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Towards the Development of Network Service Cost Modeling-An ISP Perspective

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Abstract

Accurate network costing provides insightful information to any ISP for better network planning, profits, and decision making. Developing precise cost models for communication network services has always been a challenge for Internet Service Providers (ISP) due to the complex nature of today's advanced shared cloud and network infrastructure. Currently, developing and maintaining such cost models require significant effort and time for the network planners in an ISP. The proposed novel methodology reduces the development cycle time significantly for the cost model, which leads to the ISP's operational cost savings. We also experimented with K-means clustering for grouping router costs in the study, which provided similar unit cost results. To prove the operational savings, we evaluated a quantitative example considering the current practice as well as our proposed methods. We considered three network services: IPVPN service, Transport Lease service, and High-Speed Internet service for the experiments. We conducted simulations, and estimated service unit costs to validate the accuracy and effectiveness of our proposed approaches. We have compared results from proposed strategies with the existing cost mechanism and computed the performance improvement cost gap for different network sizes. This cost gap (delta) exhibited that the difference between the service cost values is significantly negligible, which proved the efficiency of our cost model.

Keywords

Network cost models, ISP, network costing, Capex, Opex, network services

Summary for Lay Audience

There is a significant increase in communication services from the past several years. Service providers need to manage their network as well as their associated costs. For this purpose, a sustainable cost model facilitates them to evaluate decisions for their network. This thesis aims to present a novel approach in developing a cost model for network services that helps the network planners and modelers that would result in potential operational savings.

The thesis briefly explained the notion of network costing and investigated several methodologies related to network costs, which we classified into wireline and wireless networks. Our primary focus is to explore and analyze service cost modeling methodology from an ISP perspective. We first investigated the mechanism that already being used by the researchers and industry and then proposed two service cost modeling methodologies for grouping router cost values. We analyze our approach using publicly available router data. We implemented the service cost model framework, in which the computation involved cost and capacities data of the relevant network nodes/routers. The first method is the simple mathematical approach of grouping the router's cost and capacity values into three types comprised of minimum, median, and maximum values. In the second method, we applied the K-means clustering algorithm that grouped the data into three router types based on the cost values similarity. This thesis considered three network services: IPVPN service, Transport Lease service TLS, and High-speed internet service HSI for various network sizes for unit cost estimation applying both approaches.

The service unit cost results obtained from the service cost model framework for all three services considered. We also compared the unit cost results estimated from the current cost method practiced in the industry with the unit costs values achieved from the proposed methods. The purpose of the comparison is to demonstrate the closeness of service cost results. Also, to validate the accuracy of the results obtained from the proposed cost modeling methodologies that would assist in saving ISP Opex by reducing the employee hours spent to model service costs.

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Table of Contents

Abstract ii

Summary for Lay Audience iii

Acknowledgments iv

Table of Contents v

List of Tables ix

List of Figures x

Chapter 1 1

1 Introduction and Motivation 1

1.1 Significance of Network Economics 2

1.2 Research Problem 2

1.3 Contribution and Scope 3

1.4 Novelty 4

1.5 Thesis Structure 4

Chapter 2 5

2 Background 5

2.1 Network Costing 5

2.2 Basis of Network Cost Structure 5

2.2.1 Network Capital Expenditure (Capex) 5

2.2.2 Network Operational Expenditure (Opex) 7

2.3 ISP Network Architecture 8

2.3.1 Access Layer 9

2.3.2 Edge / Aggregation Layer 9

2.3.3 Core Layer 9

2.4 Network Components 10

2.4.1 Customer Premise Equipment CPE 10
2.4.2 Next-Gen Ethernet Switch 10
2.4.3 Edge Router 10
2.4.4 Optical Cross-connect (OXC) 10
2.4.5 Optical Transport Switch 11
2.4.6 Core Router 11
2.4.7 Gateway or Border Router 11
2.5 Router Capacity Configuration 11
2.5.1 Chassis 12
2.5.2 Slots 12
2.5.3 Line Cards 12
2.5.4 Gigabit Ports 12
2.6 Service Definitions 13
2.6.1 IPVPN Service 13
2.6.2 Transport Lease Service 13
2.6.1 High-Speed Internet Service 14
Chapter 3 15
3 « Literature Review 15
3.1 Cost Strategies for Wireline Networks 15
3.1.1 Capacity Costing 16
3.1.2 Infrastructure Costing 16
3.1.3 Service Costing 17
3.1.4 SDN Migration Costing 19
3.2 Cost Strategies for Wireless Networks 19
3.2.1 Capacity Costing 19
3.2.2 Infrastructure Costing 21

3.2.3 SDN Migration Costing 22
3.2.4 SDN Infrastructure Costing 22
3.3 Discussion and Contribution 23
Chapter 4 26
4 Problem Formulation 26
4.1 Network Size 27
4.2 Router Cost 27
4.3 Router Capacity 27
4.4 Unit Cost of Service 28
4.5 Cost Gap (Delta) 28
Chapter 5 30
5 Service Cost Model Framework 30
5.1 Model Description 30
5.2 Total Network Infrastructure Cost Module 31
5.3 Service Cost Module 32
5.4 Existing Service Cost Approach 34
5.5 Proposed Service Cost Model Approach 35
5.5.1 Grouping in Three Router Types (T1, T2, T3) 35
5.5.2 CPE 37
5.5.3 Edge 37
5.5.4 Optical Transport Switch 38
5.5.5 Core 38
5.5.6 Unit Cost 38
5.6 K-Means Clustering for Grouping Router Cost 39
5.6.1 Clustering for T1 T2 and T3 39
5.6.2 CPE 42

5.6.3 Edge 42
5.6.4 Optical Transport Switch 42
5.6.5 Core 43
5.6.6 Unit Cost 43
5.7 Cost Gap Analysis 43
5.8 Opex Saving Example 44
5.8.1 Opex Parameters 45
5.8.2 Opex Calculations 45
5.8.3 Opex Savings 46
Chapter 6 47
6 Simulation Results 47
6.1 Evaluation Metrics 47
6.2 Experimental Analysis Utilizing Various Network Sizes 47
6.2.1 IPVPN Service 48
6.2.2 Transport Lease Service (TLS) 49
6.2.3 High-Speed Internet Service (HSI) 51
6.3 Additional Results for Different Number of Groups 52
6.3.1 Grouping Router Cost into 2, 3, 5 and 7 Different Types 52
6.4 Result Summary 53
Chapter 7 55
7 Conclusion 55
7.1 Limitations and Future Work 56
References 57
Curriculum Vitae 63

List of Tables

Table 1: Core Router Config Example 12

Table 2: Nodes Used in Three Services 14

Table 3: Node Configuration 31

Table 4: Total Cost of Network Nodes 32

Table 5: Total Capacity of Network Nodes 32

Table 6: Service Unit Cost (Existing Approach) 34

Table 7: CPE Node for T1, T2, T3 37

Table 8: Edge Node for T1, T2, T3 37

Table 9: Optical Node for T1, T2, T3 38

Table 10: Core Node for T1, T2, T3 38

Table 11: CPE Node for T1, T2, T3 42

Table 12: Edge Node for T1, T2, T3 42

Table 13: Optical Node for T1, T2, T3 42

Table 14: Core Node for T1, T2, T3 43

Table 15: Cost Gap-Min-Max Approach 44

Table 16: Cost Gap - Clustering Approach 44

Table 17: General Opex parameters for employee hours 45

Table 18: Employee hours assignment 46

Table 19: Opex Savings: Proposed methods 46

Table 20: IPVPN Service Results – Grouped in 3 Router Types 49

Table 21: TLS Service Results – Grouped in 3 Router Types 50

Table 22: HSI Service Results– Grouped in 3 Router Types 51

Table 23: IPVPN Service Results from Different Number of Groupings 53

Table 24: Results Comparison from Proposed Methods – 3 Groups 53

List of Figures

Figure 1: General Expenditure Structure of a Network 6

Figure 2: ISP Network 9

Figure 3: Network Cost Strategies Tree... 15

Figure 4: TDM and WDM Passive Optical Network 16

Figure 5: SDN Control Plane Architecture 18

Figure 6: 4G LTE / 5G Wireless Network.. 20

Figure 7: Network Nodes in ISP Network 26

Figure 8: Cost Model Flow 30

Figure 9: Service Nodes... 33

Figure 10: Assigning Values to router types.. 36

Figure 11: Three Clusters for IPVPN service nodes.. 41

Figure 12: Cost Gap – IPVPN Service 48

Figure 13:Cost Gap-Transport Lease Service 50

Figure 14: Cost Gap – High-Speed Internet Service 51

Chapter 1

1 Introduction and Motivation

As networking requirements and protocols are growing and evolving rapidly, service providers need to comprehend network economics. It includes network infrastructure, services provided, deployments, migration from legacy network elements. It is required to understand the factors which affect the cost of the overall network. Therefore; to develop a network cost model becomes an essential part of any Internet service provider. They need a sustainable cost model to attribute and evaluate decisions for a total cost, by evaluating capital expenditures (Capex), saving operational expenses (Opex) and understand the profitability of the services provided to users.

In the era of next-generation networking, there is a significant surge in internet traffic for both fixed and mobile networks. This increment reflects the rise in the number of users as well as internet protocol IP traffic [7] per end user. With the rapid growth in such factors, costs associated with internet service provider's network are affected in terms of their network infrastructure, speed, bandwidth, and services. As mentioned, costing a network has become a crucial part of better and futuristic decisions in terms of revenues and profits. There have been many approaches [32-45] to model costs, which considered the network infrastructure, capacity, migration from legacy networks to software defined network (SDN). However, to develop a viable service costing methodology remains an open problem for ISPs and requires attention in academia.

The actual motivation comes from the approaches used in academia and also from industry, where most of the costing methodologies consume lengthy modeling hours. This thesis aims to provide a general end-to-end network service costing framework for the shared networks. It would facilitate network planners in service cost models development and to save operational overhead to ISP. Here, the main focus is providing a novel approach for modeling service unit cost and compare the results with the existing service cost modeling methods already being used by researchers and industry. We evaluated a cost gap difference between the service costs of existing and our proposed approach.

Further, to show how this approach helps in reducing Opex to ISP, we considered three ISP services in the thesis: IPVPN Service, Transport Lease Service (TLS), and High-Speed Internet Service (HSI) [31]. Additionally, we applied the K-means clustering algorithm [50], an existing machine learning technique, to derive router cost values that simplify cost model development for any service. The unit cost results are compared to show the utilization of the machine learning approach to contribute and generate expected results. The purpose of the comparison is to validate the accuracy of the unit cost of service obtained from our proposed cost modeling approaches. Moreover, to show the potential operational savings, we created a scenario for estimating the Opex cost of ISP.

In this section, we have discussed the introduction and motivation. The rest of this chapter explained the notion and significance of network costing or economics and presented our research challenge, which is the core of the thesis.

1.1 Significance of Network Economics

Over the years, we can notice the growth in the number of internet users or subscribers, which increases the user demands in terms of different resources such as applications, bandwidth. Consequently, we can see a significant rise in internet traffic [1]. To bring value to the network, all network service providers are handling the user demands for consistent bandwidth or speeds while managing their network costs effectively. The ISPs are reliant on their internet infrastructure, services, and cost information that helps them to set up the price for their services offered to end-user yet yield enough profit.

1.2 Research Problem

The above paragraphs draw the importance of a complete service costing structure to ISP, which leads to a significant research problem:

> "*How to develop an efficient approach that minimizes employee hours spent in service cost model development and leads to potential operational savings for ISPs.*"

Our goal is to address the real-world challenge for network planners in any ISP that requires significant time and effort in developing sustainable cost models for network services offered by ISPs.

1.3 Contribution and Scope

There are various methodologies and approaches have been carried out in the area of network costing. Our contribution towards service cost modeling methodology aims to minimize the complicated process, hours of operation and effort spend on modeling cost for any single service. The main objective is to provide a methodology that simplifies the cost modeling process and minimize the number of modeling hours with significant reduction in operational cost to ISP. We presented the novel approach to model the service unit costs by classifying the router cost into three types. We also investigated and adapted an existing machine learning algorithm, namely the K-means clustering algorithm, for grouping router cost values into three types. The cost of each network service is based on the following network components: Customer Premise Equipment, NG- Ethernet Router, Edge Router, Optical Cross-Connect, Optical Transport Switch, Gateway, and Core Routers. We calculated the cost [2] and capacity for each node for the total network cost and service unit cost values. Below are the technical contributions of our proposed models.

- We modeled an end-to-end service costing framework for shared networks of small to large network sizes. The framework structure consists of the implementation of four modules for the estimation of Unit Costs.

  I. Existing Approach.

  II. Proposed (Novel Min-Max) Approach.

  III. Proposed (K-Means Clustering) Approach.

- Validation of Proposed Approaches

  IV. Cost Gap(delta): Compared service cost results from the Service Cost Module I with proposed methodologies in II and III.

- The thesis presented a scenario to estimate the Opex overhead from the existing cost modeling practice and analyze its savings to the ISP utilizing our proposed methods.
- We simulated the results for different size networks (small, medium, large) considering a various number of nodes into account for every network size.

1.4 Novelty

The novelty of the research is the efficient cost modeling of network services of any network size for any ISP. As in later sections, literature work shows that there has not been much work done on the complete network cost structure for network services. This thesis will play a part in helping researchers, operators, and service providers to understand the comprehensive methodology of modeling the service unit costs.

1.5 Thesis Structure

The structure of the thesis is as follows; Chapter 1 provided an overview of the notion of network costing, motivation, research objective, and contribution. In Chapter 2, we presented a background, terminologies, and service definitions. Chapter 3 is the related work where we analyze the existing research in wireline and wireless network cost modeling. Chapter 4 discussed the problem formulation and assumptions considered in the study. In Chapter 5, we demonstrated the service costing framework employing our proposed modeling approaches and explained Opex saving example. Chapter 6 discussed the results and analysis. Chapter 7 concluded the thesis and discussed the limitations and directions of future work.

Chapter 2

2 Background

A brief overview of the general network cost structure, network components, and service definitions are presented in this chapter.

2.1 Network Costing

Network costing is a process to evaluate the total value for physical network equipment, deployment, transmission, capacities, and services provided by network operators. The network cost model is a tool to estimate the cost values of network equipments and related network elements. These tools are used by regulators to monitor the prices and regulate it for connection and services provided to end-users. However, over the period, ISPs and network operators also develop cost models for their networks [3]. For the next-generation networks, the notion of accurate network cost information demands new approaches for the assessment of network costs to service providers for the delivery of various services provided to customers [4].

