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Analysis, Modeling, and Evaluation of Service Provider Legacy Network Migration to Software-Defined IPv6 Network

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A DISSERTATION SUBMITTED IN FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

DEPARTMENT OF ELECTRONICS AND COMPUTER ENGINEERING

August, 2021

Dedicated to my Family and Parents . . .

Bhim Prasad Dawadi (Father)
Uma Devi Dawadi (Mother)
Er. Roshani Ghimire (Wife)
Cherisha Dawadi (Daughter)
Chunoj Dawadi (Son)

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Declaration of Authorship

Dissertation entitled "**Analysis, Modeling, and Evaluation of Service Provider Legacy Network Migration to Software-Defined IPv6 Network**", which is being submitted to the Department of Electronics and Computer Engineering, Pulchowk Campus, IOE, TU, Nepal for the award of the degree of Doctor of Philosophy (PhD) is a research work carried out by me under the supervision of Prof. Dr. Shashidhar R Joshi, Department of Electronics and Computer Engineering, IOE Pulchowk Campus, TU, Nepal and Prof. Dr. Danda B Rawat, Department of Electrical Engineering and Computer Science, Howard University, USA between November 2017 to January 2021. I declare that this is my work and has not been previously submitted by me at any university for any academic award.

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Signed: ______________________

Date: August 20, 2021

Recommendation

The undersigned certify that they have read and recommended for acceptance, a dissertation entitled **"Analysis, Modeling, and Evaluation of Service Provider Legacy Network Migration to Software-Defined IPv6 Network"**, submitted by **Babu Ram Dawadi** in partial fulfillment of the requirement for the award of the degree of **Doctor of Philosophy in Computer Engineering**.

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Research Motivation

My professional path towards networking field was determined by my involvement as a research system operator of AI3/SOI-ASIA project in 2005 conducted by WIDE University Japan. I had represented from Institute of Engineering (IOE), a member among several universities in South Asia. At that moment, IPv6 network deployment World-wide was in the early stage. My active participation on that research project encouraged me towards research activities in next generation networking viz. IPv6 networking. I was able to migrate the university research network into IPv6 only operable network on 2007 at our institute Tribhuvan University (TU)-IOE. This was the first and only operable IPv6 network established in Nepal.

During the period of 2009 to 2012, I worked as an Asst. Director at Nepal Telecommunications Authority (NTA), which looks after the regulation of Internet service providers (ISP) and Telecommunications (Telcos) operators of Nepal. My experiences at NTA were more productive to me towards investigation of economic conditions, and technical status of licensed operator's and their investment in technology as well as current networking technology standards that operators were running. My major responsibility, while working in NTA were bench-marking the ISP networks with traffic monitoring, development of .np ccTLD domain administration policy for Nepal, VoIP monitoring, and involvement on ISP and Telecom networks expansion for rural ICT. This motivated me more towards the research on network technologies. In addition with regular office duties, I was more oriented towards research on the field, where I was involving. In search of the best research platform, I joined back to TU, IOE Pulchowk Campus as an Asst. Professor and continues working on networking technologies since 2012. As a research consultant of Department of Information Technology (DoIT), Government of Nepal (GoN), to carry out research and development of policy document for IPv6 network migration in 2012, I got an opportunity to deeply inspect the government and operator's network status, economic activities, and business and network expansion plan. Additionally, being worked as a technical investigation experts at Department of Revenue Investigation-GoN and research consultant of NTA to develop regulatory framework on IPv6 network migration, I got ample opportunities to deeply inspect the government enterprise network, and ISPs/Telcos network status with their challenges and issues regarding the quality of service, network expansion, and technology adoption strategies. It was also the major concern of NTA, whether the subsidization is required or not for those licensed operators to migrate their network into new networking paradigms.

We could not find the proper migration planning and cost optimization technique for ISP and Telcos networks to upgrade towards IPv6 and Software-defined networking (SDN), maintenance, and replacement as well. Another major concern is the amount of energy consumed by networks. The increasing network size and continuous support increase the energy consumption by the network devices, for which the companies pay a significant percentage of their revenue to power their network infrastructures. It is also required to evaluate the energy efficiency of migrated technologies for the service provider sustainability. This encouraged me towards this research, where, if we perform the techno-economic analysis on technology migration, would be contributory to the fairly sustained service providers of developing nations and the government to ease the network migration.

IPv6 network migration World-wide is in some stages of transition. In addition with IPv6, Edge/Cloud computing and virtualization, and SDN are the new paradigms in the application and networking domains, which turns over the world's technology standards into faster, secure, flexible, and reliable technology together with the challenges and issues of network migration for service providers to adapt those latest technologies and standards. Service providers, and Small/Medium Enterprises (SME) of developing countries are basically waiting to see the world's migration status. Their major concerns are the total cost of migration, service availability, reliability, security, and other resources like skilled human resource development for the new system. For those service providers and SMEs, the early stage of IPv6 network migration would be fruitful to incorporate the emerging SDN migration as a joint migration approach to reduce the Capital and Operational Expenditure (CapEX/OpEX) of the organization. Hence, this research has been carried out as a techno-economic analysis of legacy network migration to Software-defined IPv6 (SoDIP6) Network as a joint migration approach.

Abstract

SDN and IPv6 networks are the latest networking paradigms emerged to avoid all the control, management, and operation complexities with issues of routing and security in legacy IPv4 networking system. But the lack of backward compatibility with IPv6 and SDN creates many challenges for service providers to migrate their legacy networking infrastructure into such latest generation networking paradigms. The adaptation of IPv6 addressing World-wide (just crossing 27% World-wide) is still not in a satisfactory level. Similarly, SDN implementation in the service provider networks is still in the early stages. In this regard, being underlying network layer paradigms, SDN and IPv6 joint network migration under the framework of Software-Defined IPv6 (SoDIP6) network is introduced. SoDIP6 network is an IPv6 capable network fully controlled/managed by SDN controller.

