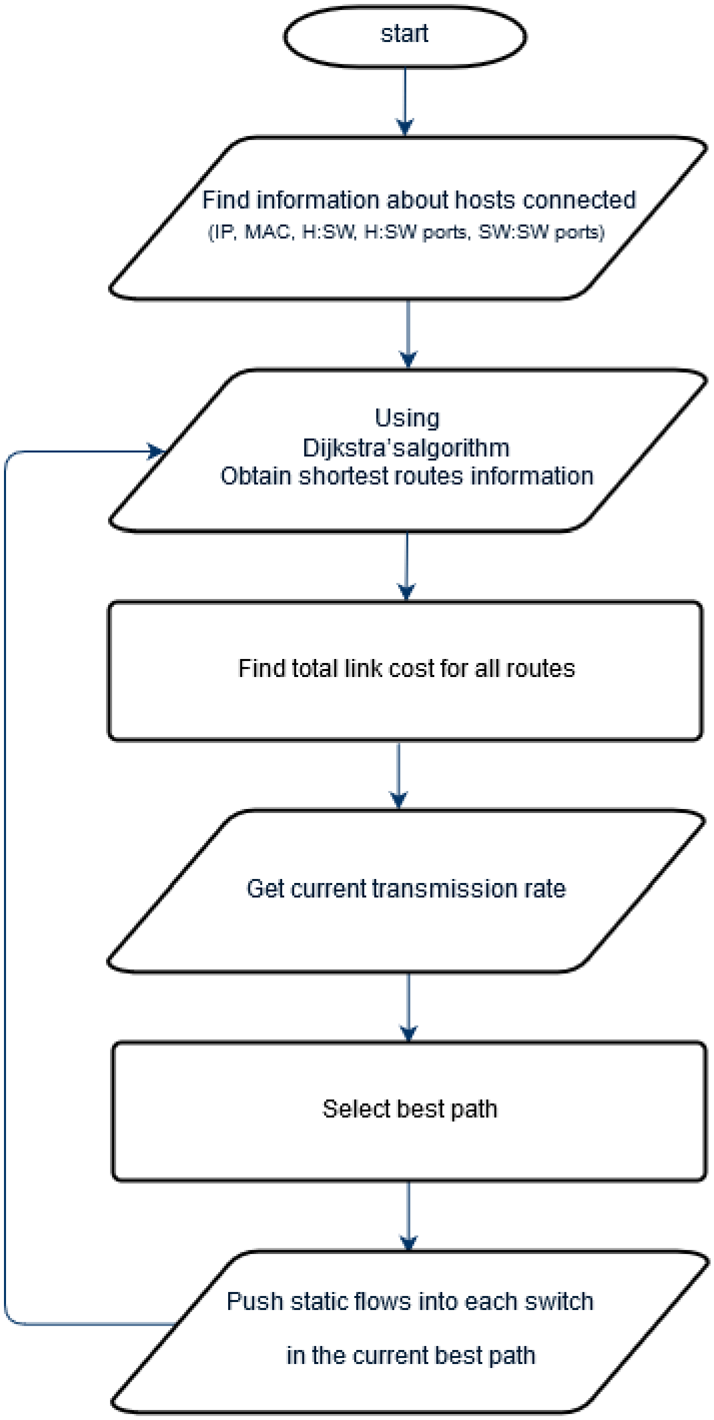

start
Find information about hosts connected
(IP, MAC, H:SW, H:SW ports, SW:SW ports)
Using
Dijkstra'salgorithm
Obtain shortest routes information
Find total link cost for all routes
Get current transmission rate
Select best path
Push static flows into each switch
in the current best path

Figure 3-1: SDN Dynamic Load Balancing algorithm.

The first step of the algorithm is to collect operational information of the topology and its devices. Such as IPs, MAC addresses, Ports, Connections, etc.

Next step is to find route information based on Dijkstra's algorithm (see Chapter 2 section 8), the goal here is to narrow the search into a small segment of the Fat-Tree topology and to find the shortest paths from source host to destination host. And then find total link cost for all these paths between the source and destination hosts.

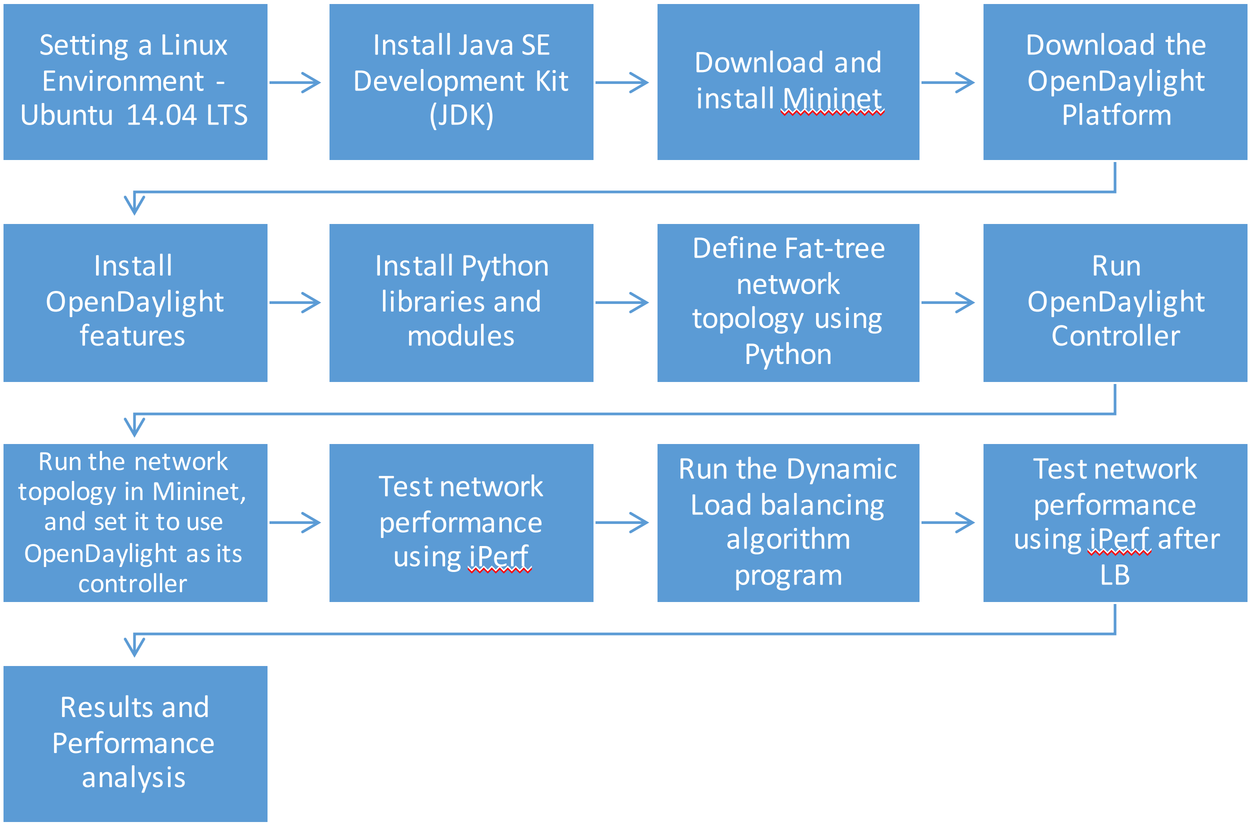
Once the transmission costs of the links are calculated, the flows are created depending on the minimum transmission cost of the links at the given time.

Based on the cost, the best path is selected and static flows are pushed into each switch in the current best path. with that, every switch within the selected path will have the necessary flow entries to carry out the communication between the two end points.

Finally, the program continues to update this information every minute thereby making it dynamic.

3.3. Implementation Overview

In this research a test-bed has been implemented under Linux, using Mininet software to emulate the network, the open-source OpenDaylight platform (ODL) as SDN controller, and Python programming language to define the fat-tree topology and to write the load balancing algorithm program, and iPerf to test network performance. The following diagram illustrate the design steps.


Setting a Linux Environment - Ubuntu 14.04 LTS
Install Java SE Development Kit (JDK)
Download and install Mininet
Download the OpenDaylight Platform
Install OpenDaylight features
Install Python libraries and modules
Define Fat-tree network topology using Python
Run OpenDaylight Controller
Run the network topology in Mininet, and set it to use OpenDaylight as its controller
Test network performance using iPerf
Run the Dynamic Load balancing algorithm program
Test network performance using iPerf after LB
Results and Performance analysis

3.4. Components and Software Tools

3.4.1. Mininet

Mininet is a network emulator that allows prototyping large networks on a single machine. It runs a collection of end-hosts, switches, routers, and links on a single Linux kernel. It uses lightweight virtualization to make a single system look like a complete network, running the same kernel, system, and user code.

Mininet main advantages:

1. Mininet is an open source project.
2. Custom topologies can be created.
3. Mininet runs real programs.
4. Packet forwarding can be customized.

Compared to simulators, Mininet runs real, unmodified code including application code, OS kernel code, and control plane code (both OpenFlow controller code and Open vSwitch code) and easily connects to real networks.