2.2 Basis of Network Cost Structure

Generally, the cost structure comprised of capital expenditures or initial investment and operational or running expense of any wireline and wireless network in the telecommunication industry. Figure 1 shows a general structure of network expenditure. However, we explained some of the vital cost categories in the report.

2.2.1 Network Capital Expenditure (Capex)

We mainly asses the Capex cost as the expenses related to fixed network infrastructure. It is related to the land and site cost, purchase, and installation of physical infrastructure. Some of the Capex related items include physical network devices (routers and switches), links (Fiber or microwave), software cost, and cost of network upgrade [35].

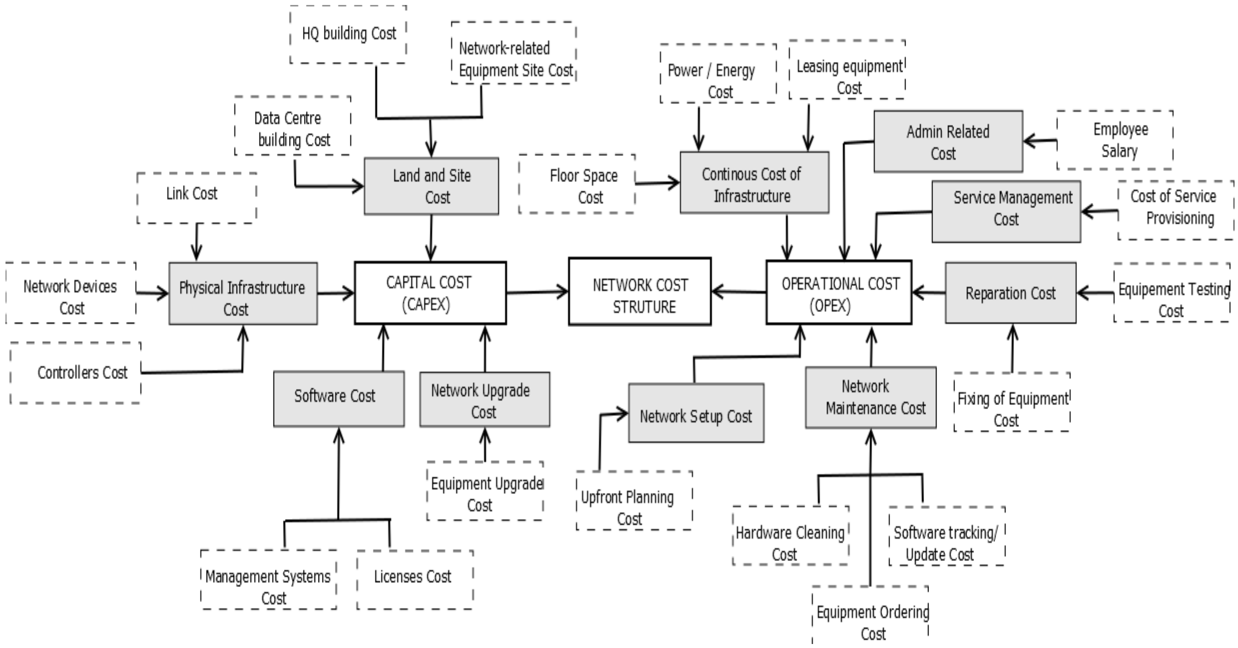

Figure 1: General Expenditure Structure of a Network [52]

2.2.1.1 Land and Site Cost

It is the vital cost factor for the network operator. Mostly it comprised of existing capital assets. These are the fixed assets used for the network's setup, such as purchase cost of land and poles, cost of leasing property for the network headquarters building, data center, central office location. The site-related capital costs consist of the expense of site preparation, base station, tower structure, and installation for microwave or optical fiber.

2.2.1.2 Physical Infrastructure Cost

Physical network infrastructure ensures the systematic and efficient transmission of end to end internet data traffic and proper connectivity through the network devices. These devices include access, edge, distribution, core, border routers, links, and servers. These costs are related to the hardware and network infrastructure elements. It includes the cost of routers, switches, controllers for SDN, and ethernet and optical fiber links.

2.2.1.3 Software Cost

Generally, the network management systems monitor both software and hardware resources in the network. The software management systems used in SDN separates the software from the hardware plane. However, in traditional networks, the software was embedded with the hardware devices. These software costs include the purchase of software management systems and controller software licenses.

2.2.1.4 Network Upgrade Cost

The network upgrade helps to keep the network operational by managing and maintaining any network, its bandwidth, performance, and availability of network devices. These expenses in this category occurred from the ongoing network upgrade activities such as adding/deleting/upgrading the network devices, controllers, and links[35].

2.2.2 Network Operational Expenditure (Opex)

Operational Expenditures (Opex) are the ongoing costs/expenses of an ISP. It includes but not limited to maintenance cost, reparation cost, service provisioning cost, floor space cost, cost of network planning, energy cost [5].

2.2.2.1 Continuous Cost of Infrastructure

It involves the framework that runs the business flow steady each day. These costs are the expenses that any network operator acquires in the process of depreciation of fixed assets. It includes the costs to keep up the operations without any network failing, such as floor space cost, energy-related cost, and cost of leasing the equipment.

2.2.2.2 Maintenance Cost

Maintenance is the fundamental process that occurs periodically in any network. It is the cost to operate the ISP network and its connected devices and maintaining them from failures. It includes the cost of such measures that keep the network protected from any fault and malfunction, such as hardware or software repair, and installs updates.

2.2.2.3 Reparation Cost

Reparation is the process of fixing any failure that happens in a network, includes the failure of any network node or service. These expenses are occurred due to the tasks related to repairing and fixing various types of failures in the network. It consists of the cost of diagnosis and analysis, technician truck roll, network failure fixing and repairs, and testing and verification.

2.2.2.4 Service Management Cost

Service management and provisioning is another primary process used to set up network services for end-users. It depends on the number of service requests from potential customers. It includes the service provisioning cost, moves or stops an existing network service, its order processing, and the necessary actions and test for the service provided to customers/end-users.

2.3 ISP Network Architecture

An Internet Service Provider (ISP) offers different communication services by providing internet connectivity to its subscribers [6]. Figure 2 shows the general network topology of a typical ISP and network components used in estimating the costs of network infrastructure and services. With the development in next-generation networks and an increase in technology-enabled applications and services, the network and service providers modify their information and communication architecture and its associated cost structures accordingly.

The evolving network services require a scalable, flexible, and efficient network infrastructure, which is typically composed of three main subnetworks, i.e., access, edge, and core networks [7]. The access network links the access equipment to the edge routers; the edge network aggregates the traffic flows to the core routers, and the core network consists of high-speed routers meshed together with high-speed links [7]. The three main components of IP networks are:

Access Layer, Edge Layer, and Core Layer.

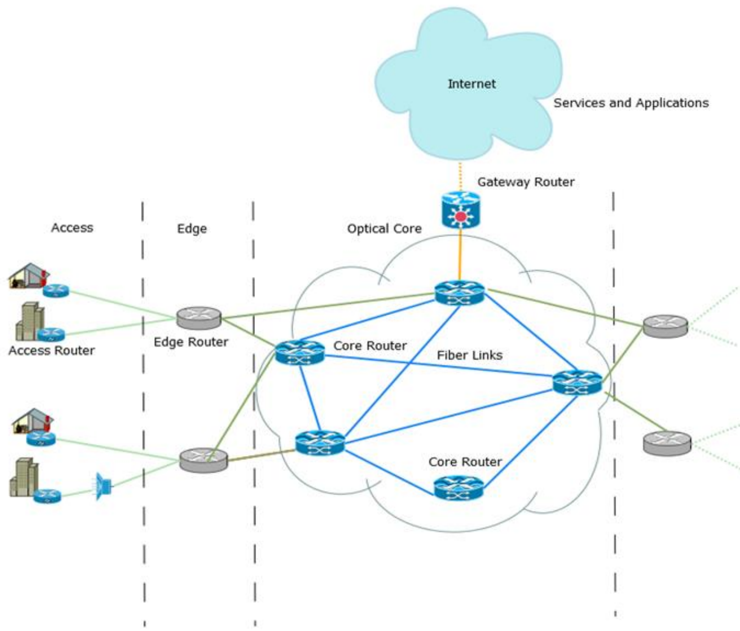

Figure 2: ISP Network

2.3.1 Access Layer

The access layer connects end-users' to an ISP, and other carriers engage in providing the internet connection [6]. It provides user access to the provider's network either by fixed access, which is a physical connection or mobile access which provides wireless connectivity through various technologies such as coaxial cable, optical fiber, LTE.

2.3.2 Edge / Aggregation Layer

In this layer, a single edge router can be connected to many customers directly. It acts as an intermediate layer which aggregates multiple subscribers to deliver network services by providing the connection to the ISP core network [8]. An additional layer is added for larger networks called the distribution layer, which aggregates the edge devices in a network [9].

2.3.3 Core Layer

The core layer in the network consists of core routers where network devices can communicate in a partial or full mesh network [8]. It provides connectivity for the aggregate, edge, access layers [8], and acts as the network backbone. Generally, the purpose of the backbone of the network is routing, delivery of data packets, and also used to control traffic carrying internet data of the various group of network connections [9].

2.4 Network Components

The network components used in this thesis for our service cost model are defined below.

2.4.1 Customer Premise Equipment CPE

Customer Premise Equipment (CPE) is the device that resides on the customer premises- either for residential or business subscribers. It provides network connectivity to the service provider network [10]. It offers specific services to the customer through components such as Modems, Wi-Fi gateways that are provided by ISPs [12].

2.4.2 Next-Gen Ethernet Switch

Ethernet is the most extensively used device over the years. An Ethernet gigabit switch or router manages the traffic or the bandwidth of the network to different nodes or devices connected. However, ethernet switches require a modem or router to communicate with various network systems [13]. Gigabit Ethernet is the technology that enables and brings together internetwork communication through internet protocol IP [15]. It can provide higher capacities up to 100 Gbps and is cost-efficient for LAN, MAN, and WAN networks [14].

2.4.3 Edge Router

The edge node or router is the point in the network that aggregates multiple subscriber connections [21]. It is also called the provider's edge, which is placed at the edge of the ISP backbone network. It aggregates network traffic and connects to the network core [25].

2.4.4 Optical Cross-connect (OXC)

The optical cross-connect is used to switch and manage the high-speed optical signals. It creates an interconnection between input and output ports in optical networks [11].

2.4.5 Optical Transport Switch

Optical transport networks (OTN) is a widely used technology that supports both fixed and mobile services that provides flexibility and high bandwidths [17]. It consists of optical nodes or transport switches based on *Wavelength Division Multiplexing (WDM)* that transmits a large amount of traffic and multiplexes the flow of data packets using different wavelengths [19]. WDM networks use the OTN switch, which is a high capacity network node that can operate at above 100 Gbps and achieve the service requirements of the core optical network [18]. In the transport networks, optical nodes are a significant part of the transport framework because of high capacity networks [20].

2.4.6 Core Router

The core router performs the function of the transmission of data packets. It connects to other core routers [10]. The Core networks utilize high capacity that serves to aggregate data packets from the edge node and transmits the traffic from source to its destination network [22]. These network routers serve as the service provider's IP backbone network [10].

2.4.7 Gateway or Border Router

A network gateway or border router connects two different ISPs such that the customers in different ISPs can communicate with each other [23]. These are the routers that provide border gateway routing protocol (BGP) [16] and facilitates data packets communication between two or multiple ISPs [24].

2.5 Router Capacity Configuration

The general elements in the router include chassis, memory, processor, slots, line cards, number of ports. Table 1 shows the necessary components of the ISP router. However, we have included line cards and several gigabit ports per line cards for router bandwidth calculation.

Table 1: Core Router Config Example

Router Type: CORE	Config	Card Type	Total Ports	Slot Utilization %	Port Utilization %	Port BW Utilization %
Chassis	Standard					
Memory	Standard				30 - 90	
Processor	Dual				50 - 90	
Power	Dual				one active, one backup	
EDGE facing slots	10			50-90		
		GE	10		50-80	50-90
		10GE	10		50-80	50-90
		40GE	6		30 - 80	50-90
		100GE	4		30 - 80	30-90
Core facing slots	8			50-90		
		40GE	6		30 - 80	50-90
		100GE	4		30 - 80	30-90

2.5.1 Chassis

A router chassis is a frame or structure that mounts and protects the internal router hardware elements [46]. It contains a different number of slots for hardware modules.

2.5.2 Slots

A router can have several slots in chassis to install memory, line cards, and ports.

2.5.3 Line Cards

A line card consists of various communication ports linked with the network through gigabit ports that operate at different speeds.

2.5.4 Gigabit Ports

Gigabit port specifies the transmission capacity of a billion bits per second. Generally referred to as gigabit ethernet ports. It supports various port types indicating their maximum transmission speeds such as 10GBase-T, 100GBase-T, 10GBase-X and more.

2.6 Service Definitions

We have used three types of services in the thesis for our cost model framework mentioned below:

i. IPVPN Service

ii. Transport Lease Service

iii. High-Speed Internet Service

2.6.1 IPVPN Service

The IPVPN services offered by ISPs create a logical virtual network by providing an encrypted and dedicated data connection [27]. As mentioned in AT&T white paper [28], IPVPN service creates an encrypted site to site secure connection between the service provider network and the customer carrying Voice over internet protocol VoIP data. In a virtual private network, designated private network end-points connect to each other through virtually dedicated connections securely [26]. Virtual encrypted tunnels between the customer endpoints are managed by this service [27]. IP VPN runs an IPsec protocol that protects the data from unwanted attacks or any malicious activity. Our IPVPN cost model includes particular network elements comprised of CPE, Edge routers, Optical switches, and Core routers for estimation of the unit cost of IPVPN service.

2.6.2 Transport Lease Service

A transport leased service is a reserved optical link used to connect two endpoints for data services [30]. The most common type these days is fiber leased line service, which employs fiber optic cables using different wavelengths of light to send the data packets over the glass fiber [29]. It shares a significant part of the transport lease and provides maximum speed. This service is mostly used by enterprises so that they connect to their departments or branches and avail continuous bandwidths for exchange of information utilizing a dedicated communication between two endpoints. The fiber lease line is reliable in terms of speed and scalability; however, it is expensive to deploy. Our cost model for transport lease service comprised of essential network elements includes CPE, optical cross-connect (OXC), and optical switches for unit cost estimation of transport lease service.