Present research considered IP routers migration in the ISPs/Telcos network and implemented adaptive neuro fuzzy inference system (ANFIS) to identify router status, whether it is upgradable or replaceable. ANFIS outperforms well as compared with other recent classification algorithms viz. linear regression, support vector machine (SVM), SVM optimizable, ensemble tree etc. Additionally, the joint migration analysis and modeling of SDN and IPv6 network optimized the total migration cost. For joint migration modeling, the cost metrics of individual and joint network migration to SDN and IPv6 are identified; then the joint migration problem is formulated with customer priority based on service level agreement (SLA) and implemented a greedy algorithm to migrate routers in the shortest path. Shared cost coefficient(μ) and the strength of correlation (ϵ) as optimization variables are introduced for SDN and IPv6 joint migration cost optimization. A joint migration cost optimization of up to 42.57% at $\mu = 2$ and $\epsilon = 0.8$ has been achieved.

Migration of one ISP affects the business process of another interconnecting ISPs. Hence, an evolutionary approach for Tier-3 multi-ISP network migration has been

simulated by following Moran's birth-death process for finite number of interconnected ISPs. Adaptation variable (σ_{4t}) and strength of migration (δ_{4t}) are introduced for decision making of an ISP to evaluate fitness for migration. The increasing value of σ_{4t} in the consequent previous phases of migration and $\delta_{4t} \geq 0.6$ is considered to decide for network migration implementation with higher utilities.

The functionality of legacy network interoperability with SoDIP6 network is evaluated using open network operating system (ONOS) controller and SDN-IP application in which longest span shortest path (LSSP) routers are migrated using breadth first router replacement (BFR) approach and the suitable placement of controller is identified using minimum control path latency (MCPL) between switch and the controller communication.

SoDIP6 network contributes to service provider sustainability with operational and capital expenditure reduction with significant saving in energy consumption. Energy efficiency of SoDIP6 network is evaluated using smart sleeping and dynamic adaptation of traffic volume in the link via simulation. For an end-access ISP network, 31.50% energy saving in switches and 55.44% energy saving in links of SoDIP6 network have been achieved as compared with legacy IPv4 network. A discussion on energy optimization and CO2 emission reduction practices with SoDIP6 network are provided with recommended sustainable solution using SoDIP6 network in the early stages of nationwide broadband network expansion in the context of Nepal.

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With immense pleasure, I would like to express my sincere gratitude to my advisors Prof. Dr. Shashidhar R. Joshi, Dean, Tribhuvan University-Institute of Engineering, Nepal, and Prof. Dr. Danda B. Rawat, Director, cybersecurity and wireless networking lab, Howard University, USA for their continuous and enormous supports during my PhD study. I felt very lucky to have such a patient, motivated, and knowledgeable professors as my supervisors, whose fruitful guidance, in fact properly landed me with such a big recognition in my life. Additionally, Prof. Joshi is not only my PhD supervisor, he was my M.Sc. thesis supervisor as well as instructor of many subjects in my bachelor and masters level studies, who actually directed me properly into this career path.

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List of Abbreviations

AFRINIC	African Network Information Centre
ALR	Adaptive Link Rate
ANFIS	Adaptive Neuro Fuzzy Inference System
APNIC	Asia Pacific Network Information Center
ARIN	American Registry for Internet Numbers
AS	Autonomous System
API	Application Programming Interface
BGP	Boarder Gateway Protocol
BFR	Breadth First Router Replacement
BFT	Breadth First Traversal
CARD	Center for Applied Research and Development
CG	Customer Gateway
CGNAT	Carrier Grade NAT
CIDR	Classless Inter Domain Routing
CapEx	Capital Expenditure
CP	Conference Paper
CPE	Customer Premise Equipment
CMOS	Complementary Metal Oxide Semiconductor
DC	Data Center
DCN	Data Center Network
DFS	Dependency Fuzzy System
DHCP	Dynamic Host Configuration Protocol
DS	Dual Stack
EnPe	Energy for Petrolium Program
EoL	End of Life
EoS	End of Support
EUI	Extended Unique Identifier
FG	Foreign Gateway
FIS	Fuzzy Inference System
FTP	File Transfer Protocol
4RD	IPv4 Residual Deployment
GR	Gateway Router
GoN	Government of Nepal
HR	Human Resource
ISATAP	Intra-Site Automatic Tunnel Addressing Protocol
JP	Journal Paper
ICANN	Internet Corporation for Assigned Name and Numbers
ICMP	Internet Control Message Protocol
IEEE	Institute of Electrical and Electronic Engineers

IETF	Internet Engineering Task Force
IOS	Internetwork Operating System
IT	Information Technology
ITU	International Telecommunications Union
IoT	Internet of Things
IOE	Institute of Engineering
ICT	Information Communication Technology
IPv4	Internet Protocol version 4
IPv6	Internet Protocol version 6
IPSec	Internet Protocol Security
ISP	Internet Service Provider
IXP	Internet eXchange Point
KB	Knowledge Base
L2G	Legacy to Greenfield
L2H	Legacy to Hybrid
L2M	Legacy to Mixed
LSSP	Longest Span Shortest Path
MAP-E	Mapping of Address and Port using Encapsulation
MAP-T	Mapping of Address and Port using Translation
MCPL	Minimum Control Path Latency
MPLS	Multi Protocol Level Switching
MSESSD	M.Sc. in Energy for Sustainable Social Development
MTU	Maximum Transmission Unit
NAT	Network Address Translation
NDP	Neighbor Discovery Protocol
NOC	Network Operation Center
NORAD	Norwegian Agency for Development Cooperation
NFV	Network Function Virtualization
NTA	Nepal Telecommunications Authority
OB	Objective
ONF	Open Networking Foundation
ONOS	Open Network Operating System
OpEx	Operational Expenditure
ONF	Open Networking Foundations
OSPF	Open Shortest Path First
PPP	Public Private Partnership
QoS	Quality of Service
REST	Representational State Transfer
RMSE	Root Mean Square Error
RIP	Routing Information Protocol
RSS	Root Source Switch
RQ	Research Question
RTDF	Rural Telecommunications Disbursement Fund
SDN	Software-Defined Networking
6RD	Six Rapid Deployment
SoDIP6	Software-Defined IPv6
SLA	Service Level Agreement

SNMP	Simple Network Management System
SP	Shortest Path
SSSP	Shortest Span Shortest Path
TCAM	Ternary Content Addressable Memory
Telcos	Telecommunications
ToIP	Text over Internet Protocol
ToS	Type of Service
TSP	Tunnel Setup Protocol
USD	United States Dollar
VLAN	Virtual Local Area Network
VLSM	Variable Length Subnet Masking
VM	Virtual Machine
VoIP	Voice over Internet Protocol
VPN	Virtual Private Network
WoL	Wake on LAN
WSN	Wireless Sensor Network
WWW	World Wide Web

Contents

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Chapter 1

Introduction

The research will be introduced in this chapter with background and statement of the problem. After designing research questions and use case presentation, research objectives will be defined. List of publications throughout the study period will presented and the overall structure of the thesis will be outlined in this chapter.