3.4.2. The OpenDaylight Project (ODL)

The OpenDaylight Project (ODL) is a highly available, modular, extensible, scalable and multi-protocol controller infrastructure built for SDN deployments on modern heterogeneous multi-vendor networks. ODL provides a model-driven service abstraction platform that allows users to write apps that easily work across a wide variety of hardware and south-bound protocols.

Furthermore, it contains internal plugins that add services and functionalities to the network. For example, it has dynamic plugins that allow to gather statistics as well as to obtain the topology of the network [17].

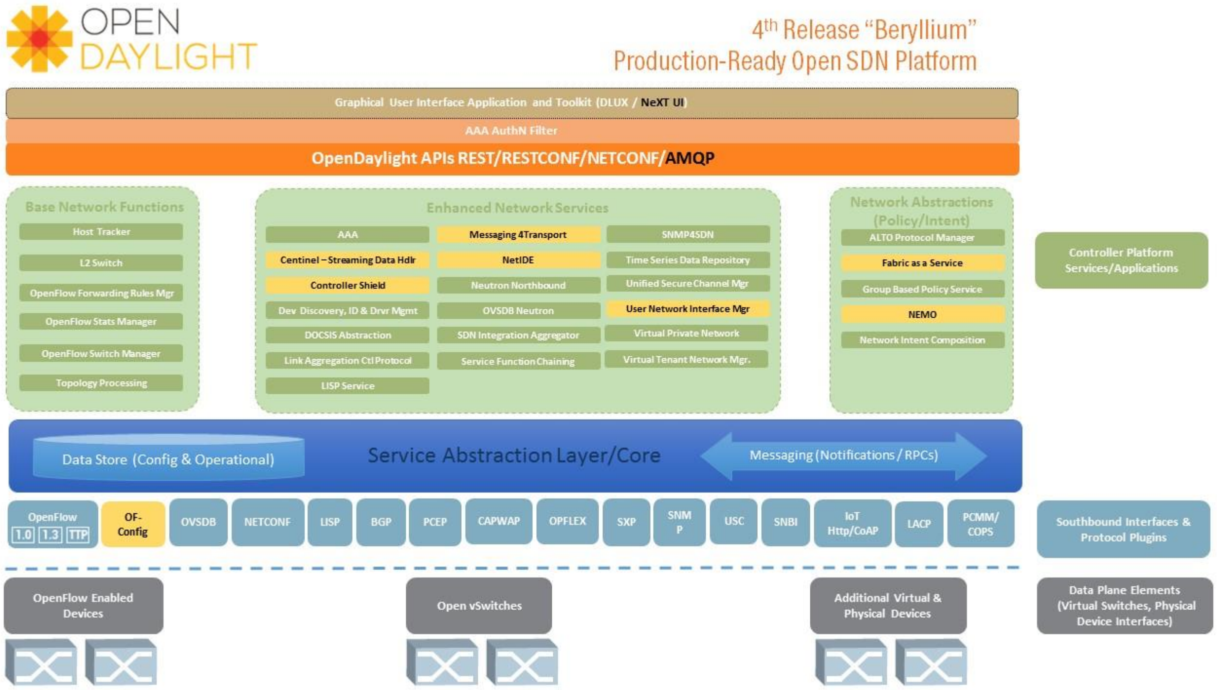

OPEN DAYLIGHT
4th Release "Beryllium"
Production-Ready Open SDN Platform
Graphical User Interface Application and Toolkit (DLUX / NeXT UI)
AAA AuthN Filter
OpenDaylight APIs REST/RESTCONF/NETCONF/AMQP
Base Network Functions
Host Tracker
L2 Switch
OpenFlow Forwarding Rules Mgr
OpenFlow Stats Manager
OpenFlow Switch Manager
Topology Processing
Enhanced Network Services
AAA
Messaging 4Transport
SNMP4SDN
Centinel – Streaming Data Hdlr
NetIDE
Time Series Data Repository
Controller Shield
Neutron Northbound
Unified Secure Channel Mgr
Dev Discovery, ID & Drvr Mgmt
OVSDB Neutron
User Network Interface Mgr
DOCSIS Abstraction
SDN Integration Aggregator
Virtual Private Network
Link Aggregation Ctl Protocol
Service Function Chaining
Virtual Tenant Network Mgr.
LISP Service
Network Abstractions (Policy/Intent)
ALTO Protocol Manager
Fabric as a Service
Group Based Policy Service
NEMO
Network Intent Composition
Controller Platform Services/Applications
Data Store (Config & Operational)
Service Abstraction Layer/Core
Messaging (Notifications / RPCs)
OpenFlow 1.0 1.3 TTP
OF-Config
OVSDB
NETCONF
LISP
BGP
PCEP
CAPWAP
OPFLEX
SXP
SNMP
USC
SNBI
IoT Http/CoAP
LACP
PCMM/ COPS
Southbound Interfaces & Protocol Plugins
OpenFlow Enabled Devices
Open vSwitches
Additional Virtual & Physical Devices
Data Plane Elements (Virtual Switches, Physical Device Interfaces)

Figure 3-2: Beryllium-SR4 architecture framework.

3.4.3. iPerf

iPerf is a commonly used network testing tool for measuring Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) bandwidth performance and the quality of a network link. By tuning of various parameters related to timing, buffers and protocols (TCP, UDP, SCTP with IPv4 and IPv6), the user is able to perform a number of tests that provide an insight on the network's bandwidth availability, delay, jitter and data loss.iPerf is an open source software and runs on various platforms including Linux, UNIX and Windows.

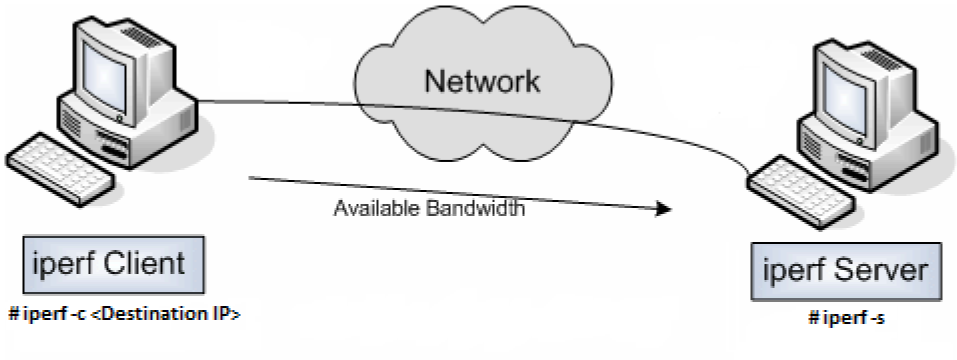


Figure 3-3: iPerf Bandwidth measurement.

3.4.4. Programming Language used: Python

In this research, Python has been used in mininet to define the Fat-tree topology, also it has been used to write the load balancing algorithm program.

Python is an interpreted, object-oriented language suitable for many purposes. It has a clear, intuitive syntax, powerful high-level data structures, and a flexible dynamic type system. Python can be used interactively, in stand-alone scripts, for large programs, or as an extension language for existing applications. The language runs on Linux, Macintosh, and Windows machines [18].

Python is easily extensible through modules written in C or C++, and can also be embedded in applications as a library. There are also a number of system-specific extensions. A large library of standard modules written in Python also exists.

Compared to C, Python programs are much shorter, and consequently much faster to write. In comparison with Perl, Python code is easier to read, write and maintain. Relative to TCL, Python is better suited for larger or more complicated programs [18].

Chapter Four

Results and Performance Evaluation

Chapter Four

Results and Performance Evaluation

4.1. Introduction

This chapter describes the proposed scenarios, then shows and explains the results obtained with the scenarios proposed.

4.2. Network Topology

The network topology used in this research is a three-levels fat-tree Data Center topology. It consists of 8 servers, 4 edge switches, 4 aggregation switches, and 2 core switches. As presented in Figure 4-1.

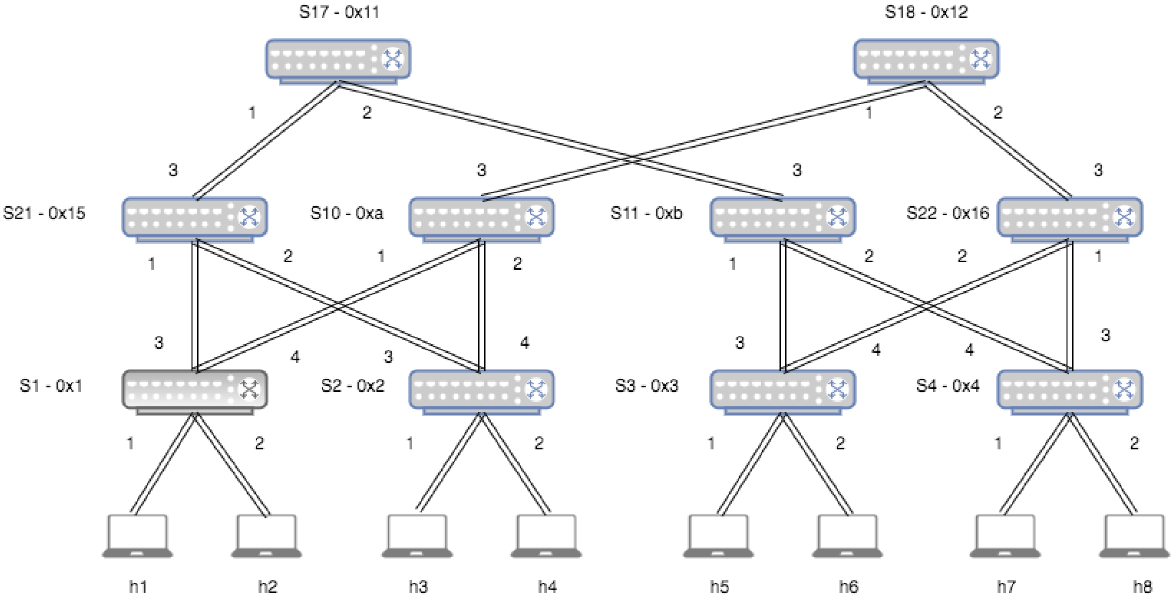


Figure 4-1: Datacenter Network Topology used.