2.6.1 High-Speed Internet Service

The term high-speed internet also referred to broadband access, which offers high-speed internet services to residential and business customers [31]. High-speed internet (HSI) consists of CPE, Edge routers, Optical switches, Core, and Gateway routers in a network. We calculated the unit cost of HSI service based on these relevant network nodes in our model. Fiber optics is the newest and fastest technology in providing high-speed internet connections. The most common fiber connections that offer high internet speeds are [51]:

Fiber to the home (FTTN): In Fiber to the Node connection, the ISP provides fiber lines to the nearest central node shared among various numbers of users, which then connects through the traditional copper or coaxial cables to the end-user.

Fiber to the Node (FTTH): In Fiber to the Home connection, the ISP provides fiber lines directly to the customer premises. It offers high speeds; however, it is more expensive to install.

The below table 2 shows the network nodes included in each service for our cost model.

Table 2: Nodes Used in Three Services

Network Nodes	CPE	NG-Ethernet Router	Intermediate Node		Optical Transport Switch	Core Router	Gateway Router
Service			IP Edge	OXC			
HSI	✓	-	✓		✓	✓	✓
IPVPN	✓	-	✓		✓	✓	-
TLS	✓	-		✓	✓	-	-

Chapter 3

3 « Literature Review

Numerous amounts of research work have already been carried out to investigate the techno-economical methodologies for modeling network cost. In this thesis, we surveyed some of the relevant studies. It includes infrastructure costing, capacity costing, cost of SDN migration, and service cost values associated with optical networks, including fiber networks, heterogeneous wireless networks including 4G LTE, 5G. We have categorized the cost strategies in traditional and SDN based approaches for both wireline and wireless networks, respectively. The below Figure 3 presented the organization of methodologies studied for the thesis.

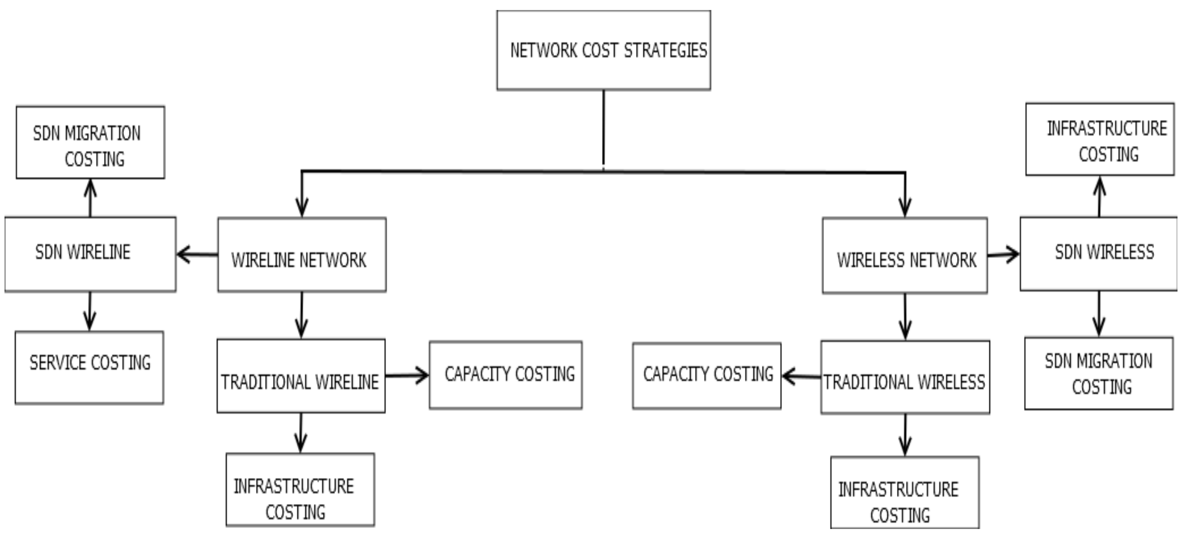

Figure 3: Network Cost Strategies Tree

3.1 Cost Strategies for Wireline Networks

We segregated the wireline network cost methods into the *traditional and SDN wireline networks*. In traditional wireline networks, the main functionalities are dependent on the dedicated hardware components such as switches, routers, copper cable, optical fiber, ethernet cables, that require manual installation and configuration for the devices requiring vendor interference. Whereas, SDN provides the functionality to mitigate the physical connectivity with the help of OpenFlow protocol, which keeps control plane and data plane separate, bringing hardware and software independence in the network infrastructure. We further classified the traditional and SDN based wireline into Infrastructure, Capacity, and SDN Migration and Service cost methodologies, respectively.

3.1.1 Capacity Costing

Czékus et al. [32] utilized an access traffic model to estimate the equipment cost for passive optical networks, as shown in Figure 4. The model used Time Division Multiplexing TDM PON and Wavelength Division Multiplexing WDM PON concerning bandwidth. Statistical multiplexing used in the study where active users can avail bandwidth from inactive users, which in turn optimizes cost for the network operator. Cost values of each TDM network element estimated as a sum of the cost of Optical Line Terminal OLT, Optical Network Unit ONU, Splitters depending on the total bandwidth of shared medium, and the number of end-users connected to the network. WDM cost calculated as the sum of each device OLT, ONU, Array Waveguide Grating AWG depending on the number of users and wavelengths. Czékus et al. [32] have well presented the comparison of TDM and WDM in terms of cost. However, the model is suitable for a limited number of users only and utilized the limited types of equipment for cost calculations.

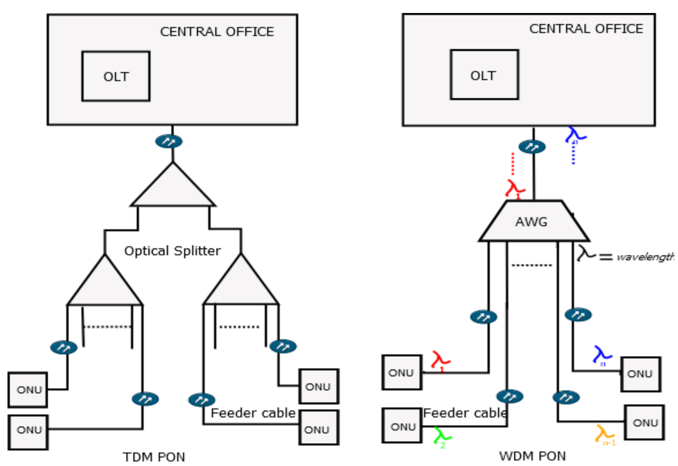

Figure 4: TDM and WDM Passive Optical Network

3.1.2 Infrastructure Costing

Maina and Kamau [33] proposed cost model considering two architectures, centralized fiber, and hierarchical star based on existing cost models: Tolly group cost model and The

Tia Fols LAN cost model. For both network architectures, desktop equipment, telecommunication room TR cost, main cross-connect cost, labor cost, and maintenance cost considered as parameters for the two-story building having three floors per building with 40 end-user ports. The total cost for both architectures was summarized where Network Interface Controller, Horizontal and vertical Cabling, TR Support Equipment, Switches considered as Capital Expenditures. Whereas labor cost, maintenance cost, upgrade costs, and other miscellaneous cost values considered as Operational Expenditure. The initial investment when installing the optical fiber has high labor cost as it does not require reinstalling the cables in the long term as it needed in hierarchical UTP copper network architecture, which makes copper network's overall cost higher than the fiber-based network architecture. Maina and Kamau [33] mainly discussed the mechanism and devices in evaluating the cost model, which can save the deployment cost.

Authors Van der Wee et al. [34] discussed a general fiber to the home FTTH network based on the number of customers and flexibility points where network equipment placed. Fiber networks categorized as Passive Optical Networks PON having a splitter with a ratio of 1:32 and Active Optical Network AON. The cost calculation based on the area, which is the hierarchical structure that further consists of sub-areas divided into modules: adoption module for forecasting number of subscribers, dimensioning module calculates the amount of fiber and trenching as street-based estimation, equipment module for the cost of equipment and number linked to customers. The Capex includes expenses for fiber employment, installation, and reinstallation of network equipment, whereas Opex includes maintenance, reparation, provisioning of connections and services, floor space, and power consumption. In the evaluation, the module combines all the calculated values results in final values using a discounted method over a specific number of years.

3.1.3 Service Costing

Karakus and Durresi [35] assessed the unit cost of service for a customer as the ratio of Capex and Opex over service requests or workload in a certain period with possible extra cost. There are three types of network architecture considered for overhead messages and workload: Centralized single controller, Distributed controllers, and Hierarchical controllers, as shown in Figure 5. Capex amounts to $5000 and is determined by the sum of physical infrastructure, which consists of the cost of network devices such as switches, routers, optical fiber, controller, links between devices, and software expenses. Opex changes concerning workload and overhead messages, which comprised the floor space cost, power, and energy-related cost, leasing network equipment cost, service provisioning and maintenance, and reparation cost. An architecture setting generating less overhead messages results in less Opex. When the number of requests from customers reaches overloading points in each architecture, extra CAPEX of $2500 added to the total cost, which shows more workload or service requests result in less unit service cost of the network.

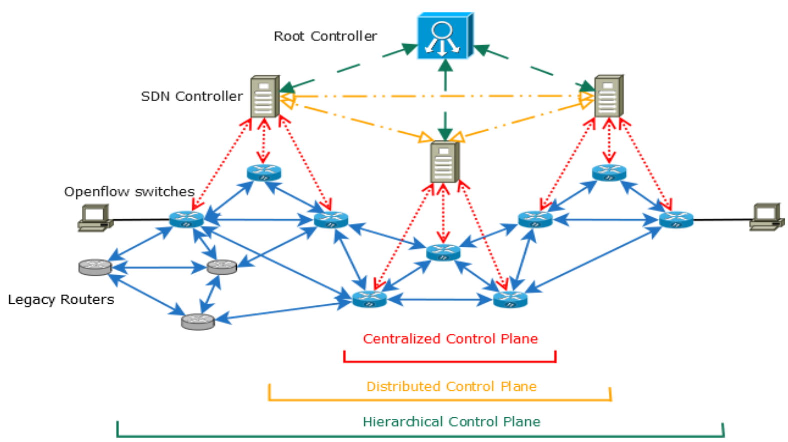

Figure 5: SDN Control Plane Architecture[53]

Chi et al. [56] proposed a new pricing methodology that charged each cloud tenant reasonably and offered efficient utilization of resources that, in turn, benefit the cloud providers in terms of cost and revenue generated. A task scheduling algorithm is used for fair resource allocation and utilization. The price weight depends upon the number of requests or virtual machines (VM) assigned to each cloud tenant hence change the price each tenant pay. The authors also examined the enhancement of the total revenue of the cloud providers. They also studied their proposed pricing methodology with the total unit price redistribution and total revenue redistribution that would increase the total revenue of the cloud service providers by 11.60% and 11.18%, respectively.

3.1.4 SDN Migration Costing

A network migration scheduling from legacy IP routers to SDN open flow switches is presented by Das et al. [36], as shown in Figure 5. Two scenarios of migration of nodes considered in the study. In the first scenario discussed, ISP has a limit on the number of routers to be migrated first. In the second scenario, the ISP has a limited amount of Capex for the migration of nodes at a single time. An algorithm presented to analyze the cost that indicates key nodes and ensures the migration scheduling between two paths and same node pair by computing the least cost path than the cost value of the first node between source and destination. With the limited investment, the cost (Capex) of migrating nodes invested for migration per time step is lower or equal than the Capex required for the entire migration period. The authors Das et al. [36] presented the algorithms that focused only on the initial investment in detail.

3.2 Cost Strategies for Wireless Networks

Conventional wireless networks operate the same as a wired network to connect the network components but work by radio-frequency technology. In wireless networking, SDN is overcoming the challenges of dedicated network systems, vendor dependence by decoupling the data and control plane and provided a centralized view of network devices and merged with the next-generation technologies, including 4G LTE and 5G.

3.2.1 Capacity Costing

The study examined by Nikolikj and Janevski [37], [38] and [39] is the cost capacity model for radio access technologies considering 4G LTE A Wi-Fi and 5G as presented in Figure 6. The model employed various band ranges of heterogeneous wireless networks with varied coverage and capacity parameters [37], [38] for the deployment of new and existing cell sites. Different base station classes (Macro, Metro Pico, Femto, and Wi-Fi) are studied where input parameters are used to estimate the unit cost for the base station, which is calculated using a discounted cash flow method. Nikolikj and Janevski [37], [38] and [39] considered deployment for 20 MHz bandwidth in 2.6 GHz band. Capex took as 110K for radio link and 10K of radio equipment, which gives a total of 120K of initial investment of number new sites. Upgrading Capex cost (reuse sites) as 10K besides of radio equipment cost of 10K makes 20K of total upgrade Capex cost.

In contrast to other two, Nikolikj and Janevski [38] mentioned Capex investment includes base station related Capex items which are base station equipment, base station (site) installation & buildout, backhaul transmission equipment, and radio network controller whereas Opex items include electric power, operation & maintenance, site lease, and backhaul transmission.

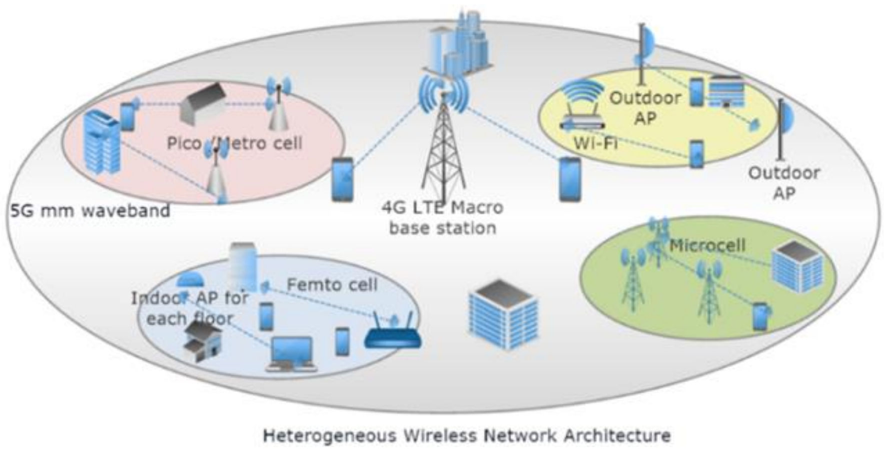

Figure 6: 4G LTE / 5G Wireless Network

LTE is also being utilized for multiuser localized single carrier frequency division multiple access (SC-FDMA) for the energy-efficient resource allocation for transmission of uplink traffic, where resources are dynamically allocated with the throughput demand [55]. Yunas et al. [40] mainly focused on the densification of the network and compared various parameters, including coverage, energy, capacity, and cost-efficiency of traditional macro and microcell technologies. The indoor femtocell deployment strategy assessed by increasing the number of base stations in the covered area to achieve a high capacity level. Different types of base stations considered for cost estimation; macro, micro, Femto sites, macro-Femto hybrid site, The Capex cost comprised of the cost of equipment, including radio base station, transmission equipment, antenna, cables, site deployment, and installation of equipment. Opex cost refers to the running cost of the rental site, leased line, operation, maintenance, and administration. Power consumption increases with the increase in the number of base stations. The total cost of a base station is the sum of capital and operational expenditures and calculated by the discounted method considering greenfield deployment over eight years with a 10% discount rate.