1.1 Background

The World-wide legacy network infrastructure has been transforming to digital packet based communication infrastructure. With the rapid growth of Internet users, evolvement of Internet of Things (IoT) smart devices and massive use of wireless sensor network (WSN) in the cyber physical system (CPS), the researchers, developers, and the networking enterprises World-wide are obliged to enhance the intelligence in networking technologies by moving to latest generation networking paradigms, for example, Internet protocol version 6 (IPv6) addressing, Software-defined networking (SDN), network function virtualization (NFV), cloud computing, and many other advancing technologies to develop smart societies.

The growth of internet users with the increase of information and communication technology (ICT) businesses in the World already led the exhaustion of IPv4 address space. To avoid the address depletion issues with other several problems existing in legacy IPv4 networking system, it has already been two decades that the migration to IPv6 addressing was initiated. Except few developed countries, the World-wide IPv6 capability with region-wise capabilities are shown in Figure 1.1 [1]. World's IPv6 capability is just crossing 27.5%, while less than 2% IPv6 capability in Africa, nearly 34%, 32% and 21% in Americas, Asia, and Europe respectively indicate that IPv6 deployment is still in early stage of network transformations . SDN implementation in data center (DC) network is popular and progressive, while its migration in the telecommunications (Telcos) and Internet service provider (ISP) networks are still in the premature stage [2].

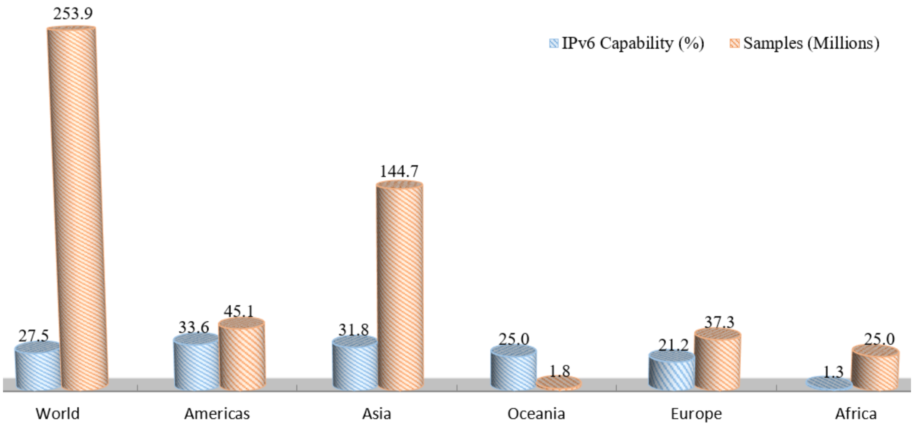


Figure 1.1: IPv6 capabilities measurement at given samples in the Regions and the World

The depletion of IPv4 address space enforces the networking organizations Worldwide in the phase of transition to IPv6 addressing mechanism by following best migration approaches with optimum cost. Additionally, the existing legacy network has identified with several problems including security, quality of service (QoS), routing, device configurability, monitoring, control and many more. The major concern is the vertically integrated legacy IPv4 networking system having control and data plane bundled on a single network device that increases several management and operation complexities with the increase of network size. Meanwhile, the SDN [3], a new concept in network operation and management has been introduced making the considerable changes in networking paradigms by introducing open standards and enabling the programmable network with the segregation of data and control plane for efficient network management.

IPv6, on the one hand, improves the efficiency of internet protocol, as a whole including routing and addressing, on the other hand, SDN improves the controllability of networking equipment by implementing vendor neutral and open protocols, such as Open-Flow, to apply globally aware software control to network devices, which are operating by closed and vendor specific firmware [4]. The networking stakeholders worldwide are in the rush of not only for the migration to IPv6, but also towards the migration to other recent technologies like SDN, 5G, cloud computing, and virtualisation, where *"migrating togetherness"* is coined to enter into the era of new IT based services.

The bigger shift in networking paradigms creates many challenges for service providers to migrate their existing legacy networks into such latest networking paradigms like Software-defined based IPv6 enabled network. Considering the migration issues, the major concerns [5] for the Internet and Telcos service providers are:

1. Lack of guarantee of quality and reliable services to the customers with latest technologies.
2. Higher investment costs of network transformations towards newer technologies.
3. Higher cost of skilled human resource (HR) development.
4. Lack of stable applications and protocols to operate over latest networking infrastructure.
5. Lack of proper migration plan, procedure, and strategies.
6. Higher operational expenditures in terms of energy consumption by ICT network.
7. Security issues during and after the migration.

It is inevitable to transform running legacy network into such latest networking, however, immediate migration of the existing network into SDN and IPv6 based networking is not possible [6]. The migration is a gradual process, for which proper strategy has to be developed considering the technology needs, customer demand, capital expenditure (CapEx), operational expenditure (OpEx), and traffic engineering perspectives towards smooth transitioning [5]. The transition period spans longer during when the service providers should have to move on by following best migration planning with optimum migration cost.

Migration means the upgrade of the existing network devices, applications, and services to make them operable with newer technologies. Routers and the switches are the main components of the service network, which are to be able to operate with the newer technologies. To transform the existing networks, either upgrade of the software/firmware version or device replacement is required with sufficient investment on CapEx and OpEx for the service providers.

In this research study, the common concerns of SDN and IPv6 network with their benefits and challenges of migration are introduced, migration modeling and analysis of legacy network transformations to Software-defined IPv6 (SoDIP6) network for service providers are being carried out to develop the suitable plan and strategies with intelligent approach for network migration so that successful transition can be accomplished with proper planning and migration cost optimization.

1.2 Statement of the Problem

Especially the small and medium enterprises (SMEs) and Internet/Telcos service providers feel challenging to migrate their current service network infrastructure into latest networking paradigms viz. IPv6 and the SDN. This is due to limited cost, lack of trained HRs, and also the lack of proper migration planning/strategies. Hence, a requirement on techno-economic analysis for proper migration of existing network into SDN based IPv6 network is realized.