4.3. Scenario Description

4.3.1. First Scenario: Performance Measurement at the Aggregation Layer

In this scenario the severs h1 and h4 has been selected to perform the load balancing between them. As shown is the figure 4-2 below.

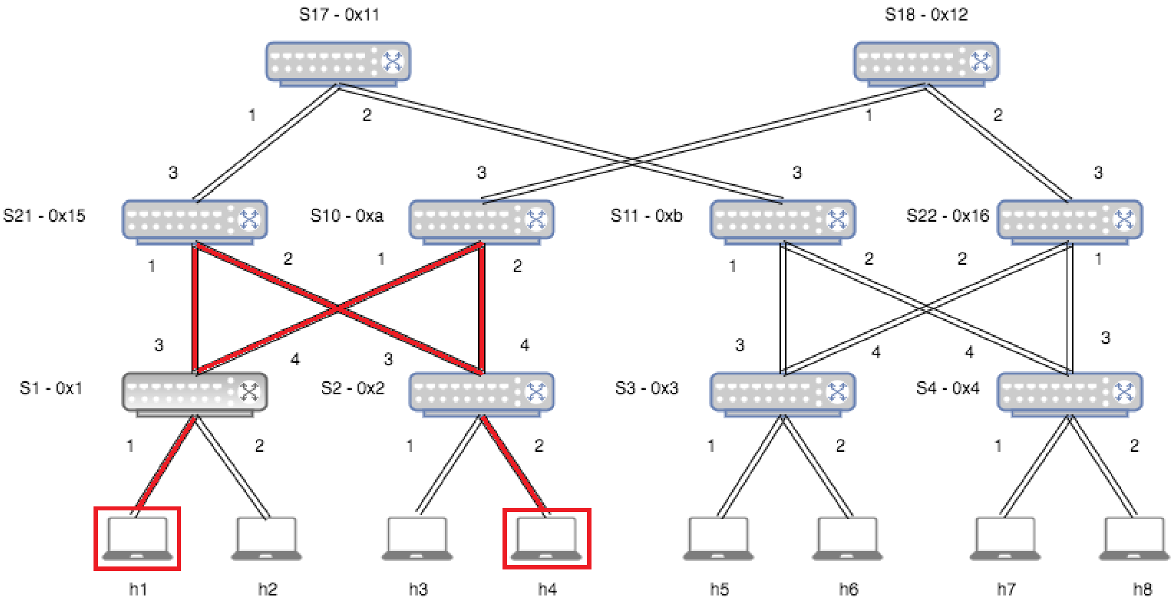


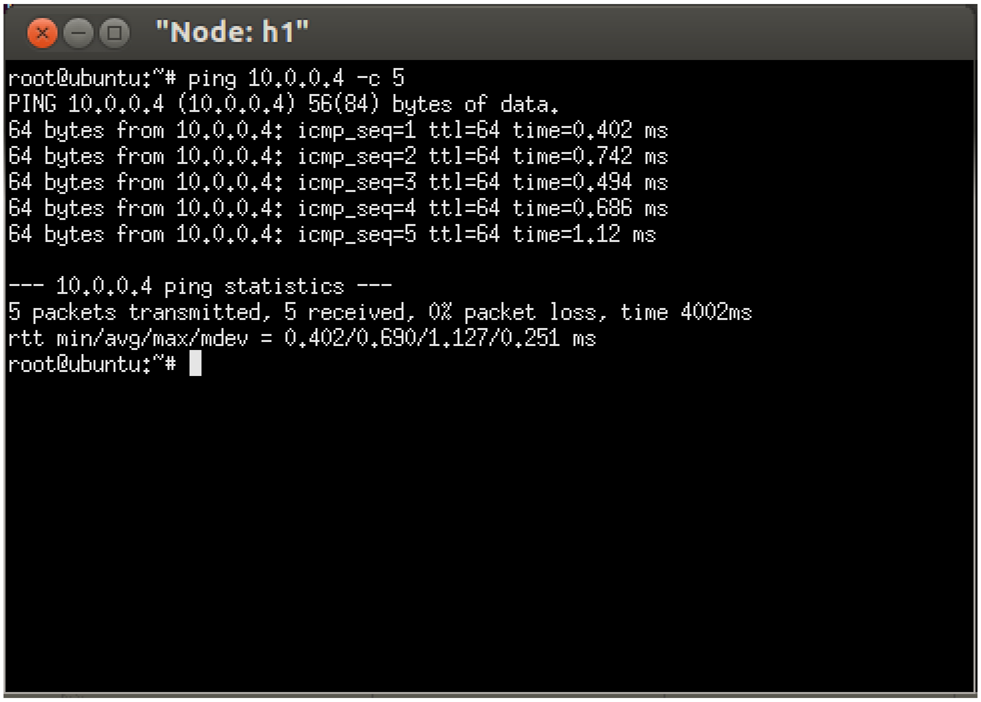
Figure 4-2: The selected hosts and possible paths in the first scenario.

The network was tested before and after running the load balancing algorithm. The testing focused on some of QoS parameters such as throughput, delay, jitter, and packet loss between the two servers in the fat-tree network.

Delay has been measured by sending five Internet Control Message Protocol (ICMP) Echo Request packets to the destination host and calculated the time until ICMP Echo Reply was received at the source host.

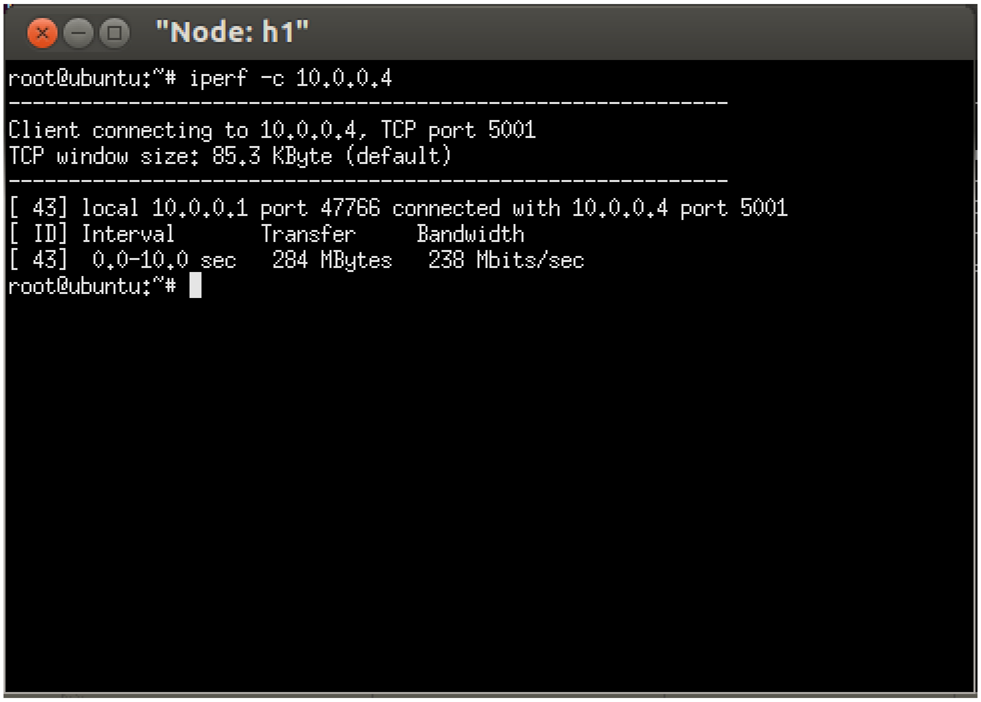
Throughput, Jitter, and Packet Loss has been tested using iPerf, first case by using the TCP and then by using UDP, with 10 seconds for each test.

The following figures 4-3 to 4-5 show examples of the testing results.