3.2.2 Infrastructure Costing

The total cost of ownership model of the complete backhaul lifecycle is presented by Mahloo et al. [41] in terms of Capex and Opex cost considering both wireless microwave and fiber to the building technology. The Capex includes Equipment and Infrastructure cost. The Opex items include an annual fee for spectrum and fiber leasing, the energy cost of equipment (CO, cabinets, microwave sites, indoor cells) in different locations along with maintenance, reparation costs. Capex and Opex components result in the Total Cost of Ownership TCO for mobile networks.

Rahman et al. [42] presented the cost structure for the virtual wireless access network. The wireless usage consumes high energy, which leads to an increase in operational expenses. Here, Capex refers to infrastructure cost, and Opex dealt with power consumption, which modeled for both traditional and virtualized networks. However, Capex for locally virtualized networks includes of cost infrastructure model per user with an increase in virtual base stations. Same as conventional network Opex, it refers to the total power consumption of base station allocated concerning the network capacity. Virtualized network Opex is the same as the traditional network Opex, which refers to the power consumption per bit of Super Base Station SBS. The SBS is the same as the typical BS with a slight difference of additional increase in each number of slices or virtual base stations by 20%. Total cost is mainly analyzed based on the number of base stations and did not consider the other hardware cost used in the network to calculate the overall cost values.

A combined cost model is presented by Knoll [43] for LTE network architecture with the number of points of presence POP locations for distributed and centralized scenarios. The cost of the LTE network is modeled by calculating Capex and Opex. It considered three scenarios where LTE equipment installed. The first scenario reviewed sixty POP locations for distributed architecture, second with three POP for centralized and last is less centralized with 13 POP regions. Capex components for LTE network categorized in the radio access network for 20000 base stations, aggregation, and core networks. Home Subscriber Server HSS, cache server, operator services server. Opex cost includes marketing, connection cost, upfront planning, initial network setup, non-telco infrastructure, and administration. The total cost yields as the sum of Capex and Opex of the network. The Capex and Opex values vividly imply that centralized architecture with 13 POP locations is the most cost-effective amongst the other two.

3.2.3 SDN Migration Costing

Naudts et al. [44] focused on exploring a new method by facilitating multiple mobile network operators on one common infrastructure and proposed the architecture for the network virtualization called Open Flow OF. This method can save the entire cost structure by upgrading the network to current standards. Naudts et al. [44] considered two scenarios of SDN non-shared network and virtualized shared-network for the techno-economic analysis and compared with the typical distributed architecture. In SDN non-sharing scenario, OF is used to decouple the control and forwarding plane. The Capex for SDN scenario includes the cost of network devices along with the extra cost of open flow controllers, line cards, transceivers. In the virtualized shared network scenario, several operators share network resources utilizing network virtualization, which includes the cost of radio base station RBS, network devices, and the number of switches run by OF controller. A reference network scenario considered in the study with two network operators with the same design and a different number of customers. The quantitative analysis results in less Capex cost values in comparison with the distributed network situation. Although SDN based shared scenario provides reduced Capex in comparison with SDN(non-shared) network.

3.2.4 SDN Infrastructure Costing

Bouras et al. [45] presented a techno-economic analysis to estimate the total cost of ownership (TCO) for the proposed 5G architecture employing Evolved Core Network EPC and Cloud Radio Access Network RAN for 5G mobile networks. Their work incorporated the new technologies (SDN and Network Function Virtualization NFV) in the next-generation network architectures (5G) and compared the cost of virtualized networks with the traditional one based on base stations deployed. Both NFV and SDN depend on the virtualization technology [57] that assists in implementing the scalable and programmable next-generation networks. The cost of network equipments and the energy costs of the network service provider can be affected significantly by the decoupling of hardware and software in a network. Bouras et al. [45], first evaluated the cost values of RAN concerning both conventional and virtualized networks, as estimated in [42]. Total energy cost assuming the BS antenna is shared among operators to reduce Opex cost. Bouras et al. [45] proposed Capex and Opex for virtualized Evolved Packet Core vEPC for 5G architecture. Capex for virtualized vEPC formulated as the sum of the total cost of servers, license fees, and leasing costs for the data center. Opex of vEPC refers to the power consumption of servers consist of servers required for HSS, and power consumes by each server and energy cost. Hence, the proposed total cost formulated as the sum of Capex and Opex for vRAN and vEPC. The proposed architecture utilized virtualization technology for resource sharing between physical infrastructure. A meaningful cost reduction in terms of Capex and Opex achieved, which leads to significant savings in TCO.

3.3 Discussion and Contribution

The above paragraphs explained the background notions and significant research works in the area of network cost modeling. Most of the researchers have considered a limited number of cost elements related to infrastructure, capacity, and SDN migration costing in their studies. However, there is not much work done for cost modeling of network services. In this thesis, we have discussed the relevant papers related to network costs and presented novel methodologies for the development of the service cost model. In research work [32] performed a comparison of Time Division Multiplexing (TDM) and Wavelength Division Multiplexing (WDM). They utilized the limited cost types of equipment for cost calculations, where bandwidth allocation is dependent on the number of users. Costing approach in [37], [38], [39] have mainly considered the costs for wireless networks relied on the value of base stations. Capacity cost strategy provides insight into cost modeling. However, it has not mentioned the detailed analysis of capital cost.

The authors in [33] followed the existing costing approaches in which the reinstallation of copper makes the overall cost higher than the optical networks. As fiber installation is a one-time cost, we have not considered in our service cost model for network services. Modeling Approach used in [34] is based on FTTH PON and AON, in which hardware cost is limited for a fiber network. However, we have attempted to utilize significant routers and switches to estimate the service unit cost values. The cost evaluation [41] well explained in terms of Total Cost of Ownership (TCO) for heterogeneous networks. However, an essential aspect of the cost for the radio base station for mobile networks not considered.

The cost model [43] presented is specifically for LTE networks used fixed number Point of Presence (PoP) locations discussed for distributed and centralized scenarios. In our approach, we have tried to analyze the results for various network sizes. Authors in [42] and [45] have mainly focused on the cost structure for virtual wireless access in which the capacity only depends on the base stations. However, our model has used the detailed computations of capacity values of routers and switches to estimate cost values. Cost strategies in [36] and [44] have shown the migration cost from traditional networks to SDN. However, authors in [44] have presented more broad aspects of SDN and shared SDN scenarios with a primary focus on core layer network types of equipment and their costs. Research work done in [35] has focused on service unit cost for three architectures mentioned; however, it ignored the installation of network devices or nodes in the study. Our work focused on network service cost modeling which considered purchase and installation cost for relevant network nodes in the study.

Most of the research works presented different areas of network costing. However, cost modeling for ISP network services is still an open research problem. Considering inputs and feedback in the study about the existing cost mechanism practiced in the industry, we have put an effort towards the development service cost modeling methodology that needs exploration by the scientific community. We proposed novel approaches for service cost modeling that shortens the lengthy process of cost model development. We have implemented the framework on how to facilitate the network planners in ISP without going through a complicated and time-intensive process to estimate the unit cost for any network service. The framework comprised of four modules, in which we first implemented the current mechanism of network cost estimation which involves computations of every node in service networks. Then we employed our proposed strategies for service cost estimation. Thereby we presented a mathematical approach namely the Min-Max approach. Moreover, we also applied a machine learning technique called K- means clustering approach and investigated the possible Opex savings achieved from our proposed methodologies.

Chapter 4

4 Problem Formulation

In this section, we formulated the research problem and described the variables and assumptions used to estimate the network cost. Let the network $\boldsymbol{G}$ has $\boldsymbol{N}$ number of nodes in any ISP network. We assumed six levels of network elements to model the service cost from access to the core network. We consider that each network element or node belongs to $\boldsymbol{V}$. Customer Premise Equipment CP ($\boldsymbol{CP}$), NG-Ethernet Router ($\boldsymbol{ETH}$), Edge Router/Optical cross-connect ($\boldsymbol{ED}$), Optical Transport Switch ($\boldsymbol{OT}$), Core Router ($\boldsymbol{CR}$), Gateway Router ($\boldsymbol{GW}$). Here $\boldsymbol{V} = \{CP, ETH, ED, OT, CR, GW\}$, where $\boldsymbol{a_i} \in \boldsymbol{CP}, \boldsymbol{b_i} \in \boldsymbol{ETH}, \boldsymbol{c_i} \in \boldsymbol{ED}, \boldsymbol{d_i} \in \boldsymbol{OT}, \boldsymbol{e_i} \in \boldsymbol{CR}, \boldsymbol{f_i} \in \boldsymbol{GW}$ as shown in the below Figure 7, also, every node has $\boldsymbol{0} < \boldsymbol{i} \leq \boldsymbol{N}$ number in a network.

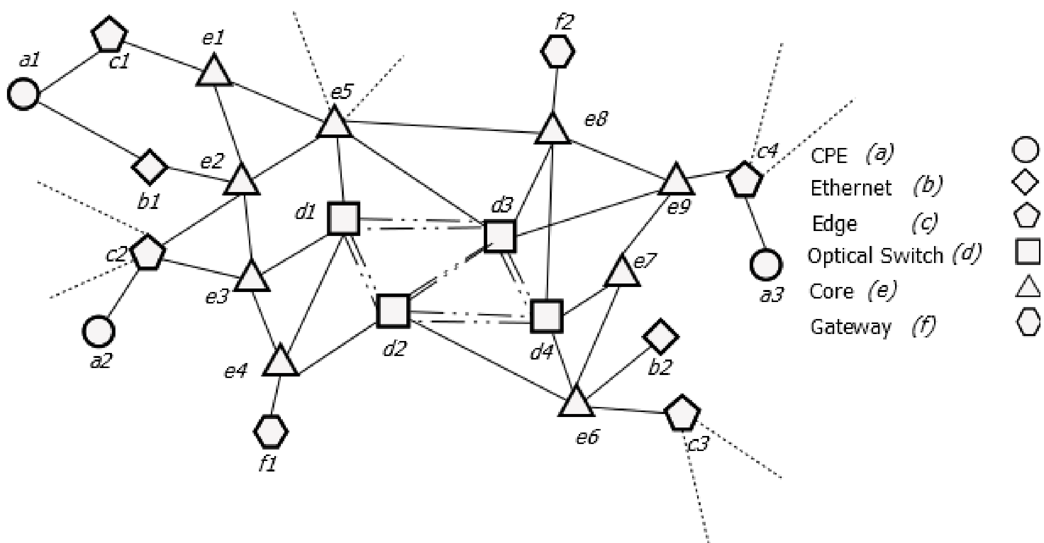

Figure 7: Network Nodes in ISP Network

Given the network and from the above considerations, our objective is to come up with a novel service cost modeling methodology for the network services offered by ISPs. Our proposed model intends to help the network planners in presuming router cost values, minimizing modeling hours as well as acquire possible Opex savings to ISPs. We investigated three services for the study, which include; IPVPN Service $\boldsymbol{S1}$, Transport Lease Service $\boldsymbol{S2}$, and High-Speed Internet Service $\boldsymbol{S3}$ and estimated the unit costs for each of them. The model considers cost and capacity input values for the unit cost computations. We have included the purchase cost of equipment/nodes, capacities in gigabits per second, and different network sizes considered in our service cost model.

4.1 Network Size

The size of the service network depends on the different number of nodes. $\boldsymbol{N_v}$ are the number of service-specific routers; where $\boldsymbol{N_v} < \boldsymbol{N}$. Each network node or router, have a range of cost and capacity values. Here the term nodes and routers are being used interchangeably in the thesis.

4.2 Router Cost

We evaluated the network service cost by the cost and capacity values of each router included in a network. The router cost is computed by the price of each router and its cost to install the router for the estimation of total cost values. Let $\boldsymbol{C^r}$ is the purchase cost of a router and $\boldsymbol{C^{ins}}$ which is the installation cost of the router in a network, so we estimate the total cost $\boldsymbol{C^R}$ of any specific node , which is the sum of router cost and its installation. Here we assume the Installation cost is 20% of Router Purchase Cost.

$$\boldsymbol{C^R} = \sum_{i=1}^{N_v} (\boldsymbol{C_i^r} + (\boldsymbol{C_i^{ins}})$$

So, the *total cost of routers/nodes in a network* $\boldsymbol{C^T}$ would be,

$$\boldsymbol{C^T} = \boldsymbol{N_v} \sum (\boldsymbol{C^R})$$

4.3 Router Capacity

The total capacity of the network depends on the capacity of each network element considered. Each Router has some of Line Cards $\boldsymbol{L}$ attached to it and there are the number of Ports per Line Card $\boldsymbol{p}$ to get the number of Ports per router $\boldsymbol{P^R}$ for estimation of the total capacity of the router $\boldsymbol{Q^R}$.

$$\boldsymbol{P^R = L * \ p}$$

Moreover, we have assumed the capacities in gigabit per second (Gbps) for every router for the calculations in the framework. We use the different number of gigabit Ports of range of 1G/ 10G / 40G /100G and 140G for every router as the technical parameter in the study. Let $\boldsymbol{K}$ be the number of gigabit ports for any of node divided in given port range; where sum of $K = k1 + k10 + k40 + k100 + k140$ should be equal to $K = P^R$.