Service providers might not be able to provide the services with the customer demand of newer technologies immediately. Hence, the customer profiling and prioritization is required to provide the service as per the service level agreement (SLA) during the network migration. Similarly, the network migration is not the single organization's business, as it depends on *"what other interconnected entities acting on about migration?"* is to be analyzed. It is crucial for every service providers to have proper migration planning with optimized cost together with the guarantee of uninterrupted services to their customers. Individual migration of two related technologies (SDN and IPv6) is fairly costly as compared with joint migration and create complexity in network migration implementations [7].

Present study focused on the joint migration implementation of SDN enabled IPv6 network. It was guided to fulfill the gap on related issues on migration of service provider legacy network into SoDIP6 network. A joint migration plan and strategy is presented through the evolutionary gaming approach. Similarly, an optimum migration cost optimization model is developed by applying heuristics based on shortest path routing and customer priority. The benefits of joint network migration are being elaborated via joint migration analysis, features comparison between legacy and SoDIP6 network with evaluation on energy efficiency of targeted network.

1.3 Research Questions

Three research questions (RQ) were designed to address the main problem outlined in this research. These are:

RQ1: What are the challenges, risks, and strategies for the migration of legacy IPv4 networks into SoDIP6 networks?

RQ2: What is/are the intelligent approach(s) for joint network migration planning and cost optimization?

RQ3: What are the roles of SoDIP6 networks for future sustainability of service providers and the society?

1.4 Research Use Case

The use case diagram depicted in Figure 1.2 shows the scope and limitations of the research. Basically, this research was designed to have study on the methods and practices to transform legacy IPv4 network into SDN enabled IPv6 network. Implementation of SDN and IPv6 is a complete paradigm shift in networking management and operations. IPv6 do take care of addressing and routing, while SDN enables the programmable networks with flexibility and openness of network management enabling all the features on next generation networking. Figure 1.2a depicts the legacy IPv4 networks as source network, through which service provider is supposed to be able to provide services to different customers. Figure 1.2b presents the transformation of source network into future network as a target network enabled with SDN and IPv6. Finding methods and planning to transform the source network into target network are the major research activities carried out in this study confining to IP routers migration.

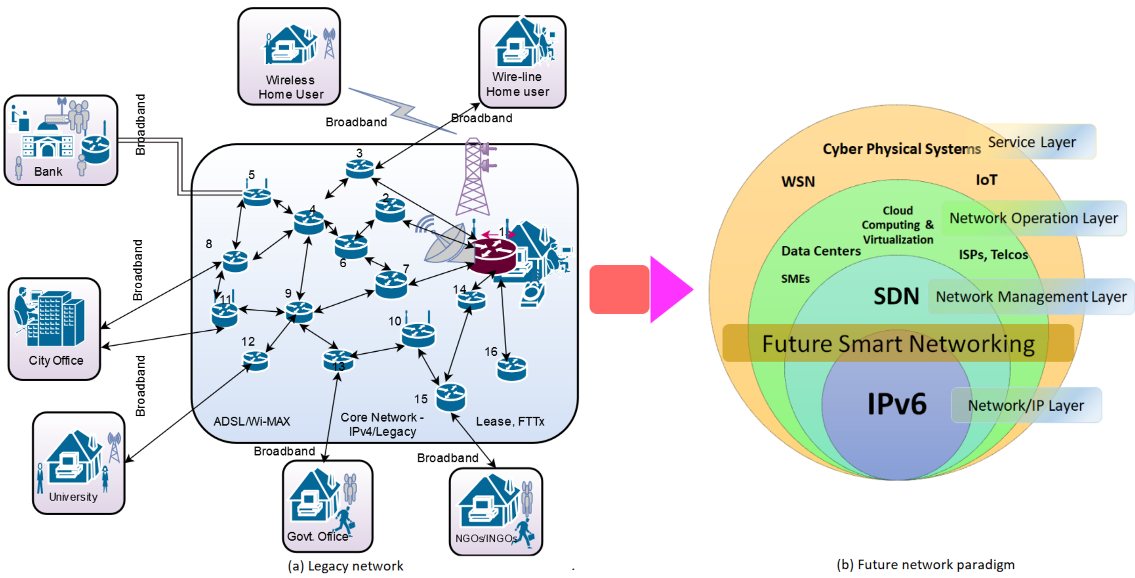


Figure 1.2: Research use case scenario

1.5 Aim and Objectives

With the aim to design and develop cost effective migration modeling to establish efficient and smart networking infrastructure, the objectives (OB) of this research were to

OB1: analyze the joint approach of legacy IPv4 network migration to SDN enabled IPv6 network.

OB2: develop intelligent approach for migration cost optimization and modeling of service provider legacy network migration to SoDIP6 network.

OB3: evaluate the features of SoDIP6 network in terms of energy efficiency for service provider sustainability.

1.6 List of Scientific Contributions

The contributions of this research are the published archival journal listed in Table 1.1 and conference presentations listed in Table 1.2. Seven journal papers (JP) were published and five conference papers (CP) were presented during the period of this research study. As a part of this research work, the concepts, analysis, algorithms, figures, and charts etc. were published in the many recognized international journals [8, 9, 10, 6, 11, 4, 2, 12] as a part of publication contributions of this research. The published contents during this research are mostly adapted in this structured thesis with appropriate permissions obtained from the copyrighted article publishers.

1.7 Thesis Organizations

The thesis is organized into seven chapters. The chapter-wise structuring of the contents are summarized here.

- **Chapter 1** (this chapter) introduces the thesis related to SDN and IPv6 joint network migration with preliminary background of the research, research use case, statement of the problem, research questions, aim, and objectives. Summary of research contributions are also listed in this chapter.