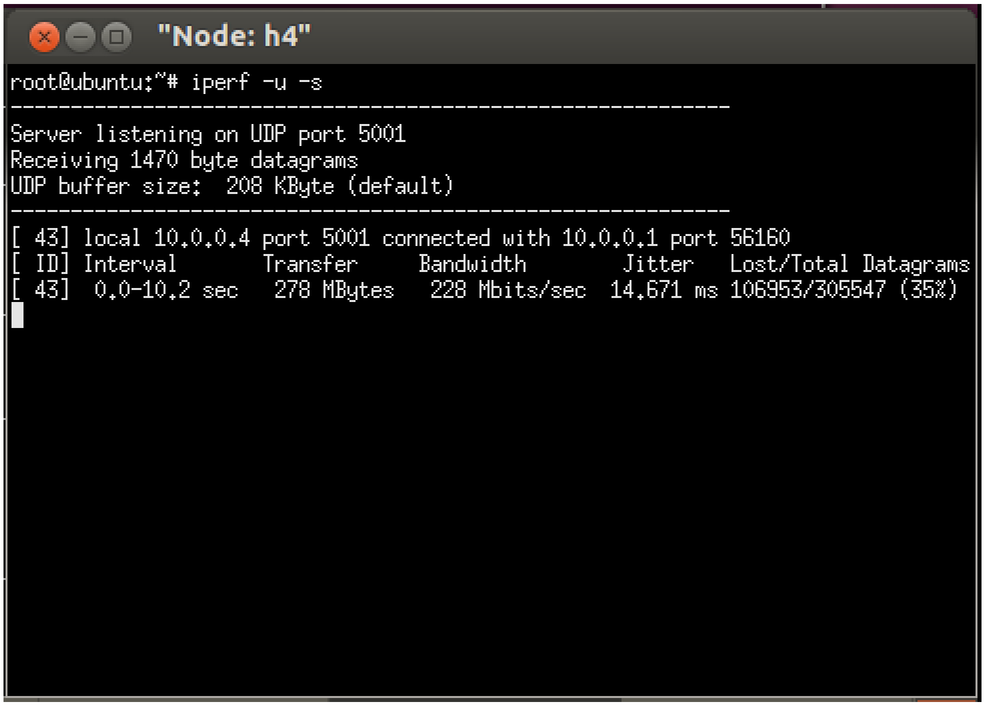
```
root@ubuntu:~# ping 10.0.0.4 -c 5
PING 10.0.0.4 (10.0.0.4) 56(84) bytes of data.
64 bytes from 10.0.0.4: icmp_seq=1 ttl=64 time=0.402 ms
64 bytes from 10.0.0.4: icmp_seq=2 ttl=64 time=0.742 ms
64 bytes from 10.0.0.4: icmp_seq=3 ttl=64 time=0.494 ms
64 bytes from 10.0.0.4: icmp_seq=4 ttl=64 time=0.686 ms
64 bytes from 10.0.0.4: icmp_seq=5 ttl=64 time=1.12 ms

--- 10.0.0.4 ping statistics ---
5 packets transmitted, 5 received, 0% packet loss, time 4002ms
rtt min/avg/max/mdev = 0.402/0.690/1.127/0.251 ms
root@ubuntu:~# 
```

Figure 4-3: ping from h1 to h4 before load balancing.



```
root@ubuntu:~# iperf -c 10.0.0.4
------------------------------------------------------------
Client connecting to 10.0.0.4, TCP port 5001
TCP window size: 85.3 KByte (default)
------------------------------------------------------------
[ 43] local 10.0.0.1 port 47766 connected with 10.0.0.4 port 5001
[ ID] Interval       Transfer     Bandwidth
[ 43]  0.0-10.0 sec   284 MBytes   238 Mbits/sec
root@ubuntu:~# 
```

Figure 4-4: iPerf h1 to h4 before load balancing – TCP connection.



```
root@ubuntu:~# iperf -u -s
------------------------------------------------------------
Server listening on UDP port 5001
Receiving 1470 byte datagrams
UDP buffer size:  208 KByte (default)
------------------------------------------------------------
[ 43] local 10.0.0.4 port 5001 connected with 10.0.0.1 port 56160
[ ID] Interval       Transfer     Bandwidth        Jitter   Lost/Total Datagrams
[ 43]  0.0-10.2 sec   278 MBytes   228 Mbits/sec  14.671 ms 106953/305547 (35%)
```

Figure 4-5: iPerf h1 to h4 before load balancing – UDP connection.

4.3.1.1. Tests results of the first scenario

The network was tested ten times before and after running the load balancing algorithm; to study any abnormal behavior. The following table illustrates the results obtained.

Table 4-1: Tests results of the first scenario.

Test No.	Load Balancing	TCP		UDP				Delay (ms)
		Throughput (Mbits/sec)	Transfer (Mbytes)	Throughput (Mbits/sec)	Transfer (Mbytes)	Jitter (ms)	Packet Loss %	
1	Before	191	228	354	422	0.641	15%	0.297
	After	13414.4	15564.8	524	594	0.081	13%	0.142
2	Before	221	265	299	357	0.325	38%	0.496
	After	28262.4	32870.4	726	866	0.011	5%	0.176
3	Before	255	304	274	327	0.521	59%	0.203
	After	16076.8	18739.2	713	849	0.006	6%	0.09
4	Before	185	220	361	431	0.491	52%	0.578

	After	21196.8	24678.4	765	912	0.001	2%	0.101
5	Before	238	284	228	278	14.67	35%	0.69
	After	28876.8	33689.6	653	778	0.005	11%	0.159
6	Before	184	223	283	338	0.42	41%	0.529
	After	26828.8	31334.4	625	745	0.176	12%	0.16
7	Before	208	249	256	305	0.365	30%	0.518
	After	30617.6	35635.2	743	885	0.014	4%	0.133
8	Before	233	278	298	355	0.543	36%	0.425
	After	34201.6	39833.6	738	880	0.013	5%	0.115
9	Before	236	281	255	304	0.691	43%	0.707
	After	24268.8	28262.4	742	885	0.193	4%	0.152
10	Before	244	292	215	256	0.172	42%	0.708
	After	36761.6	42803.2	740	881	0.015	3%	0.144

To summarize the previous table, an average performance has been calculated as shown in the following table.

Table 4-2: Average results of the first scenario.

Load Balancing	TCP		UDP				Delay (ms)
	Throughput (Mbits/sec)	Transfer (Mbytes)	Throughput (Mbits/sec)	Transfer (Mbytes)	Jitter (ms)	Packet Loss %	
Before	219.5	262.4	282.3	337.3	1.884	39.10%	0.5151
After	26050.56	30341.12	696.9	827.5	0.0515	6.43%	0.1372

4.3.1.2. Performance Analysis of the first scenario

The network showed a much better performance in the first scenario after running the load balancing program. The average network Throughput before load balancing was 219.5 Mbits/sec, and it became 25.4 Gbits/sec after load balancing. The average delay has decreased by 73.36% after load balancing with an average of 0.1372 ms, the Jitter has decreased by 97.27%, and the Packet Loss has decreased by 32.67%.

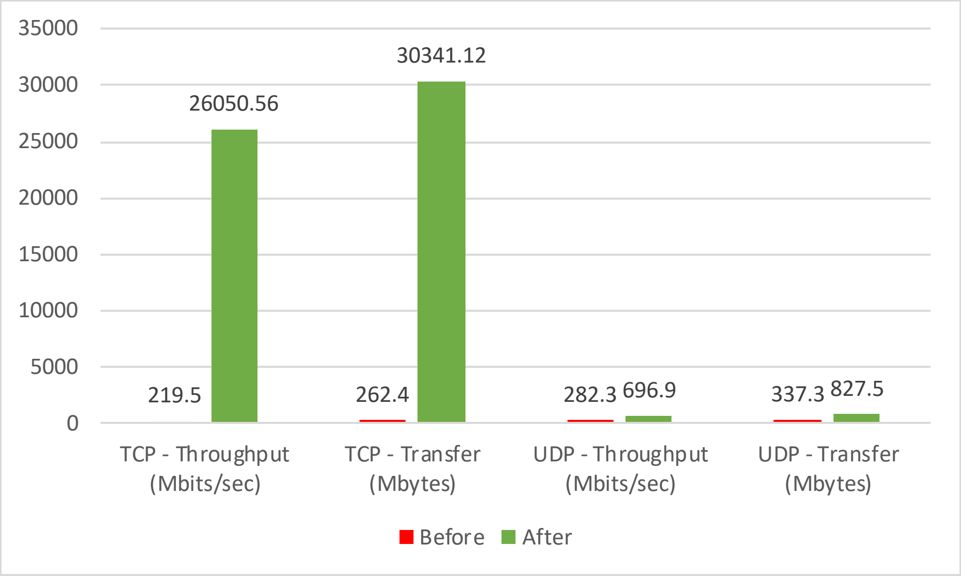


Figure 4-6: Comparison of Throughput tests results in first scenario.