We assume that the 1G port is assigned to variable $k1$ number of ports, 10G port assigned to a variable $k10$ number of ports, 40G port assigned to a variable $k40$ number of ports, 100G port assigned to variable $k100$ number of ports and 140G port is assigned to variable $k140$ number of ports then we have;

$$\boldsymbol{Q^R} = (1 * k1) + (10 * k10) + (40 * k40) + (100 * k100) + (140 * k140)$$

So, the *total capacity of the nodes in the network* as;

$$\boldsymbol{Q^T = N_v \sum (Q^R)}$$

4.4 Unit Cost of Service

The Unit Cost of a specific service (such as IPVPN) is the ratio of *Total Cost* to *Total capacity of Network Service*, as mentioned below.

$$\boldsymbol{UC = \frac{\sum C^T}{\sum Q^T}}$$

4.5 Cost Gap (Delta)

Taking variables and assumption from the above paragraphs, $\boldsymbol{UC}$, is computed for $\boldsymbol{S, Y}$, and $\boldsymbol{Z}$. Let $\boldsymbol{I}$ be total network infrastructure cost, and $\boldsymbol{S}$ be the cost of any particular service. So, if $\boldsymbol{I}$ is the total cost of network infrastructure and includes $\boldsymbol{N}$ number of nodes then $\boldsymbol{S}$ is the subset of $\boldsymbol{I}$; $\boldsymbol{S} \subseteq \boldsymbol{I}$ consist o f $\boldsymbol{N_v}$**,** the number of service nodes.

Here $\boldsymbol{Y}$ and $\boldsymbol{Z}$ are the service unit cost results obtain from our proposed methods, which are mathematical approach and K-means clustering approach, respectively, presented in the following sections. The results are further compared to determine the cost gap $\Delta\boldsymbol{d}$ of $\boldsymbol{S}$ with $\boldsymbol{Y}$ and $\boldsymbol{Z}$.

Chapter 5

5 Service Cost Model Framework

In this section, we present a network costing framework in detail. We discussed this model in different modules. The model is based on some assumptions and inputs about the network size, cost, and capacity values.

5.1 Model Description

Our model framework, as shown in the below Figure 8, comprised of inputs regarding the total number of network nodes, service network nodes or network size, purchase cost of each node, the total number of ports each node for the cost, and capacity calculations. Service cost modeling includes the assessment of total network infrastructure cost by which we are able to model the service cost. The service cost module is further divided into the implementation of the existing method and proposed approaches: Min-Max and K-means clustering, for the estimation of service unit cost as the output for all three services (IPVPN, TLS, HSI). The performance evaluation is based on the comparison of results (unit cost values) of existing mechanism with the outcomes of our proposed approaches. We have considered various network sizes with different percentages of node utilization in each service. Cost values and capacities are determined based on each router and for each service in modules explained below.

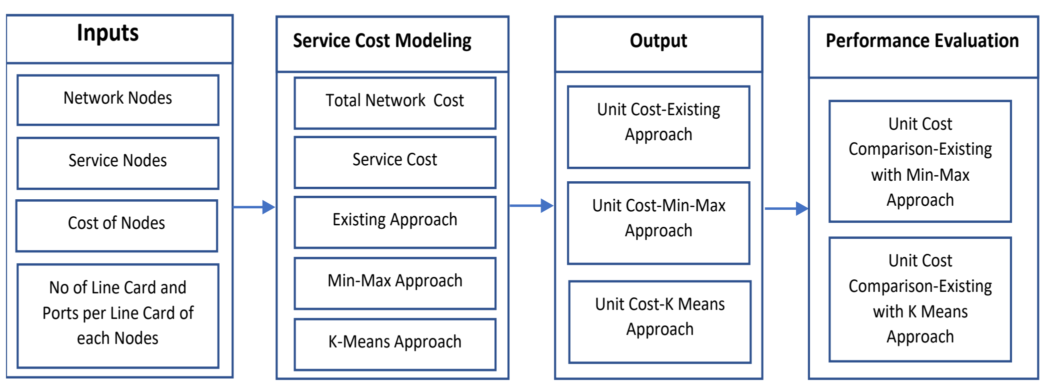

Figure 8: Cost Model Flow

5.2 Total Network Infrastructure Cost Module

Network infrastructure is the topology in which the nodes or devices in the network are connected and communicate with each other to provide various network services [47]. It enables network connectivity on which all services and applications provided by any service provider rely.

We have implemented the network infrastructure cost ***I*** in which all nodes are involved in calculating the unit cost values for entire network ***G*** as well as for each network element belongs to ***V***. The total number of nodes ***N*** divided and assigned to each router or switch. The percentage of the node usage is the utilization of each node in a network set in the model. The cost of each router/switch is the randomly generated value from the minimum and maximum price range [2] as input. Similarly, ports per router depend on number of line cards and ports per line cards, which are set by given ranges in the model for calculating total capacity. The maximum port capacity of each service node is mentioned in Table 3.

Table 3: Node Configuration

Service Node	Ports
CPE	1G/100G router
Ethernet Switch	10G/40G/100G
Edge	10G/40G/100G
OXC	10G/40G/100G
Optical Transport	100G/140G
Core	100G/140G
Gateway	100G/140G

To demonstrate, we consider the example of 25 nodes network ***N,*** divided into each network node.

Total Cost and Capacity of Network:

Below, Table 4 shows the computations for the *Total Cost of Nodes* in the network. Further, we have considered *installation cost* as 20% of the *router purchase cost*. The below Tables 4 and 5 show the computations for *Total Cost of Network Nodes* $\boldsymbol{C^T}$, and *Total Capacity of Network Nodes* $\boldsymbol{Q^T}$.

Table 4: Total Cost of Network Nodes

Network Nodes	No of Nodes N	Router Cost Range $	Purchase Cost ($) C^r	Installation Cost ($) C^{ins}	Cost / Router ($) C^R	Total Cost / Router ($) C^T
CPE	4	3500-4500	4462.00	892.40	5,354.40	21,417.60
NG-Ethernet	3	125000-175000	144,481.00	28,896.20	173,377.20	520,131.60
Edge	6	275000-375000	282,673.00	56,534.60	339,207.60	2,035,245.60
Optical Transport	4	700000-750000	719,009.00	56,534.60	862,810.80	3,451,243.20
Core	4	350000-425000	386,438.00	77,287.60	463,725.60	1,854,902.40
Gateway	4	300000-350000	320,133.00	64,026.60	384,159.60	1,536,638.40
						9,419,578.80

Here, the total cost of nodes in a network would be $\boldsymbol{C^T} = \mathbf{9419K}$

Table 5: Total Capacity of Network Nodes

Network Nodes	No of Nodes N	Line Card L	Ports per Line Card p	No of Ports per Router P^R	Gigabit port capacity					Capacity/ Router (Gpbs) Q^R	Total Capacity (Gpbs) Q^T
					1G	**10G**	**40G**	**100G**	**140G**		
CPE	4	0	0	0	1	3	0	0	0	31	124
NG-Ethernet	3	7	5	35	0	14	12	9	0	1520	4560
Edge	6	9	7	63	0	6	18	39	0	4680	28080
Optical Transport	4	11	11	121	0	0	0	31	90	15700	62800
Core	4	14	11	154	0	0	0	93	61	17480	71360
Gateway	4	7	10	70	0	0	0	42	28	8120	32480
											199404

Here, the total capacity of a network would be $\boldsymbol{Q^T} = \mathbf{199404Gbps}$

Hence, *Total Network Infrastructure Cost* would be;

$$\boldsymbol{I} = \boldsymbol{UC} = \frac{\sum C^T}{\sum Q^T}$$

=$**47.23**/Gbps

5.3 Service Cost Module

Generally, the term service costing can be used to estimate the cost of providing specific services [48]. It is the process used for determining the service unit cost to ISPs in delivering network services to the end-users. It is essential to understand the current service cost modeling approach for the estimation of service costs. In the service cost module, we have first discussed the existing cost model and then demonstrated our proposed methodologies in the report.

Here, the service cost module $\boldsymbol{S}$ is a subset of total network cost module $\boldsymbol{I}$; $\boldsymbol{S} \subseteq \boldsymbol{I}$. From the cost values of the infrastructure module, we cannot estimate the accurate cost of a single service. There are many aspects to be considered for the estimation of cost values, such as a different type of services offered, network equipment such as routers, switches capacity or bandwidth of the router or node in a network. To formulate a cost model, we need to find out the cost drivers and cost components for specific services selected for the study. Every single service involves specific network components and based on that we estimate the cost of each router or switch $\boldsymbol{C^R}$ their maximum capacities $\boldsymbol{Q^R}$ to evaluate the service *unit cost* $\boldsymbol{UC}$, as well as each node involved in service. In service cost module, we implemented the cost and capacity configurations for various number of nodes included in service.

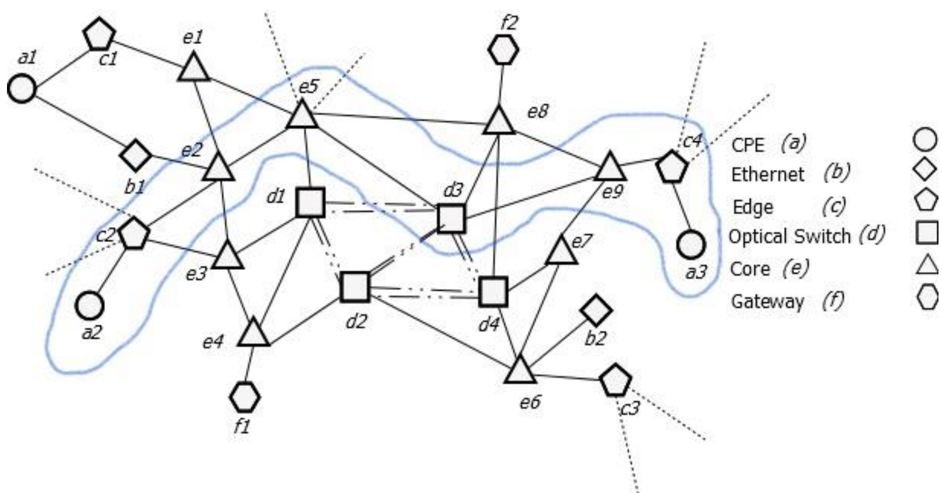

Figure 9: Service Nodes

To demonstrate, we consider an IPVPN service, The following network nodes are involved in IPVPN service; CPE, Edge node, Optical Transport node and Core node consist of $\boldsymbol{N_v}$ number of nodes in service $\boldsymbol{S}$. We consider the example network, as shown in Figure 9. Any service network is comprised of only specific network elements or nodes. To demonstrate, we consider the example 25 nodes network and assumed that 60% of total network nodes $\boldsymbol{N}$ are involved in IPVPN service. Here 15 nodes are included in the calculation. Further, we know that the following four network nodes are engaged in IPVPN service; CPE $\boldsymbol{a_i}$*; 1G/10G router*, Edge node $\boldsymbol{c_i}$*; 10G/40G/100G ports*, Optical Transport switch $\boldsymbol{d_i}$*; 100G/140G ports*, and Core node $\boldsymbol{e_i}$*; 100G/140G ports*. We assume 4 CPE, 4 Edge, 3 Optical switch, and 4 Core nodes for the cost modeling. Following is the explanation of both existing and proposed approaches for estimation of Service Unit Cost.

5.4 Existing Service Cost Approach

This cost mechanism is based on researchers' work and general industry feedback provided and Canadian Radio-Television and Telecommunication Commission CRTC [54], which is a publicly available industry standard for telecom operators. Using this modeling method, the network planners would go through the time-consuming process in developing the model with detailed computation for each node. It requires more employee hours of operation in any service architecture, which leads to the increased operational cost of ISP. We have set the minimum and maximum range of Purchase Cost values [2] for each node (CPE, Edge, Optical Transport, Core), and estimated their Router Cost, Router Capacity. Here the Total Network cost and capacity are computed. Below, Table 6 shows the detailed calculation for the service unit cost.

Table 6: Service Unit Cost (Existing Approach)

Nodes	Purchase Cost ($) C^r	Install. Cost ($) C^{ins}	Cost / Router ($) C^R	No of Ports / Router P^R	Capacity/ Router (Gpbs) Q^R
CPE ***a***	3,683.00	736.60	4,149.60	0	1
	3,638.00	727.60	4,365.60	0	10
	3,892.00	778.40	4,670.40	0	10
	4,410.00	882.00	5,292.00	0	10
Edge Router ***c***	283,123.00	56,624.60	339,747.60	54	3990
	291,906.00	58,381.20	350,287.20	56	4190
	309,369.00	61,873.80	371,242.80	63	4680
	300,665.00	60,133.00	360,798.00	48	3600
Optical Switch ***d***	728,661.00	145,732.20	874,393.20	121	15700
	732,072.00	146,414.40	878,486.40	110	14280
	725,236.00	145,047.20	870,283.20	100	13000
Core ***e***	409,479.00	81,895.80	491,374.80	150	17400
	362,822.00	72,564.40	435,386.40	165	19140
	379,702.00	75,940.40	455,642.40	140	16240
	415,093.00	83,018.60	498,111.60	154	17840
			5,944,501.20		**130091**

$\boldsymbol{C_v^T} = \; C_a^T + \; C_c^T + \; C_d^T + \; C_e^T$ = **$5,944,501.20**

$\boldsymbol{Q_v^T} = \; Q_a^T + \; Q_c^T + \; Q_d^T + \; Q_e^T$ = **130091 Gpbs**

$$\boldsymbol{S} = \boldsymbol{UC} = \frac{\sum C^T}{\sum Q^T}$$

$\boldsymbol{S_{IPVPN}}$ = $**45.69**/Gbps

5.5 Proposed Service Cost Model Approach

As discussed earlier, the above method provided us the accurate results. However, this model is challenging and costly to implement as it requires a greater number of hours of operations for every node in a network. We proposed a novel yet simple approach to obtain proximate service unit cost results, which minimize the modeling hours of any single service and operational overhead of ISP.

5.5.1 Grouping in Three Router Types (T1, T2, T3)

The purpose of implementing this novel approach is to come up with the network service cost model, which is beneficial for ISPs. Unlike the previous method, our approach helps to reduce long employee hours and save operational expenses for the ISP. We divide each network node into three types (T1, T2, T3) using capital cost components and simulate the model for network services. It is important to note that the network planner provides the cost values for each router for unit cost estimation. In our proposed service cost model, we emulate the knowledge of network planners to come up with the router cost values. Therefore, we classify the router purchase price into lowest purchase price, mid purchase price and the highest purchase price for network components involved in any particular service. These router purchase cost values are the inputs for our proposed model.