- **Chapter 2** provides the detailed literature review on network migrations to IPv6 and the SDN. The migration approaches of IPv6 and SDN are presented. A common concerns of IPv6 and SDN are discussed as a part of network layer

Table 1.1: Peer reviewed archival journal papers

ID	Description	Publisher (Objective Met)
JP1	Dawadi, B. R., Rawat, D. B., and Joshi, S. R. (2019). Software Defined IPv6 Network: A New Paradigm for Future Networking. Journal of the Institute of Engineering, 15(2), 1-13.	IOE Journal (OB1)
JP2	Dawadi, B. R., Rawat, D. B., Joshi, S. R., and Manzoni, P. (2020). Intelligent approach to network device migration planning towards migration to SoDIP6 networks.	(OB2) (Under Review)
JP3	Dawadi, B. R., Rawat, D. B., Joshi, S. R., and Manzoni, P. (2020). Migration cost optimization for service provider legacy networks migration to SoDIP6 networks. International Journal of network management.	Wiley, USA (OB2, OB3)
JP4	Dawadi B.R., Rawat D.B., and Joshi S.R. (2020). Evolutionary Dynamics of Service Provider Legacy Network Migration to Software Defined IPv6 Network. Advances in Intelligent Systems and Computing, vol 936. Springer, Cham	Springer, Cham (Book Chapter) (OB1, OB2)
JP5	Dawadi, B. R., Rawat, D. B., Joshi, S. R., and Manzoni, P. (2020). Evolutionary gaming approach for decision making of Tier-3 Internet service provider networks migration to SoDIP6 networks. International Journal of Communication Systems.	Wiley, USA (OB1, OB2)
JP6	Dawadi, B. R., Rawat, D. B., Joshi, S. R., and Manzoni P. (2020). Legacy network integration with SDN-IP implementation towards multi-domain SoDIP6 network environment. Electronics	MDPI, Switzerland (OB1, OB2)
JP7	Dawadi, B. R., Rawat, D. B., Joshi, S. R., and Keitsch, M. M. (2019). Towards energy efficiency and green network infrastructure deployment in Nepal using software defined IPv6 network paradigm. The Electronic Journal of Information Systems in Developing Countries, e12114.	Wiley, USA (OB3)
JP8	Dawadi, B. R., Rawat, D. B., Joshi, S. R., and Baral, D. S. (2020). Affordable Broadband with Software Defined IPv6 Network for Developing Rural Communities. Applied System Innovation, 3(1), 4.	MDPI, Switzerland (OB3)

technologies. Then, research approach for joint migration planning is proposed from this chapter.

- **Chapter 3** presents the details on conceptualization of SoDIP6 network with its definition. Conceptual design and problem formulations for joint migration planning, migration cost optimization, game theoretic approach on network migration, energy efficiency evaluation, and the prospects of SoDIP6 network deployment in the context of Nepal are presented in details.

Table 1.2: Peer reviewed conference papers

ID	Description	Publisher (Objective Met)
CP1	Dawadi, B. R., Rawat, D. B., Joshi, S. R., and Keitsch, M. M. (2018, October). Joint cost estimation approach for service provider legacy network migration to unified software defined IPv6 network. IEEE 4th International Conference on Collaboration and Internet Computing (CIC) (pp. 372-379).	IEEE, Pennsylvania, USA (OB 1, 2, 3)
CP2	Dawadi, B. R., Rawat, D. B., Joshi, S. R., and Keitsch, M. M. (2019). Recommendations for energy efficient SoDIP6 network deployment for the early stage rural ICT expansion of Nepal. International Conference on Computing, Networking and Communications.	ICNC2019, IEEE, Honolulu, Hawaii, USA (OB1, OB3)
CP3	Dawadi, B. R., Rawat, D. B., and Joshi, S. R. (2019, July). Evolutionary Dynamics of Service Provider Legacy Network Migration to Software Defined IPv6 Network. In International Conference on Computing and Information Technology (pp. 245-257). Springer, Cham.	Springer, Thailand (OB1, OB2)
CP4	Dawadi, B. R., Rawat, D. B., Joshi, S. R., and Manzoni P. (2021, January). ANFIS based classification model for network device upgrades planning towards SoDIP6 networks. IEEE Consumer Communications & Networking Conference.	CCNC2021, IEEE, Las Vegas, USA
CP5	Dawadi, B. R., Rawat, D. B., and Joshi, S. R. (2019, July). Affordable Broadband with Software-Defined IPv6 Network for Rural Communities. 10th International Conference on Quality, Reliability, Infocom Technology and Business Operations - Towards Smart, Reliable and Sustainable Future. Springer.	ICQRIT 2019, Springer, Nepal (OB1, OB3)

- **Chapter 4** includes the research design and methodology. An overall methodological framework based on the contributions are presented with separate conceptual frameworks for analysis and evaluation of the research works based on the concepts formulated in Chapter 3. The overall research steps are summarized via an algorithm.

- **Chapter 5** discusses on the results, analysis of experimental works, and the necessary interpretations. It also summarizes the contributions of scientific papers published.

- **Chapter 6** discusses on the overall research works with possible recommendations on the migration and implementation of SoDIP6 network in the context of Nepal.

- **Chapter 7** concludes the research study. Limitations of the study and possible future enhancements are also briefly highlighted in this chapter.

- **Appendices** (A, B, C, and D) present the dataset used for necessary simulations, experimental platforms used throughout this research studies with results and analysis snapshots including information of program code, simulations, and configuration details with questionnaire survey form.

Chapter 2

Literature Review

In this chapter, a detailed literature review on latest networking paradigms viz. SDN and IPv6 will be carried out. The individual migration approaches to SDN and IPv6 will be discussed with related works on migration implementations and practices. Suitable migration methods for service providers will be identified. A need of joint migration to SDN enabled IPv6 network will be presented with overall further research direction in joint network migration.

2.1 Overview of Latest Generation Networking

The growth of internet and social media users with their growing demand on rich multimedia contents led to the demand for higher bandwidth and connection speed in computer networks. High-end processing servers capable of computing bigger applications in the cloud is not only sufficient to provide better and reliable services to customers, but it also requires high speed and manageable network.

Last two decades were the stunning era for the World in the field of ICT. The advancement in computer and telecommunication networks transformed people's lifestyle from stone age into the modern smart societies. The invention of World Wide Web (WWW) in early 1990's led to the rapid growth of internet users such that the 32 bit length traditional Internet protocol version 4 (IPv4) addressing was immediately forecasted to be replaced by newer version of next generation addressing mechanisms – IPv6 [13].