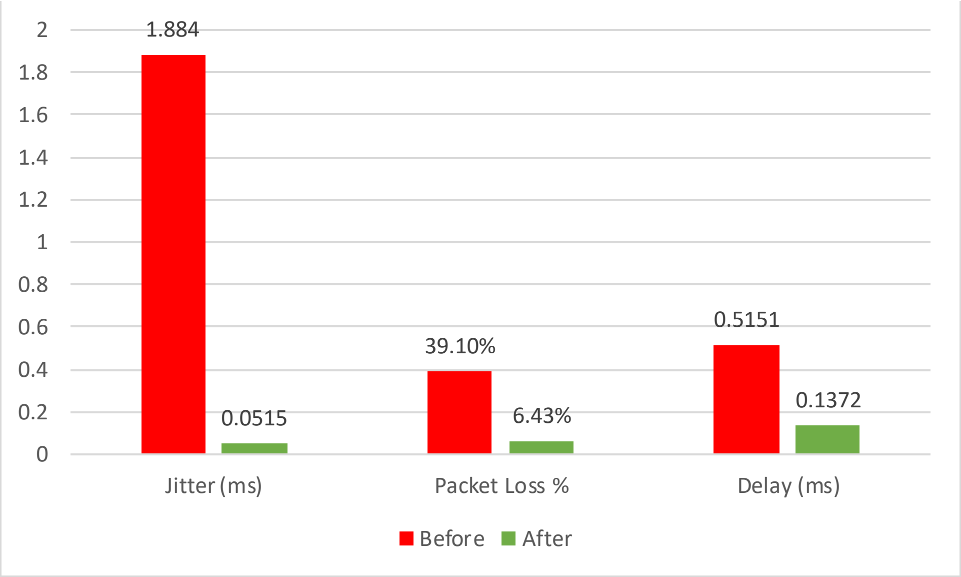


Figure 4-7: Comparison of QoS parameters in first scenario.

4.3.2. Second Scenario: Performance Measurement at the Core Layer

In this scenario the severs h1 and h6 has been selected to perform the load balancing between them. In this scenario the traffic will have to go through the core switches in order to reach its destination. The figure 4-8 below shows the selected hosts and the possible paths.

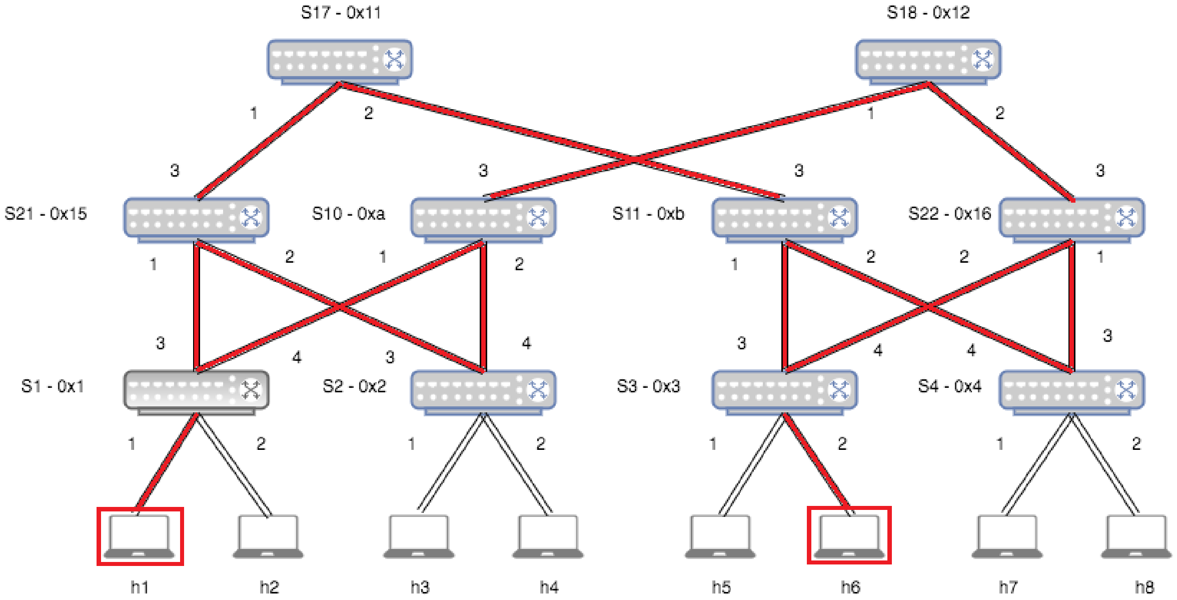
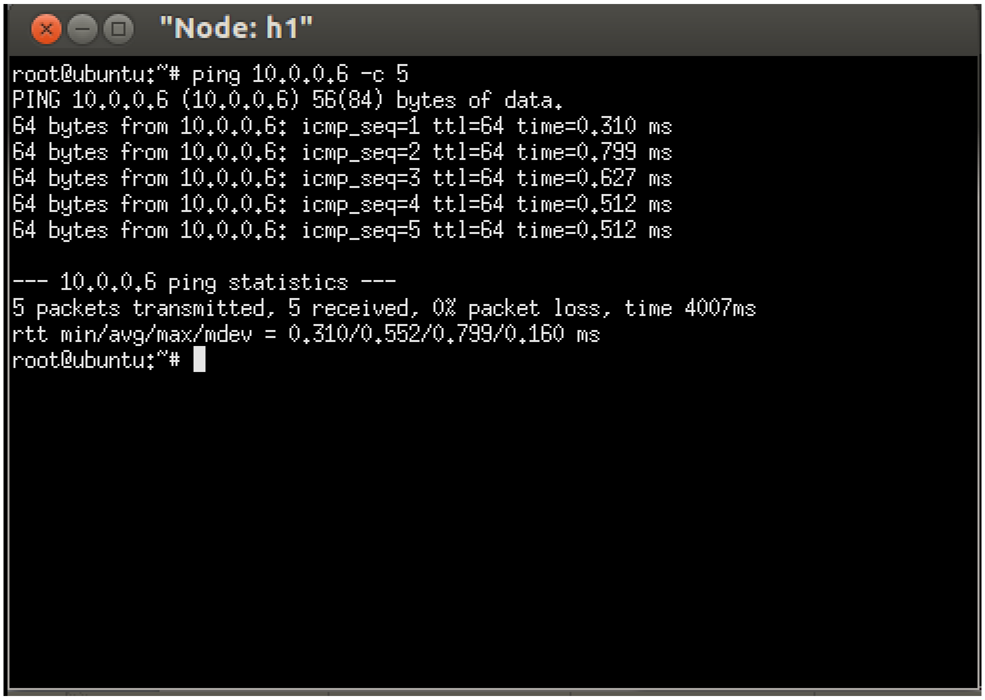


Figure 4-8: The selected hosts and possible paths in the second scenario.

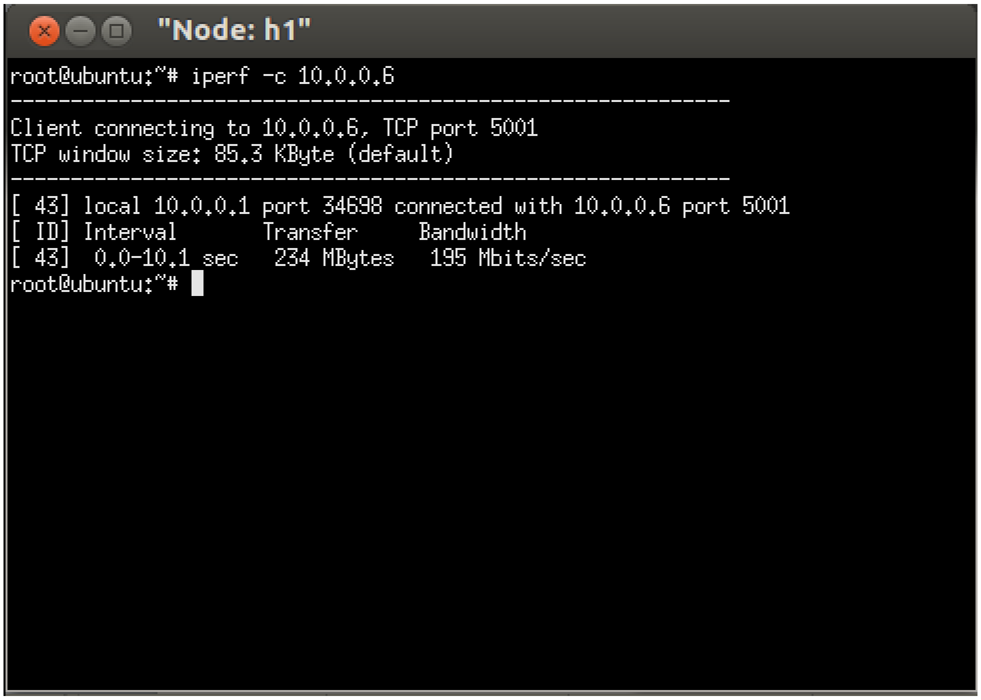
The network was tested before and after running the load balancing algorithm. The testing focused on some of QoS parameters such as throughput, delay, jitter, and packet loss between the two servers in the fat-tree network.

The following figures 4-9 to 4-11 show examples of the testing results.