Considering each service having a significant number of nodes, we divide each node (CPE, ethernet, edge, optical cross-connect, optical switch, core, gateway) into three types; **T1, T2,** and **T3,** we named it **Min-Max Approach.** It is based on the minimum, median and maximum values, and count those router cost values from the existing method, which is close to values assigned to each of the three types. Figure 10 below explains the grouping of a single node into T1, T2, and T3.

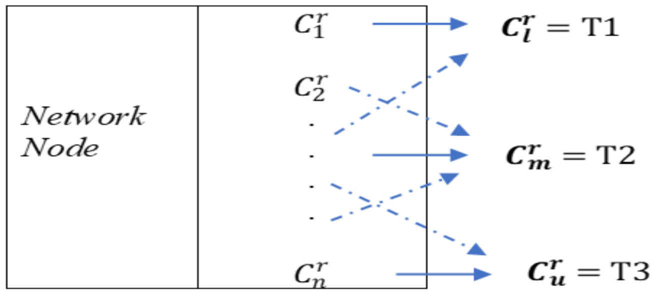

Figure 10: Assigning Values to router types

Let **T1** consist of the minimum cost value, **T2** contains median and **T3** consist of the maximum value then we can group router purchase cost value $\boldsymbol{C^r}$, and router capacity value $\boldsymbol{Q^r}$. Here each type would have; the minimum amount of router purchase cost $\boldsymbol{C_l^r}$, router capacity $\boldsymbol{Q_l^r}$ grouped in **T1**, the median value of router purchase cost $\boldsymbol{C_m^r}$, router capacity $\boldsymbol{Q_m^r}$ in **T2** and the maximum value of router purchase cost $\boldsymbol{C_u^r}$, router capacity $\boldsymbol{Q_u^r}$, grouped in **T3** for the estimation of Service Unit cost.

Pseudocode for Grouping Cost Values into T1, T2, and T3:

```
Y ← { IPVPN,  TLS, HSI}
for all v_i ∈ Y do
        if (nodedata.count > 0)
                nodecount = nodedata.count();
                C_l^r = nodedataMin(C_i^r)
                C_m^r = nodedataMid(C_i^r)
                C_u^r = nodedataMax(C_i^r)

                NodeGroupRange = (C_u^r - C_l^r) / 3
                NodeMinRange = C_l^r + NodeGroupRange
                NodeMaxRange = NodeMinRange+ NodeGroupRange

                T1nodedata = nodedata.where (C_i^r ≤ NodeMinRange)
                T2nodedata = nodedata.where (C_i^r > NodeMinRange && C_i^r <
                NodeMaxRange)
                T3nodedata = nodedata.where (C_i^r ≥NodeMaxRange)
        end if
end for
```

The above pseudocode is the grouping method of cost values into three types for each node included in the service network. The cost values are extracted and stored the minimum, median, and maximum cost values as T1, T2, and T3. The single cost value stored in one of three router types based on its proximity with a node cost range for T1, T2, and T3.

We have considered the same scenario from the previous module to demonstrate the proposed approach using 15 nodes IPVPN service presented below. Total Cost and Total Capacity are computed depending on the percentage of equipment used in each type.

5.5.2 CPE

The number of CPE nodes involved in service is 4, and then minimum, mid, and maximum cost values are set from the router purchase cost as T1, T2, and T3, respectively. Here, out of 4 CPE nodes, three nodes fall under the T1 group and the remaining one under T3, leaving T2 as an unused node.

Table 7: CPE Node for T1, T2, T3

Router Type	Node Distribution	Purchase Cost ($) C_a^r	Installation Cost ($) C_a^{ins}	Cost / Router ($) C_a^R	Total Cost / Router ($) C_a^T	Capacity / Router (Gpbs) Q_a^R	Total Capacity (Gpbs) Q_a^T
T1	75%	3,638.00	727.60	4,365.60	13,096.80	1	3
T2	0%	3,787.00	757.50	4,545.00	0	10	0
T3	25%	4,410.00	882.00	5,292.00	5,292.00	10	10
					18,388.80		13

5.5.3 Edge

Edge nodes involved in IPVPN service are 4. Here out of 4 Edge nodes, two of them falls under the T2 group, remaining falls under T1 and T3, respectively.

Table 8: Edge Node for T1, T2, T3

Router Type	Node Distribution	Purchase Cost ($) C_c^r	Installation Cost ($) C_c^{ins}	Cost / Router ($) C_c^R	Total Cost / Router ($) C_c^T	Capacity / Router (Gpbs) Q_c^R	Total Capacity (Gpbs) Q_c^T
T1	25%	283,123.00	56,624.60	339,747.60	339,747.60	3600	3600
T2	50%	296,285.50	59,257.10	355,542.60	711,085.20	4090	8180
T3	25%	309,369.00	61,873.80	371,242.80	371,242.80	4680	4680
					1,422,075.60		16,460

5.5.4 Optical Transport Switch

The number of Transport Switch nodes involved in service is 3. Here, all 3 Optical switches are grouped equally in three types.

Table 9: Optical Node for T1, T2, T3

Router Type	**Node Distribution**	**Purchase Cost ($)** C_d^r	**Installation Cost ($)** C_d^{ins}	**Cost / Router ($)** C_d^R	**Total Cost / Router ($)** C_d^T	**Capacity / Router (Gpbs)** Q_d^R	**Total Capacity (Gpbs)** Q_d^T
T1	33.33%	725,236.00	145,047.20	870,283.20	870,283.20	13000	13000
T2	33.33%	728,661.00	145,732.20	874,393.20	874,393.20	14280	14280
T3	33.34%	732,072.00	146,414.40	878,486.40	878,486.40	15700	15700
					2,623,162.80		42980

5.5.5 Core

The number of Core nodes involved is 4. Two nodes fall under T1 and T3, each leaving T2 as an unused node.

Table 10: Core Node for T1, T2, T3

Router Type	**Node Distribution**	**Purchase Cost ($)** C_e^r	**Installation Cost ($)** C_e^{ins}	**Cost / Router ($)** C_e^R	**Total Cost / Router ($)** C_e^T	**Capacity / Router (Gpbs)** Q_e^R	**Total Capacity (Gpbs)** Q_e^T
T1	50%	362,822.00	72,564.40	435,386.40	870,772.80	16240	32480
T2	0%	394,590.50	78,918.10	473,508.60	0	17620	0
T3	50%	415,093.00	83,018.60	498,111.60	993,223.20	19140	38280
					1,866,996.00		70760

5.5.6 Unit Cost

We get Unit cost of IPVPN Service as the ratio of the total cost of network service router C^T with the total capacity of network service $\boldsymbol{Q^T}$ which can be obtained as:

$$\boldsymbol{C^T} = C_a^T + C_c^T + C_d^T + C_e^T$$

$$\boldsymbol{Q^T} = Q_a^T + Q_c^T + Q_d^T + Q_e^T$$

$$\boldsymbol{Y_{IPVPN}} = \boldsymbol{UC} = \frac{\sum \boldsymbol{C^T}}{\sum \boldsymbol{Q^T}}$$

= $**45.52**/Gbps

5.6 K-Means Clustering for Grouping Router Cost

We have tried to make an effort to employ a more sophisticated approach by using the machine learning aspect to our model to emulate the analytical thinking and judgment of the network planner to come up with the router cost values. The purpose of introducing the machine learning element in our model is to reduce the time and effort of network planners and modelers in developing a cost model as well as improve the accuracy. We have opted for the unsupervised learning method and selected the K-means clustering algorithm, which is the appropriate choice to cluster the router cost values. Considering the identical scenario of cost, capacities values, and network sizes as in the previous methods, we have selected a machine learning approach as further expansion in the framework that will choose three types T1, T2, and T3 as the number of clusters we used for K-means algorithm. These types will further calculate the unit cost of each service considered. We generated a cost gap between the existing method and machine learning technique to inquire about the proximity in the results of service unit cost values. Moreover, for this purpose, we have used Python 3.6 for the implementation and integration with our application developed in C#.

5.6.1 Clustering for T1 T2 and T3

A brief introduction of the K-means clustering algorithm is presented here. This clustering algorithm belongs to unsupervised learning. The unsupervised learning algorithms are used to find patterns in data; the input data is unlabeled without any assigned output [49]. In the K-means clustering algorithm, we can analyze the unlabeled data and groups the data points together in the dataset based on object similarity [50]. The algorithm finds the number of groups or clusters. The K is the fixed number refers to the number of centroids or mean in the dataset.

The general steps involved in the K-means clustering technique are;

Step 1 - Initialization: Initial centroids or means generated at random for the clusters.

Step 2 - Assignment: Assign each data point to its nearest mean or centroid using the Euclidean distance metric.

Step 3 – Update: The centroids are recalculated and updated as the mean of the data points assigned to the respective similar centroid or cluster.

Step 4 – Repeat the steps two and three iteratively until the centroid assignment converges and no longer changes.

Here, for each service in the model, the K means clustering algorithm group the router cost values $\boldsymbol{C^r}$ for every node of any service network size $\boldsymbol{N_v}$. Given the dataset of $\boldsymbol{n}$ data points or router cost values $\boldsymbol{C_1^r, C_2^r, \ldots . C_n^r}$, the algorithm runs and put them in T1 T2 and T3 with their corresponding capacities $\boldsymbol{Q^r}$. It categorizes them based on cost values similarity. As K-means is an iterative algorithm that works on a given number of clusters(n_clusters), we need to specify n_clusters before running K means. Here we know that we need to group $\boldsymbol{C^r}$ in three types, so we have the number of clusters; n_clusters=3.

We considered the same scenario and utilized 15 IPVPN service nodes network. It starts with an initial centroid, *K* = 3 for every node. It assigns each data point to their closest centroid or means. It computes the total Euclidean distances between the data points and their centroids. Below equation shows the objective function for cost of each node.

$$dist = \sum_{k=1}^{K} \sum_{\substack{i=1 \\ C_i^r \in D_k}}^{n} || C_i^r - m_k ||^2$$

Where m_k is the mean of each cluster D_k. The algorithm then re-compute for every centroid or mean for node $\boldsymbol{v_i}$ in IPVPN service.

$$m_k = \frac{1}{n_k} \sum_{C_i^r \in D_k} C_i^r$$

Where n_k , is the number of cost values belongs to *k*. The algorithm iterates till the no purchase cost value changes clusters and minimizes the sum of the distance between the new mean and data point.

Once we get final centroids as T1, T2, and T3 for every node involved in IPVPN service (CPE, Edge, Optical Switch, Core), then as shown in our proposed Min-Max approach, we can follow the steps and calculate the service unit cost. The cost values for each node in detail is demonstrated below.

We assigned the final center or mean to each T1, T2, and T3 as the router cost values for IPVPN service. The K-means clustering runs for cost values set from the router purchase cost and their corresponding capacities as T1, T2, and T3, respectively. Total Cost and Total Capacity are computed depending on the number of equipment used in each type.

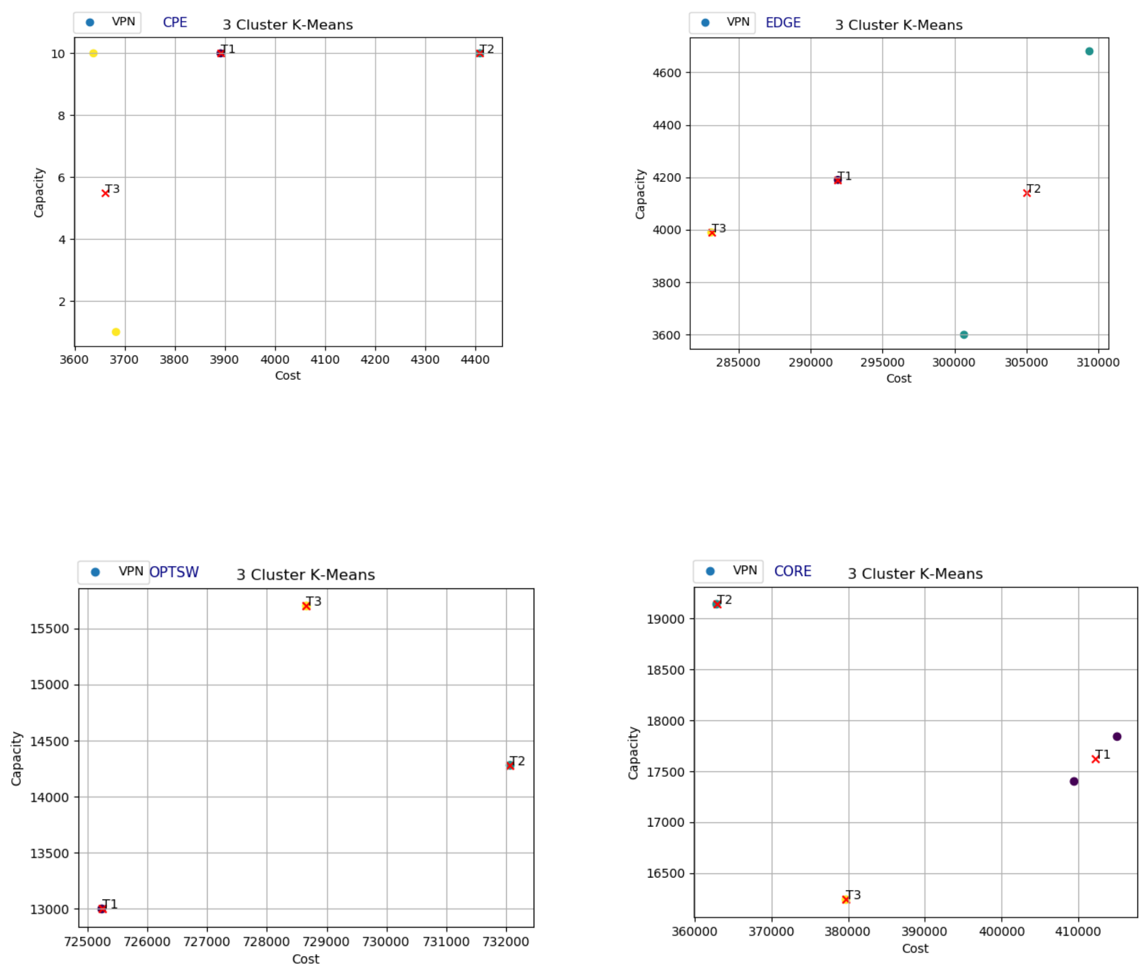

Figure 11: Three Clusters for IPVPN service nodes

5.6.2 CPE

Here, out of 4 CPE nodes, two nodes fall under the T1 group, one under T2 and one under T3.