One hundred and twenty eight bit length IPv6 addressing is the only solution to avoid IPv4 address depletion problem. Not only this, IPv6 has several added features as compared with legacy IPv4 addressing [14]. It enables to establish communication between any things in the universe. On the other hand, the drastic change in the concept of network operation and control evolved in the early decade of 2010's by the name of SDN is also gaining momentum for its implementation. Hence, IPv6 addressing, SDN, and cloud computing and virtualization are the backbone of future networking. The evolvement of Internet of things (IoT), wireless sensor networks (WSN), 5G wireless communications, society with industry 4.0, and beyond have created tremendous opportunities to build modern intelligent society. The operation challenges of legacy networks, for example, higher cost of operation, vendor dependency in support, and complexity of configuration creates sustainability issues for service providers [15].

From the networking perspectives, the convergence of communication standards of different communication types like audio, video, and text into digital packet based communications like different flavor of voice/video over IP (VoIP) and text over IP (ToIP) are the modern communication standards. 5G and beyond, low earth orbit satellites, SDN/NFV, IPv6, IoT/WSN, cloud computing, and big data analytics are the major entities of latest generation smart networking and applications. Among these, SDN and IPv6 are the prominent networking paradigms that all other entities depend upon for their operations. Hence, SDN and IPv6 are the networking standards and paradigms that the world has to move on with to develop sustainable and smart future society. In this context, all the stakeholders have to migrate their legacy networks into such operable latest networking paradigms.

2.2 Migration to IPv6 Network

2.2.1 Need of migration to IPv6 network

The functional operation of IPv6 was started in 1998 with its draft standards released by Internet engineering task force (IETF) [16]. Before entering into migration perspectives of IPv6, it is required to review on *"why such migration required?"* for this, the problems of IPv4 and features of IPv6 addressing have to be analyzed so that migration to IPv6 network is justifiable. The major issues of IPv4 and features of IPv6 addressing [13] are presented in Figure 2.1.

IPv4 public address has already been exhausted [17]. This limits the new networks expansion for service providers using public IPv4 addresses. Besides, the ISPs who migrated their networks into IPv6 only networks released the public IPv4 addresses, which is opened for address trading [9, 18] in the market, leading to higher costs for those ISPs, whose infrastructure still need to run with IPv4 compatible networks. The lack of public IPv4 addresses leads to obtain the address from black market, if

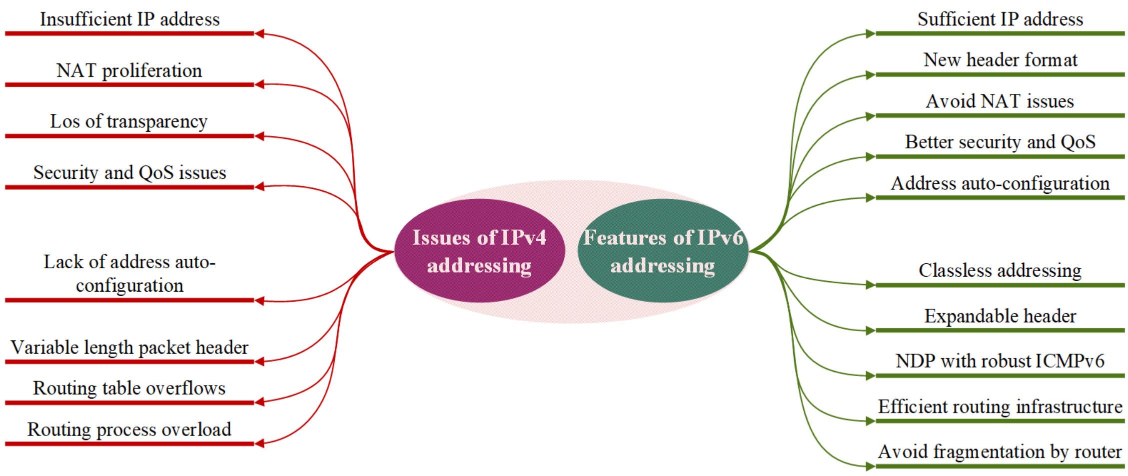


Figure 2.1: Issues of IPv4 and features of IPv6 addressing

the service providers still rely on the legacy IPv4 networking to provide the services. Alternatively, private IPv4 addresses are recursively used through network address translation (NAT) mechanism. But NAT has several drawbacks, for example, it hides several computers in private zone. Private computers are not reachable via the public scope leading to transparency and administration problem. Additionally, NAT breaks the end-to-end communication due to which some applications like file transfer protocol (FTP) does not work. Most likely, NAT fails in translating embedded IP addresses and leads to application failure. Hence, IPv4 and NAT is not the long term solution for service providers to sustain with the growth of Internet users. IP security (IPSec) is not mandatory in IP layer in the legacy IPv4 based network. Hence, security in IPv4 is limited. There is no authentication or encryption mechanism at IP level, for which IPv4 is dependent on higher level protocol. Hence, it is vulnerable to denial-of-service (DoS) and address deception or spoofing attacks. Packets sent at IP-level needs encryption to protect the private data from being viewed or modified. IPv4 has weak security implementation. In IPv4, QoS depends on the type of service (TOS) field in the header. Though the QoS in IPv4 is defined, it is not consistently used.

IPv4 lacks stateless address auto-configuration. Addressing each client personal computer (PC) can be done either manually (static addressing) or using stateful auto-configuration, for example, using dynamic host configuration protocol (DHCP) in IPv4 addressing. The static addressing in IPv4 based machines enabled only manual addressing, which, in the large network of an enterprise, is really a headache for network administrator. The stateful addressing i.e. automatic address provisioning using DHCP provides the IPv4 address to a machine only to specified lease period. Major drawback of stateful configuration is that the machine might have chances to renumber its address after the lease period is expired or the machine restarts, which creates issues in proper tracking of the machine by network administrator.

IPv4 packet header length varies from 20 to 60 bytes. In the worst case, router need to process 52 bytes except the 8 bytes source and destination addresses. Dynamic header length creates burden in routing processing. Additionally, IPv4 router fragments the oversized packets by itself. Fragmentation is an extra job that a router performs for every packets when the size is greater than the maximum transmission unit (MTU) and also re-assembles by the destination router. This creates processing overload on router due to extra task besides routing. The implementation of address aggregation [19] has somehow reduced the issues of IPv4 routing table overflows, however, more than 95k entries is not effective in routing information management, which still has routing table overflows in the core router in the internet.

One hundred and twenty eight bit length IPv6 address is designed to overcome all the issues related with IPv4 addressing. Sufficiency of IPv6 addresses led to establish Internet of everything (IoE) in the universe. IPv6 avoid NAT and related issues, as every device can have many globally unique IPv6 addresses. IPv6 header is fixed 40 bytes in length. The header field is well managed, at which router only processes 8 bytes of header fields keeping 32 bytes of source and destination addresses fixed.