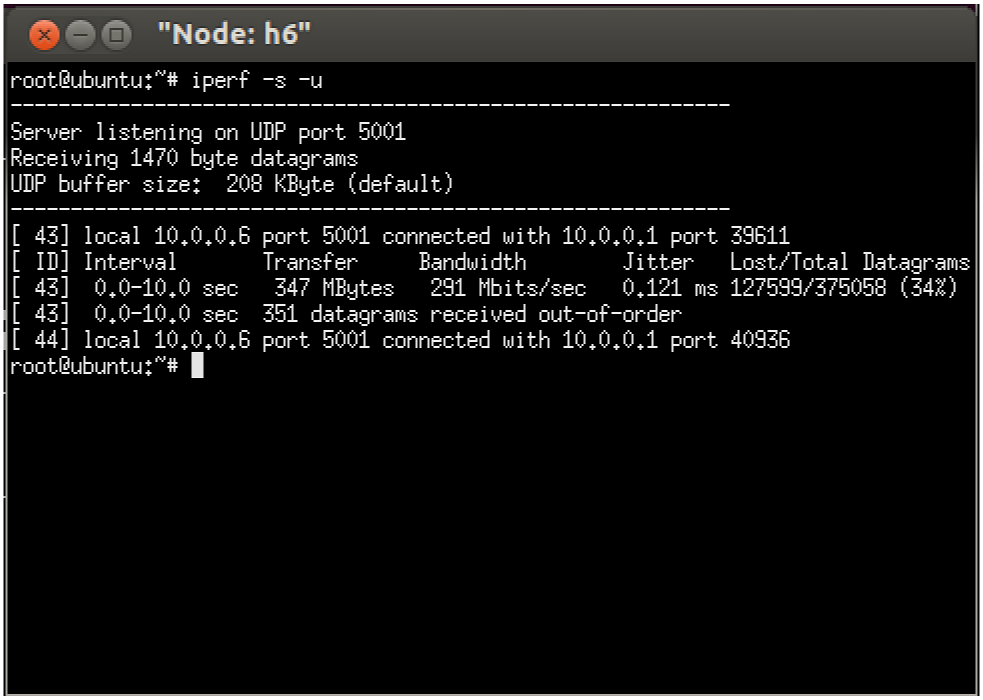
```
root@ubuntu:~# ping 10.0.0.6 -c 5
PING 10.0.0.6 (10.0.0.6) 56(84) bytes of data.
64 bytes from 10.0.0.6: icmp_seq=1 ttl=64 time=0.310 ms
64 bytes from 10.0.0.6: icmp_seq=2 ttl=64 time=0.799 ms
64 bytes from 10.0.0.6: icmp_seq=3 ttl=64 time=0.627 ms
64 bytes from 10.0.0.6: icmp_seq=4 ttl=64 time=0.512 ms
64 bytes from 10.0.0.6: icmp_seq=5 ttl=64 time=0.512 ms

--- 10.0.0.6 ping statistics ---
5 packets transmitted, 5 received, 0% packet loss, time 4007ms
rtt min/avg/max/mdev = 0.310/0.552/0.799/0.160 ms
root@ubuntu:~#
```

Figure 4-9: ping from h1 to h6 before load balancing.



```
root@ubuntu:~# iperf -c 10.0.0.6
------------------------------------------------------------
Client connecting to 10.0.0.6, TCP port 5001
TCP window size: 85.3 KByte (default)
------------------------------------------------------------
[ 43] local 10.0.0.1 port 34698 connected with 10.0.0.6 port 5001
[ ID] Interval       Transfer     Bandwidth
[ 43]  0.0-10.1 sec   234 MBytes   195 Mbits/sec
root@ubuntu:~#
```

Figure 4-10: iPerf h1 to h6 before load balancing – TCP connection.



```
root@ubuntu:~# iperf -s -u
------------------------------------------------------------
Server listening on UDP port 5001
Receiving 1470 byte datagrams
UDP buffer size:  208 KByte (default)
------------------------------------------------------------
[ 43] local 10.0.0.6 port 5001 connected with 10.0.0.1 port 39611
[ ID] Interval       Transfer     Bandwidth        Jitter   Lost/Total Datagrams
[ 43]  0.0-10.0 sec   347 MBytes   291 Mbits/sec   0.121 ms 127599/375058 (34%)
[ 43]  0.0-10.0 sec  351 datagrams received out-of-order
[ 44] local 10.0.0.6 port 5001 connected with 10.0.0.1 port 40936
root@ubuntu:~# 
```

Figure 4-11: iPerf h1 to h6 before load balancing – UDP connection.

4.3.2.1. Tests results of the second scenario

The network was tested ten times before and after running the load balancing algorithm; to study any abnormal behavior. The following table illustrates the results obtained.

Table 4-3: Tests results of the second scenario.

Test No.	Load Balancing	TCP		UDP				Delay (ms)
		Throughput (Mbits/sec)	Transfer (Mbytes)	Throughput (Mbits/sec)	Transfer (Mbytes)	Jitter (ms)	Packet Loss %	
1	Before	195	234	291	347	0.121	34%	0.552
	After	268	319	263	313	0.438	51%	0.439
2	Before	194	233	225	268	0.061	54%	0.268
	After	273	326	336	401	0.529	52%	0.323
3	Before	150	179	147	176	0.889	39%	0.943
	After	215	257	203	242	0.529	42%	0.561
4	Before	183	219	201	239	0.292	34%	0.374

	After	240	287	238	288	14.12	44%	0.401
5	Before	187	225	194	231	0.564	45%	0.242
	After	236	283	232	283	14.32	36%	0.662
6	Before	219	261	226	268	0.166	36%	0.553
	After	288	344	380	453	0.567	51%	0.618
7	Before	203	243	246	293	0.691	46%	0.566
	After	222	266	367	437	0.537	53%	0.499
8	Before	164	196	225	268	0.128	28%	0.596
	After	220	263	252	299	0.587	35%	0.432
9	Before	220	264	258	307	0.415	38%	0.615
	After	301	359	281	335	0.335	38%	0.332
10	Before	176	210	179	213	0.409	40%	0.582
	After	239	288	234	280	0.913	41%	0.54

To summarize the previous table, an average performance has been calculated as shown in the following table.

Table 4-4: Average results of the second scenario.

Load Balancing	TCP		UDP				Delay (ms)
	Throughput (Mbits/sec)	Transfer (Mbytes)	Throughput (Mbits/sec)	Transfer (Mbytes)	Jitter (ms)	Packet Loss %	
Before	189.1	226.4	219.2	261	0.3736	39.40%	0.5291
After	250.2	299.2	278.6	333.1	3.2891	44.30%	0.4807

4.3.2.2. Performance Analysis of the second scenario

In the second scenario, the network showed good performance after running the load balancing program. The average network throughput was 189.1 Mbits/sec, and it became 250.2 Mbits/sec after load balancing with 32.3% increasing percentage. The average delay has decreased by 9.15% after load balancing with an average of 0.4807ms. But the average jitter has increased from 0.3736 ms to 3.2891 ms after the load balancing, and the packet loss has also increased by 4.9%.

The load balancing program managed to increase the throughput in all cases. It showed a great performance under the second layer of the fat-tree topology, but as the network grows larger and the core layer gets involved, it presents increasing in the packet loss and jitter.

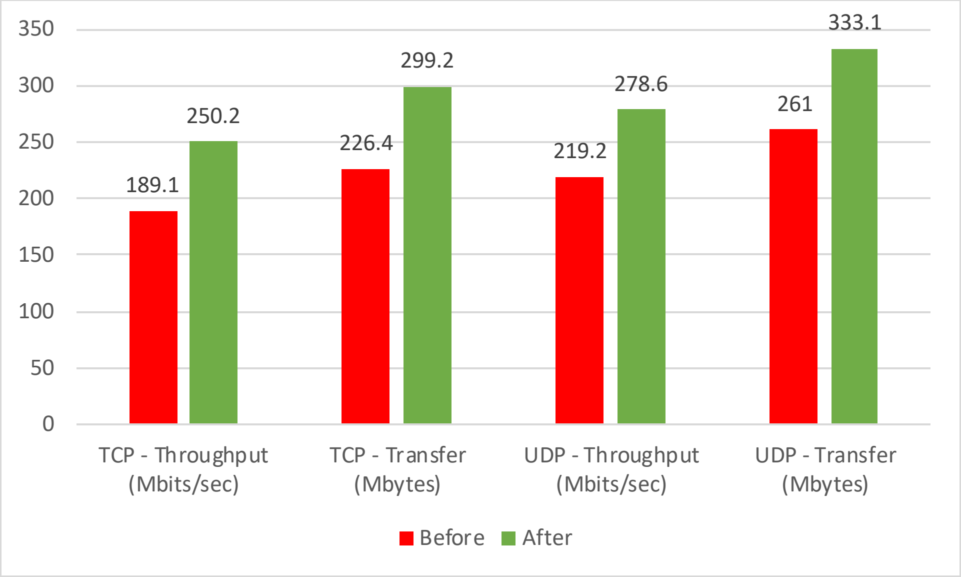


Figure 4-12: Comparison of Throughput tests results in second scenario.