Table 11: CPE Node for T1, T2, T3

Router Type	Node Distribution	Purchase Cost ($) C_a^r	Total Cost / Router ($) C_a^T	Capacity / Router (Gpbs) Q_a^R	Total Capacity (Gpbs) Q_a^T
T1	33.33%	3,660.05	8,785.20	5.5	11
T2	33.33%	4,410.00	5,292.00	10	10
T3	33.34%	3892.00	4,670.40	10	10
			18,747.60		**31**

5.6.3 Edge

Edge nodes involved in IPVPN service is 4. For this node, two of them are counted under the T3 group, remaining falls under T1 and T2, respectively.

Table 12: Edge Node for T1, T2, T3

Router Type	Node Distribution	Purchase Cost ($) C_c^r	Total Cost / Router ($) C_c^T	Capacity / Router (Gpbs) Q_c^R	Total Capacity (Gpbs) Q_c^T
T1	25%	283,123.00	339,747.60	3900	3990
T2	50%	305,017.00	732,040.80	4140	8280
T3	25%	291,906.00	350,287.20	4190	4190
			1,422,075.60		**16,460**

5.6.4 Optical Transport Switch

Transport Switch nodes involved in service is 3. Here, all 3 Optical switches are grouped equally in three types.

Table 13: Optical Node for T1, T2, T3

Router Type	Node Distribution	Purchase Cost ($) C_d^r	Total Cost / Router ($) C_d^T	Capacity / Router (Gpbs) Q_d^R	Total Capacity (Gpbs) Q_d^T
T1	33.33%	728,661.00	874,393.20	15700	15700
T2	33.33%	725,236.00	870,283.20	13000	13000
T3	33.34%	732,072.00	878,486.40	14280	14280
			2,623,162.80		**42980**

5.6.5 Core

Four Core nodes utilized here for clustering. Two nodes fall under T1, remaining falls under T1 and T2, respectively.

Table 14: Core Node for T1, T2, T3

Router Type	Node Distribution	Purchase Cost ($) C_e^r	Total Cost / Router ($) C_e^T	Capacity / Router (Gpbs) Q_e^R	Total Capacity (Gpbs) Q_e^T
T1	50%	412,286.00	989,486.40	17620	35240
T2	25%	362,822.00	435,386.40	19140	19140
T3	25%	379,702.00	455,642.40	16240	16240
			1,880,515.20		**70620**

5.6.6 Unit Cost

We compute the Unit Cost of IPVPN service as the ratio of the total router cost $\boldsymbol{C_v^T}$ **,** and capacity $\boldsymbol{Q_v^T}$of network service expressed as;

$$\boldsymbol{C_v^T} = C_a^T + C_c^T + C_d^T + C_e^T$$

$$\boldsymbol{Q_v^T} = Q_a^T + Q_c^T + Q_d^T + Q_e^T$$

$$\boldsymbol{Z_{IPVPN}} = \boldsymbol{UC_v} = \frac{\sum C_v^T}{\sum Q_v^T}$$

$\boldsymbol{Z_{IPVPN}}$ = $**45.69**/Gbps

5.7 Cost Gap Analysis

To further verify our strategy, we have analyzed the service cost results by determining the cost gap $\Delta\boldsymbol{d}$ of existing Approach $\boldsymbol{S}$ with our proposed cost modeling methodologies: Min-Max approach Y and Clustering approach $\boldsymbol{Z}$. It proves the proximity of service unit costs values achieved from $\boldsymbol{Y}$ and $\boldsymbol{Z}$ compared with $\boldsymbol{S}$. Considering Service Unit Cost results, we can quickly determine the cost gap for the 15 nodes cost model explained above.

Below Table 15 presents the result in terms of the cost gap(delta) from the proposed method using the formula:

Cost Gap for $\boldsymbol{S}$ and $\boldsymbol{Y}$:

$\Delta \boldsymbol{d} = (\boldsymbol{S} - \boldsymbol{Y})/\boldsymbol{S}$

Table 15: Cost Gap-Min-Max Approach

Service	$\boldsymbol{S_{IPVPN}}$	$\boldsymbol{Y_{IPVPN}}$	$\Delta \boldsymbol{d}$
IPVPN	45.69	45.52	0.4%

Below, Table 16 presents the result in terms of the cost gap from K means clustering method using the formula:

Cost Gap for $\boldsymbol{S}$ and $\boldsymbol{Z}$:

$\Delta \boldsymbol{d} = (\boldsymbol{S} - \boldsymbol{Z})/\boldsymbol{S}$

Table 16: Cost Gap - Clustering Approach

Service	$\boldsymbol{S_{IPVPN}}$	$\boldsymbol{Z_{IPVPN}}$	$\Delta \boldsymbol{d}$
IPVPN	45.69	45.69	0.0%

The purpose of computing the difference is to verify the accuracy of the proposed approach. We can achieve efficiency as the gap decreases.

5.8 Opex Saving Example

This section presents the summary of the whole effort of developing the new approach for grouping router cost values in three types. The process of developing cost models, its maintenance, and regular model updates and upgrades require many employee hours by the network planner team which costs significant operational overhead for ISPs. The scenario below will show the example of existing operational expenses and potential savings in Opex from our proposed methods.

Based on inputs and feedback provided by industry, the typical functional work categories that we include are:

- Developing or identifying exact Service Architecture
- Identifying correct Network Inventory for Service Architecture (nodes/routers, type of routers)
- Cost and capacity for each node/router included
- Develop a model to capture all information

- Assigning Number of Hours for modeling

Here, we already determined the first four points. We considered the above scenario of IPVPN service. We have included the cost and capacities for each node and gathered all the information necessary to model the service unit cost. We worked on the number of hours spent on a single service presented below. We assume the parameters and values for the quantitative analysis of Opex from existing methods and our proposed strategies below.

5.8.1 Opex Parameters

Below, Table 17 presented the example of the general parameters for the employee working hours in cost modeling. The business units considered for the current method are 4, whereas we specified the two working units as network planning and network costing, which require a smaller number of employees working in each group. Thereby reducing the number of hours and staff working on a single service.

Table 17: General Opex parameters for employee hours

	Parameters	**Opex: Existing Method**	**Opex: Proposed Method**
a)	Business Unit BU	4	2 (Network Planning and Costing)
b)	Number of Staff working in each BU	2	1
c)	Number of Hours each staff spend per week	20	10
d)	Opex per Employee Hour	$100	$100
e)	Total number of Staff Working	8	2

5.8.2 Opex Calculations

In the below Table 18, we have demonstrated the reduced number of hours assigned and evaluated Opex as per 20 services.

Table 18: Employee hours assignment

	Calculations	Opex: Existing Method	Opex: Proposed Method
f)	Total Hours spend per week	160	20
g)	Total hours spend in 4 weeks per Service	640	20
h)	Total hours spend in 4 weeks per 20 Services	12,800	400
i)	Total Opex per 20 Services	$1,280,000	$40,000

5.8.3 Opex Savings

Table 19 below shows the example of potential savings that we analyzed and achieved in our approaches. The proposed methods (Min-Max and Clustering) provide us significant less Opex than the existing methodology.

Table 19: Opex Savings: Proposed methods

Total amount saved	$1,240,000
Comment	32 times less Opex in the proposed approaches

Chapter 6

6 Simulation Results

In this section, we have simulated results from our proposed methods and compared them with service unit cost results computed with the existing approach considering identical scenarios.

6.1 Evaluation Metrics

We developed a Service Cost Modelling Framework using *C# .Net* for the implementation of the Min-Max approach and *python* for K-means clustering. In the cost model, the existing costing methodology is employed to validate the unit cost results achieved from our proposed strategies of grouping the router purchase cost into three types. There are various service networks consist of different network sizes and connectivity in the ISP network. For the model, we have used different scenarios comprised of different network size (Number of Nodes involved in Service) for all three services considered.

The model created a random topology network based on total network nodes and random numbers generated for router which is ser as purchase cost of router. This purchase cost value is generated from the minimum and maximum input range of purchase prices [2] to calculate the total cost of a router. The router capacity depends on the number of ports per router or node. We calculated the service unit cost and cost gap delta of different network sizes in the model. The cost gap provides information about the difference in service unit cost results obtained from the proposed model and the existing model. Also, we have conducted various runs and computed the average cost gap(delta) values of every single network size and for every service. The purpose of using average value is to minimize the bias in results achieved. The below tables show the observations for Service unit Cost from Existing Method $\boldsymbol{S}$ with results from the Min-Max approach $\boldsymbol{Y}$ and clustering approach $\boldsymbol{Z}$.

6.2 Experimental Analysis Utilizing Various Network Sizes

The results are based on the cost gap (delta) we achieved for various network sizes for each service. The network size is the total number of nodes of the entire network. The service network is comprised of service-specific nodes only. We assumed the percentage of network utilization for all three services to calculate the total number of service nodes in a network. For a **small network**, we generated results for 25 to 50 number of total network nodes. For **medium-size networks**, we have computed for 55 to 80 network nodes and simulated for unit cost values and their respective cost gaps.

Similarly, for a **large network** scenario, we have estimated the service cost results for the different range of the number of nodes. We experimented for 100 to 125 network nodes in large network sizes.

6.2.1 IPVPN Service

As mentioned earlier, IPVPN service involves four significant network nodes; CPE, Edge node, Optical Transport switch, and Core node. We considered three different network size scenarios utilizing 60% of total network nodes ***N***.

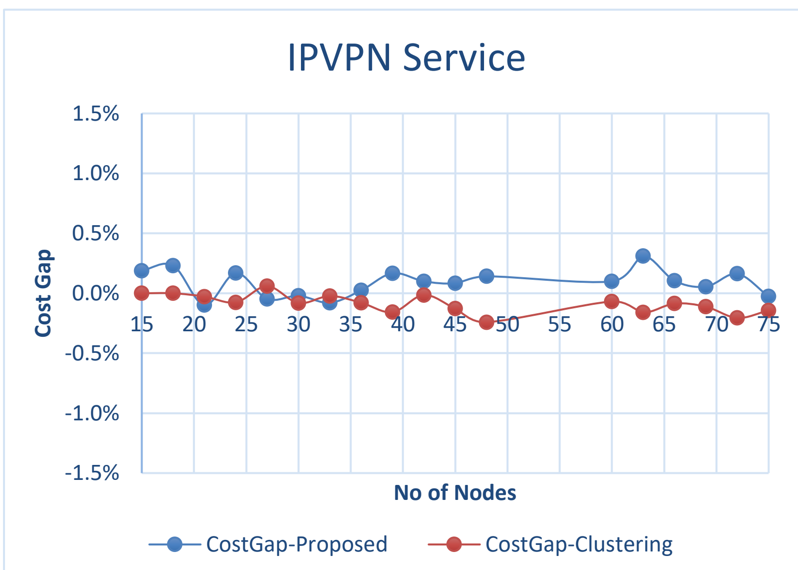

Figure 12: Cost Gap – IPVPN Service

The above Figure 12 presented cost gap difference for each network size considered in IPVPN service.

Table 20: IPVPN Service Results – Grouped in 3 Router Types

Service	N	N_v	S_{IPVPN}	Y_{IPVPN}	Δd	s^2	Z_{IPVPN}	Δd	s^2
IPVPN-Small Networks	25	15	45.61	45.52	0.2%	0.000123	45.61	0.0%	0.000
	30	18	45.96	45.85	0.2%	0.000208	45.96	0.0%	0.000023
	35	21	48.10	48.14	-0.1%	0.000182	48.11	0.0%	0.000055
	40	24	46.98	46.90	0.2%	0.000142	47.02	0.1%	0.000037
	45	27	46.92	46.94	0.0%	0.000221	46.90	0.1%	0.000055
	50	30	47.00	47.00	0.0%	0.000191	47.04	-0.1%	0.000110
IPVPN-Medium Networks	55	33	47.60	47.63	-0.1%	0.000126	47.61	0.0%	0.000091
	60	36	47.51	47.49	0.0%	0.000174	47.54	-0.1%	0.000069
	65	39	47.41	47.32	0.2%	0.000190	47.48	-0.2%	0.000070
	70	42	46.94	46.89	0.1%	0.000154	46.95	0.0%	0.000094
	75	45	47.47	47.43	0.1%	0.000158	47.54	-0.1%	0.000090
	80	48	47.43	47.36	0.1%	0.000141	47.55	-0.2%	0.000076
IPVPN-Large Networks	100	60	47.60	47.55	0.1%	0.000156	47.63	-0.1%	0.000073
	105	63	47.39	47.24	0.3%	0.000124	47.46	-0.2%	0.000064
	110	66	47.25	47.19	0.1%	0.000109	47.29	-0.1%	0.000049
	115	69	47.89	47.85	0.1%	0.000164	47.94	-0.1%	0.000067
	120	72	47.56	47.48	0.2%	0.000100	47.65	-0.2%	0.000066
	125	75	47.45	47.46	0.0%	0.000129	47.52	-0.1%	0.000051

We calculated the services unit costs and cost gap delta for small, medium and large networks. The unit cost values of proposed approaches are compared with existing model. For the Min-Max approach, we achieved the minimum cost gap difference of -0.1% and maximum difference of 0.3%. The K-means clustering provided us more better results in terms of cost gap. We obtained minimum cost gap difference of -0.2% and maximum difference of 0.1% using clustering method. We also calculated the variance of average cost gap result for each network size. The above Table 20 shows the statistics of cost gap (Δd) and Variance (s^2) for both Min-Max and K-means Clustering.

6.2.2 Transport Lease Service (TLS)

Transport Lease Service involves three significant network nodes; CPE, optical cross-connect, and Optical Transport switch. Simulations run for various network nodes employing 50% of the total network in TLS.