The fragmentation related fields in IPv4 header are removed from the main header so that IPv6 router never fragment the oversized packet by itself. The routing process overloading problem is avoided that the role of fragmentation is transferred to source host. Features addition in IPv6 is fairly easy. It supports extension headers after its fixed 40 bytes header that can support several optional headers to be managed in a daisy chain fashion. The size of extension headers in IPv6 is only constraints by its packet size unlike IPv4 has fixed 40 bytes optional header field. Stateless address auto-configuration (SLAAC) in IPv6 simplifies the host configuration by enabling automatic address configuration for the link (called link-local address) and derived from the prefixes advertised by a router [20]. IPv6 enabled devices are plug-n-play as they automatically configured addresses in a link and establish communication without manual configuration.

IP security (IPSec) support is mandatory in IPv6 that provides a standard-based solutions for security as well as promotes interoperability in different IPv6 based implementations. The dedicated flow-label field in IPv6 header provides a special handling of packets belonging to a flow, a series of packets between source and destination, enabled a prioritized delivery of packets. As compared with Internet control message protocol (ICMP) version v4, ICMPv6 is robust to monitor network health. The neighbor discovery protocol (NDP) features in IPv6 consists of several ICMPv6 messages like router/network advertisement, ICMP redirect, and multicast communications. IPv6 NDP replaces the address resolution protocol (ARP) and Internet group management protocol (IGMP) of IPv4. IPv6 addresses are categorized into unicast, anycast and multicast. The concept of broadcast addressing of IPv4 is incorporated in the IPv6 multicast network.

In summary, IPv6 has stunning features and improvement in the IPv4 addressing issues [21]. The address shortage problem with associated issues of IPv4 enabled service providers and enterprises World-wide to migrate their existing IPv4 network into operable IPv6 network.

2.2.2 IPv6 transition methods

IPv6 addressing implementation by a single organization is not mean that this organization can provide fully operable IPv6 based services to their clients. It needs to consider what other service providers interconnecting with each other, are doing in the internet related to migration [22]. Individual organizations depend on the status of external interconnected networks that lead to the speed of migration in the chain [23]. Different migration methods are developed and implemented in real practice. Figure 2.2 presents a taxonomy of different IPv6 transition methods[17, 24].

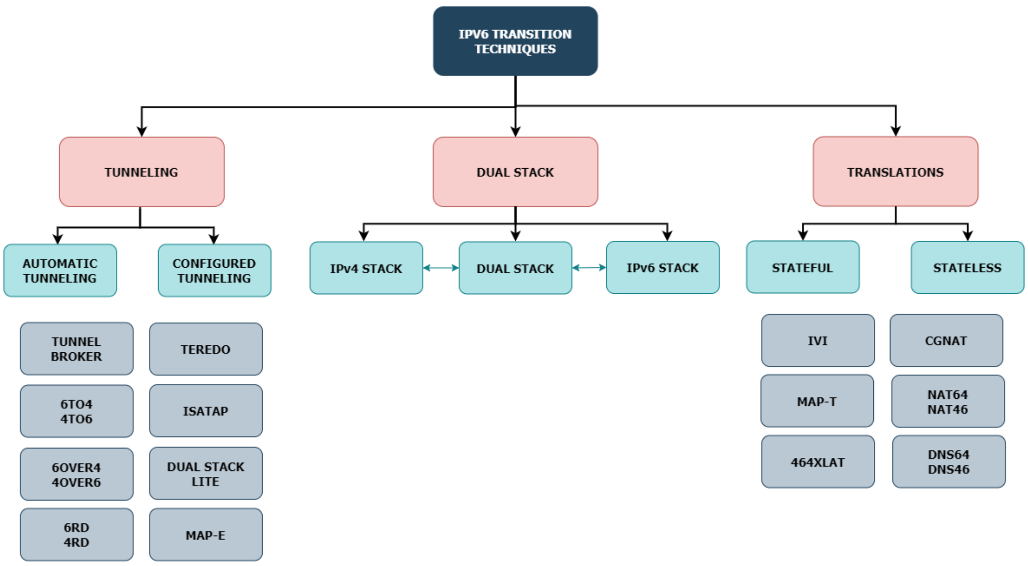


Figure 2.2: Taxonomy of IPv6 transition approaches

1. **Overview of tunneling techniques**

In the pre-migration phase, encapsulation of IPv6 packet over IPv4 payload provides the solution to communicate between IPv6 only sites over IPv4-only networks, while the reverse is applicable in the post migration, during when IPv4 traffic will be encapsulated into IPv6 payload to communicate between IPv4 sites within the IPv6 networks. In the configured tunneling, network administrator simply configures the tunnel endpoint routers and fix the traffic to destine to proper network [25]. As depicted in Figure 2.2, different approaches are available under automatic tunneling, in which traffic is automatically tunneled and destined to the proper networks for communication.

Tunnel Broker comes with tunnel setup protocol (TSP) is an automatic tunneling approach that allows IPv4 or IPv6 packets to be encapsulated and carried over IPv4 or IPv6 networks [26]. To establish communication between IPv6 networks and IPv4 only users residing beyond IPv4 NAT, Teredo [27] tunneling approach is used. In this approach, the UDP/IPv4 datagram containing IPv6 datagram can be routed over IPv4 Internet and through NAT devices. Hence, Teredo is only the solution to work behind NAT.

The 4to6 [28] approach is assumed to be the reverse scenario of 6to4 [29]. It is applicable in the post-migration phase during when separate IPv4 islands can communicate over IPv6 internet infrastructure by creating 4to6 tunnels. Note that 6to4 approach was deprecated in 2015 [30]. Unicast and multicast connectivity between IPv6 nodes over IPv4 intranet infrastructure is provided by the 6over4 [31] technique, in which IPv4 infrastructure is treated as a single link with multicast capabilities. The 4over6 method is basically categorized into public 4over6 [32] and lightweight 4over6 [33].