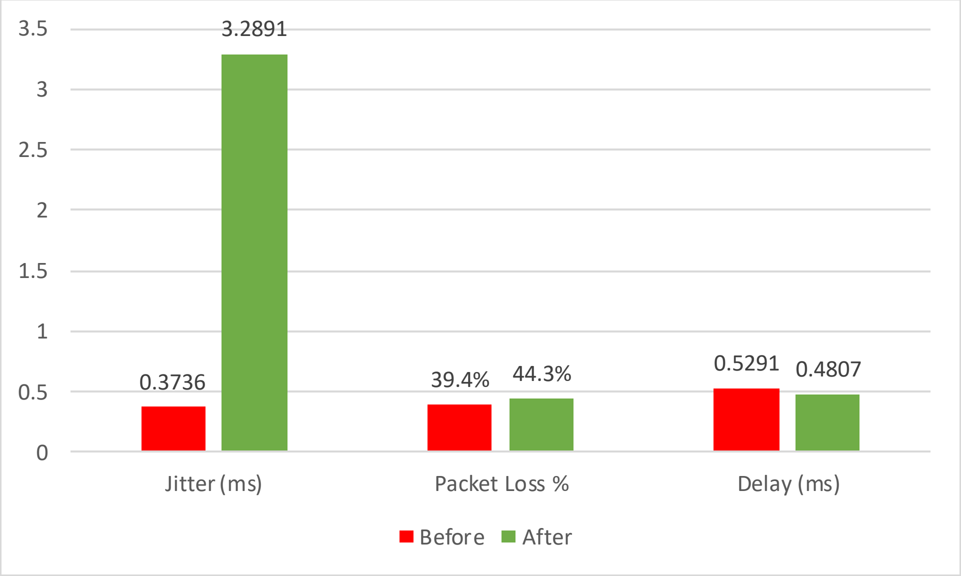


Figure 4-13: Comparison of QoS parameters in second scenario.

Chapter Five

Conclusion and Recommendations for Future Work

Chapter Five

Conclusion and Recommendations for Future Work

5.1. Conclusion

This research describes the implementation of Nayan Seth’s dynamic load balancing algorithm to efficiently distribute flows for fat-tree networks through multiple alternative paths between a single pair of hosts.

The network was tested before and after running the load balancing algorithm. The testing focused on some of QoS parameters such as throughput, delay, and packet loss between two servers in the fat-tree network.

The results showed that the network performance has increased after running the load balancing algorithm program, the algorithm was able to increase throughput, and improve network utilization. However, in large networks it increased packet loss and jitter.

5.2. Recommendations for Future Work

In future work, next suggestions are planned: The first suggestion is to investigate the performances of the dynamic load balancing program on a different popular SDN controllers, such as Research Floodlight, Beacon, NOX/POX, etc. and compare the results.

The second suggestion is to investigate the performances of different topologies of different sizes, other than the fat-tree topology. To test if there are any other limitations with the algorithm.

And finally is to extend the algorithm to traditional networks, or hybrid networks with both OpenFlow and regular switches.

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Appendixes

A Mininet topology

```
#!/usr/bin/python

from mininet.node import CPULimitedHost, Host, Node
from mininet.node import OVSKernelSwitch
from mininet.topo import Topo

class fatTreeTopo(Topo):

    "Fat Tree Topology"
    def __init__(self):
        "Create Fat tree Topology"

     Topo.__init__(self)

#Add hosts
h1 = self.addHost('h1', cls=Host, ip='10.0.0.1', defaultRoute=None)
h2 = self.addHost('h2', cls=Host, ip='10.0.0.2', defaultRoute=None)
h3 = self.addHost('h3', cls=Host, ip='10.0.0.3', defaultRoute=None)
h4 = self.addHost('h4', cls=Host, ip='10.0.0.4', defaultRoute=None)
h5 = self.addHost('h5', cls=Host, ip='10.0.0.5', defaultRoute=None)
h6 = self.addHost('h6', cls=Host, ip='10.0.0.6', defaultRoute=None)
h7 = self.addHost('h7', cls=Host, ip='10.0.0.7', defaultRoute=None)
h8 = self.addHost('h8', cls=Host, ip='10.0.0.8', defaultRoute=None)

#Add switches
s1 = self.addSwitch('s1', cls=OVSKernelSwitch)
s2 = self.addSwitch('s2', cls=OVSKernelSwitch)
s3 = self.addSwitch('s3', cls=OVSKernelSwitch)
s4 = self.addSwitch('s4', cls=OVSKernelSwitch)
s10 = self.addSwitch('s10', cls=OVSKernelSwitch)
s11 = self.addSwitch('s11', cls=OVSKernelSwitch)
s17 = self.addSwitch('s17', cls=OVSKernelSwitch)
s18 = self.addSwitch('s18', cls=OVSKernelSwitch)
s21 = self.addSwitch('s21', cls=OVSKernelSwitch)
s22 = self.addSwitch('s22', cls=OVSKernelSwitch)


#Add links
self.addLink(h1, s1)
self.addLink(h2, s1)
self.addLink(h3, s2)
self.addLink(h4, s2)
self.addLink(h5, s3)
self.addLink(h6, s3)
self.addLink(h7, s4)
self.addLink(h8, s4)
self.addLink(s1, s21)
self.addLink(s21, s2)
self.addLink(s1, s10)
self.addLink(s2, s10)
self.addLink(s3, s11)
self.addLink(s4, s22)
self.addLink(s11, s4)
self.addLink(s3, s22)
self.addLink(s21, s17)
self.addLink(s11, s17)
self.addLink(s10, s18)
self.addLink(s22, s18)

topos = { 'mytopo': (lambda: fatTreeTopo() ) }
```