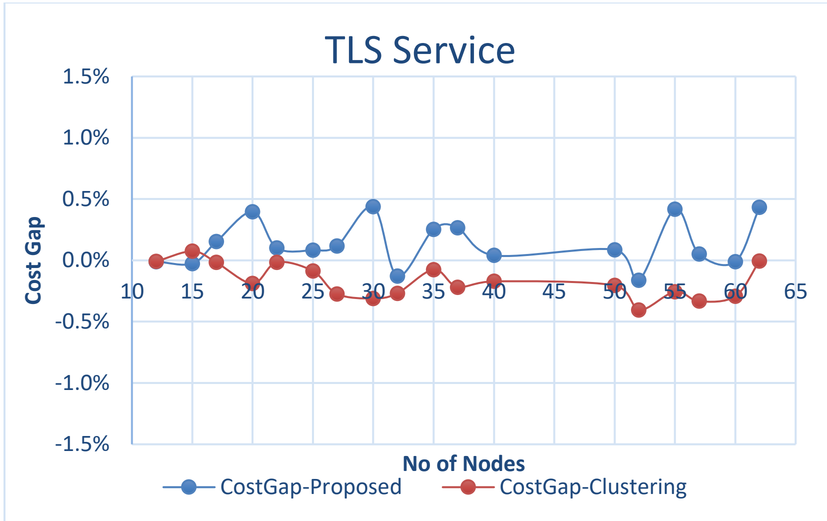

Figure 13:Cost Gap-Transport Lease Service

The above Figure 13 shows the cost gap of Transport Lease Service for both Min-Max and K-means Clustering method.

Table 21: TLS Service Results – Grouped in 3 Router Types

Service	N	N_v	S_{TLS}	Y_{TLS}	Δd	s^2	Z_{TLS}	Δd	s^2
TLS-Small Networks	25	12	67.88	67.88	0.0%	0.000338	67.89	0.0%	0.000009
	30	15	68.00	68.00	0.0%	0.000507	67.95	0.0%	0.000115
	35	17	68.81	68.69	0.2%	0.000428	68.83	0.2%	0.000061
	40	20	68.18	67.89	0.4%	0.000372	68.30	0.4%	0.000091
	45	22	68.14	68.06	0.1%	0.000390	68.16	0.1%	0.000161
	50	25	68.02	67.95	0.1%	0.000306	68.08	0.1%	0.000157
TLS-Medium Networks	55	27	68.35	68.26	0.1%	0.000379	68.54	-0.3%	0.000140
	60	30	68.53	68.22	0.4%	0.000371	68.74	-0.3%	0.000171
	65	32	68.20	68.27	-0.1%	0.000389	68.39	-0.3%	0.000117
	70	35	68.19	68.01	0.3%	0.000292	68.25	-0.1%	0.000184
	75	37	68.65	68.46	0.3%	0.000280	68.80	-0.2%	0.000161
	80	40	68.32	68.28	0.0%	0.000251	68.44	-0.2%	0.000157
TLS-Large Networks	100	50	68.39	68.32	0.1%	0.000268	68.53	-0.2%	0.000176
	105	52	68.16	68.26	-0.2%	0.000224	68.44	-0.4%	0.000144
	110	55	68.32	68.02	0.4%	0.000257	68.50	-0.3%	0.000141
	115	57	68.40	68.35	0.1%	0.000253	68.63	-0.3%	0.000123
	120	60	68.40	68.40	0.0%	0.000205	68.60	-0.3%	0.000131
	125	62	68.61	68.30	0.4%	0.000258	68.61	0.0%	0.000101

We calculated the services unit costs and cost gap delta for small, medium and large networks for Transport Lease service TLS. The unit costs of Transport Lease service from proposed approaches are compared with the results of existing model for various network sizes. For the Min-Max approach, we achieved the minimum cost gap difference of -0.2% and maximum difference of 0.4%. For K-means clustering method, we obtained minimum and maximum difference of -0.4% and 0.4% respectively. We also calculated the variance of average cost gap result for each network size. The above Table 21 shows the statistics of cost gap (Δd) and Variance (s^2) for both Min-Max and K-means Clustering.

6.2.3 High-Speed Internet Service (HSI)

High-Speed Internet Service involves five significant network nodes; CPE, Edge, and Optical Transport, Core, and Gateway. Simulations run utilizing 70% of the network.

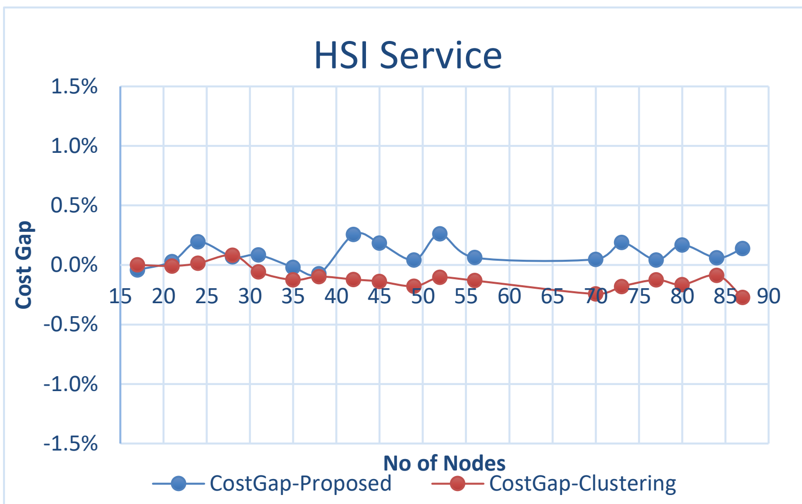

Figure 14: Cost Gap – High-Speed Internet Service

The above Figure 13 shows the cost gap of Transport Lease Service for both Min-Max and K-means Clustering method.

Table 22: HSI Service Results– Grouped in 3 Router Types

Service	N	N_v	S_{HSI}	Y_{HSI}	Δd	s^2	Z_{HSI}	Δd	s^2
HSI-Small Networks	25	17	49.05	49.06	0.0%	0.000114	49.05	0.0%	0.00
	30	21	51.15	51.13	0.0%	0.000165	51.16	0.0%	0.000004
	35	24	50.95	50.85	0.2%	0.000185	50.94	0.0%	0.000039
	40	28	50.46	50.42	0.1%	0.000165	50.42	0.1%	0.000047
	45	31	49.34	49.30	0.1%	0.000155	49.37	-0.1%	0.000055
	50	35	50.53	50.54	0.0%	0.000124	50.59	-0.1%	0.000065

HSI-Medium Networks	55	38	50.56	50.59	-0.1%	0.000126	50.61	-0.1%	0.000066
	60	42	50.29	50.16	0.3%	0.000136	50.36	-0.1%	0.000072
	65	45	51.12	51.02	0.2%	0.000152	51.19	-0.1%	0.000059
	70	49	51.08	51.05	0.0%	0.000183	51.17	-0.2%	0.000084
	75	52	50.74	50.60	0.3%	0.000150	50.79	-0.1%	0.000068
	80	46	50.44	50.40	0.1%	0.000166	50.51	-0.1%	0.000068
HSI-Large Networks	100	70	51.05	51.02	0.0%	0.000149	51.17	-0.2%	0.000065
	105	73	51.10	51.00	0.2%	0.000106	51.19	-0.2%	0.000066
	110	77	50.75	50.72	0.0%	0.000104	50.81	-0.1%	0.000048
	115	80	50.61	50.52	0.2%	0.000118	50.69	-0.2%	0.000047
	120	84	51.09	51.06	0.1%	0.000092	51.14	-0.1%	0.000054
	125	87	51.08	51.01	0.1%	0.000132	51.22	-0.3%	0.000056

We calculated the services unit costs and cost gap delta for small, medium and large networks for High-speed internet Service HSI. We compared the unit cost of HSI service determined from proposed approaches with the results of existing model for various network sizes. For the Min-Max approach, we achieved the minimum cost gap difference of -0.1% and maximum difference of 0.3%. For K-means clustering, we obtained minimum and maximum difference of -0.3% and 0.1% respectively. The service unit cost, cost gap $\Delta \boldsymbol{d}$ results and Variances $\boldsymbol{s^2}$ are shown in above Table 22 for different network sizes.

6.3 Additional Results for Different Number of Groups

We experimented a different number of groups to estimate service unit costs for validation of the proposed model. We conducted simulations for large network size of 100 to 125 network nodes ***N*** and generated results of service unit costs from Min-Max ***(Y)*** compared them with results from the existing model ***(S)***. The Cost gap results ($\Delta \boldsymbol{d}$) are generated for IPVPN service, We considered 60% of total network nodes involved in IPVPN service.

6.3.1 Grouping Router Cost into 2, 3, 5 and 7 Different Types

Below Table 23 presented the statistics of the results we obtained from different number of grouping applied on router purchase cost values using our proposed Min-Max method. Here, ***N*** is the total number of network nodes and $\boldsymbol{N_v}$ is IPVPN service nodes. We compared the service unit cost results obtained from different groupings with the existing model.

Table 23: IPVPN Service Results from Different Number of Groupings

IPVPN Service		**Existing Model**	**Router Types into 2 Groups**		**Router Types into 3 Groups**		**Router Types into 5 Groups**		**Router Types into 7 Groups**	
N	N_v	**Unit Cost**	Unit Cost	Δd	Unit Cost	Δd	Unit Cost	Δd	Unit Cost	Δd
100	60	47.5845	47.6658	-0.17%	47.6429	-0.14%	47.5114	0.14%	47.5531	0.05%
105	63	47.2304	47.0057	0.47%	47.1690	0.12%	47.2841	-0.11%	47.2777	-0.10%
110	66	47.2678	47.1301	0.28%	47.1632	0.21%	47.2910	-0.05%	47.2742	-0.01%
115	69	47.7835	47.7059	0.15%	47.8423	-0.13%	47.7216	0.13%	47.7779	0.01%
120	72	47.5587	47.3406	0.45%	47.4354	0.25%	47.4400	0.25%	47.6429	-0.18%
125	75	47.5198	47.3615	0.32%	47.4312	0.18%	47.4370	0.17%	47.5720	-0.11%

We analyzed that the different grouping provided us the similar results as achieved from the existing method. The increase in number of groups resulted in more proximate unit cost values in general.

6.4 Result Summary

From the above simulation results utilizing various ranges of values of cost, capacity, and the number of service nodes, we validated our proposed modeling approaches for IPVPN, TLS, and HSI service. We compared both strategies with the existing one and evaluated the cost gap Δd. We noticed that the Δd obtained for most network sizes the range of ± 1%, which is negligible. The service cost results would affect as cost and capacity values are changed. Different number of groupings of router types are also tested for large network sizes and achieved improved outcomes.

Table 24: Results Comparison from Proposed Methods – 3 Groups

	IPVPN	TLS	HSI
Small (%)	0.1	0.2	0.1
Medium (%)	0.2	0.4	0.3
Large (%)	0.3	0.4	0.3
Average (0.25%)	0.20	0.33	0.23

Moreover, we compared the unit cost results obtained from the proposed approaches of grouping into three router types, which shows that the delta obtained from K means 0.25% improved results. As shown in Table 24, we can say that the clustering method offers not only similar and expected outcomes but slightly more proximate values on average. Our proposed methods would facilitate the network costing and planning team in any ISP. The proposed model would simplify the cost model development process and assist in minimizing service cost modeling hours. As shown in Chapter 5, the Opex savings example demonstrated that the number of employee hours spent on a single service in our model presented a significant reduction in terms of operational cost.

Chapter 7

7 Conclusion

The advancements in various domains of the communication industry deliver new challenges to stakeholders that require a holistic view of decision making. The accurate cost values about network infrastructure and services bring in-depth knowledge for network planners. This thesis emphasized and administered on a novel service cost modeling method. We contributed to simplify the modeling process and reduce the employee modeling hours to come up with network service costs. This decrease in the number of employee hours brings a significant reduction in operational cost to ISP. Our proposed methodology provides a more efficient way to determine the cost and obtained similar service unit cost values as achieved from the existing model. First, the thesis explores the various predominant cost modeling methodologies for both wireline and wireless networks by investigating the cost strategies concerning network infrastructure, capacity, SDN migration from legacy networks, and service cost modeling. Secondly, the focus of the thesis is to advances the practice of cost modeling approach for network services as the accurate cost model for any single service has always been a challenge for network planners and modelers.

Our model framework first explained and calculated service unit cost from the existing mechanism [54]. Most of the researchers also applied it by considering each cost item in their cost models. Then we presented proposed strategies in developing an efficient cost model for network services. Any network planner would achieve the unit costs considering three types of routers/nodes in a network instead of spending long hours on computations of each node involved in service network architecture. This time-consuming process in developing cost models increases the Opex. Our model is an effort towards minimizing the employee hours spent on modeling cost for any single service that would lead to potential operational savings to ISP. An example of Opex savings is discussed to verify the effectiveness of our model. Simulations conducted for various network sizes. By doing so, we achieved the cost gap results that affirm the accuracy and efficiency of our proposed methodology (Min-Max approach). We compared both methods to evaluate the gap. We noticed that the cost gap (delta) $\Delta \boldsymbol{d}$ obtained is within the range of which is less than ±1% in all network size, which shows proximity in service cost results.

Additionally, we have also utilized the machine learning technique to extend the research and applied the K-means clustering algorithm to perform clustering for router cost values. We have worked on three clusters to obtain three types of router cost values for every single node involved in service. Like the mathematical approach, we have performed the cost gap analysis for the clustering technique and calculated the difference for existing and clustering methods. The comparison exhibited the closeness in results obtained and provide similar results in terms of service unit cost and delta achieved.

7.1 Limitations and Future Work

There are some challenges we came across during the modeling process of the research work, which is to be acknowledged. It is essential to mention that we have considered the number of assumptions regarding scenario and cost values [2]. Firstly, we restricted the study to the internet service provider network and utilized some relevant network components for cost calculations, as specifying the suitable scope for the research is crucial for the results achieved from the cost model. However, if we have the opportunity in the future, we could incorporate other related network elements to this existing work, which may include the cost of links, DNS servers, firewalls, load balancers, controllers. We could consider these cost elements as per each service we covered in the study.

Our work presented the techno-economical model based on theoretical networks. We have examined the limited number of small to large nodes for simulation due to the computation time it would take. As mentioned, we have chosen the limited network nodes, which are from an ISP perspective. We could extend the research on cost of content delivery networks CDN, which consists of distributed servers and data centers in networks. Another important aspect is the use of machine learning in our study. We could discover and test other clustering algorithms for grouping the cost values that would yield similar results. Because of time constraints, we opted for a single clustering method; K means clustering, which divides the data points into subgroups. Even though K means clustering provides expected results, we would further like to investigate other machine learning algorithms.

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