B Load balancing algorithm program

```
#!/usr/bin/env python
# Orignal Code written by: Nayan Seth
# Date: Apr 26, 2016

import requests
from requests.auth import HTTPBasicAuth
import json
import unicodedata
from subprocess import Popen, PIPE
import time
import networkx as nx
from sys import exit

# Method To Get REST Data In JSON Format
def getResponse(url,choice):
      response = requests.get(url, auth=HTTPBasicAuth('admin', 'admin'))
      if(response.ok):
            jData = json.loads(response.content)
            if(choice=="topology"):
                  topologyInformation(jData)
            elif(choice=="statistics"):
                  getStats(jData)
      else:
            response.raise_for_status()

def topologyInformation(data):
      global switch
      global deviceMAC
      global deviceIP
      global hostPorts
      global linkPorts
      global G
      global cost

      for i in data["network-topology"]["topology"]:
            for j in i["node"]:
                  # Device MAC and IP
                  if "host-tracker-service:addresses" in j:
                        for k in j["host-tracker-service:addresses"]:
                              ip = k["ip"].encode('ascii','ignore')
                              mac = k["mac"].encode('ascii','ignore')
                              deviceMAC[ip] = mac
                              deviceIP[mac] = ip

                  # Device Switch Connection and Port
                  if "host-tracker-service:attachment-points" in j:
                        for    k    in    j["host-tracker-service:attachment-
points"]:
                              mac              =              k["corresponding-
tp"].encode('ascii','ignore')
                              mac = mac.split(":",1)[1]
                              ip = deviceIP[mac]
                              temp = k["tp-id"].encode('ascii','ignore')
                              switchID = temp.split(":")
                              port = switchID[2]
                              hostPorts[ip] = port
                              switchID = switchID[0] + ":" + switchID[1]
                              switch[ip] = switchID

      # Link Port Mapping
      for i in data["network-topology"]["topology"]:
            for j in i["link"]:
                  if "host" not in j['link-id']:
                        src                    =                    j["link-
id"].encode('ascii','ignore').split(":")
                        srcPort = src[2]
                        dst            =            j["destination"]["dest-
tp"].encode('ascii','ignore').split(":")
                        dstPort = dst[2]
                        srcToDst = src[1] + "::" + dst[1]
                        linkPorts[srcToDst] = srcPort + "::" + dstPort
                        G.add_edge((int)(src[1]),(int)(dst[1]))

def getStats(data):
      print "\nCost Computation....\n"
      global cost
      txRate = 0
      for i in data["node-connector"]:
            tx   =   int(i["opendaylight-port-statistics:flow-capable-node-
connector-statistics"]["packets"]["transmitted"])
            rx   =   int(i["opendaylight-port-statistics:flow-capable-node-
connector-statistics"]["packets"]["received"])
            txRate = tx + rx
            #print txRate

      time.sleep(2)

      response = requests.get(stats, auth=HTTPBasicAuth('admin', 'admin'))
      tempJSON = ""
      if(response.ok):
            tempJSON = json.loads(response.content)

      for i in tempJSON["node-connector"]:
            tx   =   int(i["opendaylight-port-statistics:flow-capable-node-
connector-statistics"]["packets"]["transmitted"])
```

```
        rx = int(i["opendaylight-port-statistics:flow-capable-node-
connector-statistics"]["packets"]["received"])
        cost = cost + tx + rx - txRate

    #cost = cost + txRate
    #print cost

def systemCommand(cmd):
    terminalProcess = Popen(cmd, stdout=PIPE, stderr=PIPE, shell=True)
    terminalOutput, stderr = terminalProcess.communicate()
    print "\n*** Flow Pushed\n"

def pushFlowRules(bestPath):

    bestPath = bestPath.split("::")

    for currentNode in range(0, len(bestPath)-1):
        if (currentNode==0):
            inport = hostPorts[h2]
            srcNode = bestPath[currentNode]
            dstNode = bestPath[currentNode+1]
            outport = linkPorts[srcNode + "::" + dstNode]
            outport = outport[0]
        else:
            prevNode = bestPath[currentNode-1]
            #print prevNode
            srcNode = bestPath[currentNode]
            #print srcNode
            dstNode = bestPath[currentNode+1]
            inport = linkPorts[prevNode + "::" + srcNode]
            inport = inport.split("::")[1]
            outport = linkPorts[srcNode + "::" + dstNode]
            outport = outport.split("::")[0]

xmlSrcToDst = '\'<?xml version=\"1.0\" encoding=\"UTF-8\"
standalone=\"no\"?><flow
xmlns=\"urn:opendaylight:flow:inventory\"><priority>32767</priority><flow-
name>Load Balance 1</flow-name><match><in-port>' + str(inport) +'</in-
port><ipv4-destination>10.0.0.1/32</ipv4-destination><ipv4-
source>10.0.0.4/32</ipv4-source><ethernet-match><ethernet-
type><type>2048</type></ethernet-type></ethernet-
match></match><id>1</id><table_id>0</table_id><instructions><instruction><o
rder>0</order><apply-actions><action><order>0</order><output-
action><output-node-connector>' + str(outport) +'</output-node-
connector></output-action></action></apply-
actions></instruction></instructions></flow>\''

xmlDstToSrc = '\'<?xml version=\"1.0\" encoding=\"UTF-8\"
standalone=\"no\"?><flow
xmlns=\"urn:opendaylight:flow:inventory\"><priority>32767</priority><flow-
```

```
name>Load Balance 2</flow-name><match><in-port>' + str(outport) +'</in-
port><ipv4-destination>10.0.0.4/32</ipv4-destination><ipv4-
source>10.0.0.1/32</ipv4-source><ethernet-match><ethernet-
type><type>2048</type></ethernet-type></ethernet-
match></match><id>2</id><table_id>0</table_id><instructions><instruction><o
rder>0</order><apply-actions><action><order>0</order><output-
action><output-node-connector>' + str(inport) +'</output-node-
connector></output-action></action></apply-
actions></instruction></instructions></flow>\''

flowURL = "http://127.0.0.1:8181/restconf/config/opendaylight-
inventory:nodes/node/openflow:"+ bestPath[currentNode] +"/table/0/flow/1"

command = 'curl --user "admin":"admin" -H "Accept: application/xml" -H
"Content-type: application/xml" -X PUT ' + flowURL + ' -d ' + xmlSrcToDst

systemCommand(command)

flowURL = "http://127.0.0.1:8181/restconf/config/opendaylight-
inventory:nodes/node/openflow:"+ bestPath[currentNode] +"/table/0/flow/2"

command = 'curl --user "admin":"admin" -H "Accept: application/xml" -H
"Content-type: application/xml" -X PUT ' + flowURL + ' -d ' + xmlDstToSrc

systemCommand(command)

      srcNode = bestPath[-1]
      prevNode = bestPath[-2]
      inport = linkPorts[prevNode + "::" + srcNode]
      inport = inport.split("::")[1]
      outport = hostPorts[h1]

xmlSrcToDst = '\'<?xml version=\"1.0\" encoding=\"UTF-8\"
standalone=\"no\"?><flow
xmlns=\"urn:opendaylight:flow:inventory\"><priority>32767</priority><flow-
name>Load Balance 1</flow-name><match><in-port>' + str(inport) +'</in-
port><ipv4-destination>10.0.0.1/32</ipv4-destination><ipv4-
source>10.0.0.4/32</ipv4-source><ethernet-match><ethernet-
type><type>2048</type></ethernet-type></ethernet-
match></match><id>1</id><table_id>0</table_id><instructions><instruction><o
rder>0</order><apply-actions><action><order>0</order><output-
action><output-node-connector>' + str(outport) +'</output-node-
connector></output-action></action></apply-
actions></instruction></instructions></flow>\''

xmlDstToSrc = '\'<?xml version=\"1.0\" encoding=\"UTF-8\"
standalone=\"no\"?><flow
xmlns=\"urn:opendaylight:flow:inventory\"><priority>32767</priority><flow-
name>Load Balance 2</flow-name><match><in-port>' + str(outport) +'</in-
port><ipv4-destination>10.0.0.4/32</ipv4-destination><ipv4-
```

```
source>10.0.0.1/32</ipv4-source><ethernet-match><ethernet-
type><type>2048</type></ethernet-type></ethernet-
match></match><id>2</id><table_id>0</table_id><instructions><instruction><o
rder>0</order><apply-actions><action><order>0</order><output-
action><output-node-connector>'     +     str(inport)     +'</output-node-
connector></output-action></action></apply-
actions></instruction></instructions></flow>\''

flowURL       =       "http://127.0.0.1:8181/restconf/config/opendaylight-
inventory:nodes/node/openflow:"+ bestPath[-1] +"/table/0/flow/1"

command = 'curl --user \"admin\":\"admin\" -H \"Accept: application/xml\" -
H \"Content-type: application/xml\" -X PUT ' + flowURL + ' -d ' + xmlSrcToDst
systemCommand(command)

flowURL       =       "http://127.0.0.1:8181/restconf/config/opendaylight-
inventory:nodes/node/openflow:"+ bestPath[-1] +"/table/0/flow/2"

command  =  'curl  --user  "admin":"admin"  -H  "Accept:  application/xml"  -H
"Content-type: application/xml" -X PUT ' + flowURL + ' -d ' + xmlDstToSrc

systemCommand(command)

# Main
# Stores H1 and H2 from user
global h1,h2,h3
h1 = ""
h2 = ""

print "Enter Host 1"
h1 = int(input())
print "\nEnter Host 2"
h2 = int(input())
print "\nEnter Host 3 (H2's Neighbour)"
h3 = int(input())

h1 = "10.0.0." + str(h1)
h2 = "10.0.0." + str(h2)
h3 = "10.0.0." + str(h3)

flag = True
while flag:
      #Creating Graph
      G = nx.Graph()
      # Stores Info About H3 And H4's Switch
      switch = {}
      # MAC of Hosts i.e. IP:MAC
      deviceMAC = {}
      # IP of Hosts i.e. MAC:IP
      deviceIP = {}
      # Stores Switch Links To H3 and H4's Switch
      switchLinks = {}
      # Stores Host Switch Ports
      hostPorts = {}
      # Stores Switch To Switch Path
      path = {}
      # Stores Link Ports
      linkPorts = {}
      # Stores Final Link Rates
      finalLinkTX = {}
      # Store Port Key For Finding Link Rates
      portKey = ""
      # Statistics
      global stats
      stats = ""
      # Stores Link Cost
      global cost
      cost = 0

      try:
            # Device Info (Switch To Which The Device Is Connected & The MAC
Address Of Each Device)
            topology = "http://127.0.0.1:8181/restconf/operational/network-
topology:network-topology"
            getResponse(topology,"topology")

            # Print Device:MAC Info
            print "\nDevice IP & MAC\n"
            print deviceMAC

            # Print Switch:Device Mapping
            print "\nSwitch:Device Mapping\n"
            print switch
            # Print Host:Port Mapping
            print "\nHost:Port Mapping To Switch\n"
            print hostPorts

            # Print Switch:Switch Port:Port Mapping
            print "\nSwitch:Switch Port:Port Mapping\n"
            print linkPorts

            # Paths
            print "\nAll Paths\n"
            #for path in nx.all_simple_paths(G, source=2, target=1):
                  #print(path)
            for path in nx.all_shortest_paths(G,
source=int(switch[h2].split(":",1)[1]),
target=int(switch[h1].split(":",1)[1]), weight=None):
                  print path
            # Cost Computation
            tmp = ""
            for        currentPath        in        nx.all_shortest_paths(G,
source=int(switch[h2].split(":",1)[1]),
target=int(switch[h1].split(":",1)[1]), weight=None):
                  for node in range(0,len(currentPath)-1):
                        tmp = tmp + str(currentPath[node]) + "::"
                        key     =     str(currentPath[node])+     "::"     +
str(currentPath[node+1])
                        port = linkPorts[key]
                        port = port.split(":",1)[0]
                        port = int(port)
                        stats                                                  =
"http://localhost:8181/restconf/operational/opendaylight-
inventory:nodes/node/openflow:"+str(currentPath[node])+"/node-
connector/openflow:"+str(currentPath[node])+":"+str(port)
                        getResponse(stats,"statistics")
                  tmp = tmp + str(currentPath[len(currentPath)-1])
                  tmp = tmp.strip("::")
                  finalLinkTX[tmp] = cost
                  cost = 0
                  tmp = ""
print "\nFinal Link Cost\n"
print finalLinkTX

shortestPath = min(finalLinkTX, key=finalLinkTX.get)
print "\n\nShortest Path: ",shortestPath
pushFlowRules(shortestPath)
            time.sleep(60)
      except KeyboardInterrupt:
            break
            exit
```