The ISATAP [34] approach is applicable when dual-stack (DS) nodes have to communicate with other dual-stack or IPv6 only devices available in the site of IPv4-only access network. DS Lite [35] is the approach, where the IPv4 traffic generated by Internet users behind customer premise equipment (CPE) over private IPv4 intranet are encapsulated into IPv6 packets and sent directly to ISPs' Carrier Grade NAT (CGNAT) having global IPv4 address. An extension of the DS Lite approach is recognized as Lightweight 4over6, in which the NAT functionality from the DS Lite tunnel concentrator at ISP side is moved to the CPE.

ISPs, who are in the early stages of their network migration, can provide immediate IPv6 services to their customer on demand using 6RD as a rapid deployment approach [36]. This creates automatic tunnel to encapsulate IPv6 packet over IPv4 packet between customer edge router and ISP border gateway over IPv4 backbone network. IPv4 residual deployment (4RD) [37] is an approach just a reverse of 6RD, in which IPv4 packets are tunneled in a stateless manner across IPv6-only ISP networks. This helps to preserve the IPv4-only customers for ISPs.

2. **Dual-stack approach**

   The Dual-stack is a simple solution for service providers to have smooth migration of legacy network into IPv6 only network. In this approach, every device should be able to process with IPv4 and IPv6 packets [25]. Hence, network devices have IPv4 stack and IPv6 stack both. Either one stack can be enabled at a time in the network or both stacks can be activated based on the requirement. Migration to dual-stack network is safe and comfortable approach for service providers to provide reliable and uninterrupted services to customers of their choice.

3. **Translation techniques**

   The IVI [38] is the mechanism that performs IPv6 header, transport layer header, and ICMPv6 header translation and vice versa. Stateful IVI consists of 1:1 and 1:N translation. 1:1 means one IPv4 address is mapped to one IPv6 address, while 1:N translation has one IPv4 address to be translated into many IPv6 addresses. To achieve better throughput, stateless IVI is generally applied in the backbone network [39].

   The NAT64 [40] is a mechanism that provides a stateless approach to translate IPv4 into IPv6 and vice-versa. For one IPv4 to many IPv6 addresses mapping, stateful NAT64 [41] is required. It multiplexes many IPv6 devices into a single IPv4 address [42]. DNS64 [43] is required for both stateful and stateless NAT64 operations. NAT46 [44] allows an IPv4-only client to communicate with an IPv6-only server by translating IPv4 header to IPv6 and vice-versa for the return traffic. It needs DNS46 for large network to work.

   The 464XLAT [45] is the combination of stateful and stateless translation. CLAT is the customer-side translator of XLAT. It implements RFC6145 [46] as stateless NAT46 approach, while PLAT is the provider-side translator of

XLAT that implements RFC6146 [41] as stateful NAT64. Carrier grade NAT (CGNAT) [47] is the marketing term also called the large scale NAT that implements the translation between IPv4 private to IPv4 public address called NAT444 [48], which is, in fact a recursive NAT. CGNAT comes in different flavor like NAT444 and double NAT64 (also known as NAT464) [49].

The Mapping of Address and Port (MAP) is a combined form of MAP using Encapsulation (MAP-E) and MAP using Translation (MAP-T) [50, 51, 52]. MAP-E is a stateless DS-Lite approach that performs algorithmic mapping between IPv4 and IPv6 address. MAP-T is the implementation of double translation stateless NAT64 and NAT46 based solution for providing shared or non-shared IPv4 address connectivity [53].

2.2.3 World-wide IPv6 network deployment status

Google is continuously measuring the availability of IPv6 access among google users and achieving 32.27% users accessing google via IPv6 as of Feb., 2021 [54]. The World-wide target of migrating network into IPv6 has been shifting since 2008. Different countries are setting different targets, however, achieving the target is quite challenging and deferring to new date due to technical and financial issues [55]. Few developed countries have satisfactory level of IPv6 network deployment, but in an average, the World-wide IPv6 capability has just crossed 26% [1]. This figure is mostly led by the migration status of developed countries, while the average IPv6 adoption rate of developing countries is still below 1% [54, 1].

Based on the different IPv6 transition methods with their benefits and drawbacks found in the literature [17, 24], dual-stack is a suitable approach to provide long-term solutions that every device operates on IPv4 and IPv6 networking during migration. For the migration of existing network devices, dual-stack is considered in this study as the smooth and safe transition method for service providers. ISPs can decide suitable time to switch off the legacy IPv4 and operate over IPv6 only network. Both stacks operate during the transition periods only, while to avoid the dual-stack network operation costs, service providers can switch off the IPv4 stack after complete migration to IPv6 network.

2.3 Migration to SDN: Methods and Practices

The World-wide network infrastructure is growing with respect to the service demands. The currently operating network is highly heterogeneous, in which there is required to deal with different protocols, many platforms, and vendor specific network equipment with their own proprietary software. Network operators have to configure their individual network devices separately using either low-level or vendor specific configuration commands. This individual device configuration is highly time consuming and complex in network management, maintenance, and troubleshooting. The control plane decides how to handle network traffic and directs data plane devices based on its decision. Data plane forwards traffic according to the decisions made by the control plane. The data plane and control plane functionalities bundled inside the networking devices reduces flexibility, hindering innovation, and evolution of the networking infrastructure [3].

The non-profit consortium "Open Networking Foundation (ONF)" is the an organization dedicated to develop, standardize, and commercialize the concept of SDN. It was originally coined with the ideas by conceptualizing "OpenFlow" at Stanford University, USA. The definition of SDN is:

"Software-defined networking (SDN) is an emerging network paradigm where network control plane is decoupled from forwarding plane and is directly programmable" [56].

The forwarding state in the data plane is remotely controlled/managed by the decoupled control plane called SDN controller, which is located as an external entity, for example, at the network operation center (NOC).

A simple network consists of legacy networking devices is shown in Figure 2.3a. Legacy networking device has its control and data plane vertically integrated that makes the network complex in management and configurations. Individual legacy device also consists of application layer services that includes routing, mobility, access control, virtual private networks (VPNs), multi-protocol level switching (MPLS), traffic and security management etc. Figure 2.3b presents a simple network architecture, where the control plane and application layer services are detached from individual network devices and moved to a single controller. The control plane and north bound applications run on a commodity hardware called an SDN controller, whose major task is to control the communications in data plane devices.

The structure of SDN is divided into three layers viz. infrastructure layer (data plane) in the bottom, controller layer at the middle, and application layer in the top. The bridging between infrastructure and applications in SDN is done by controller

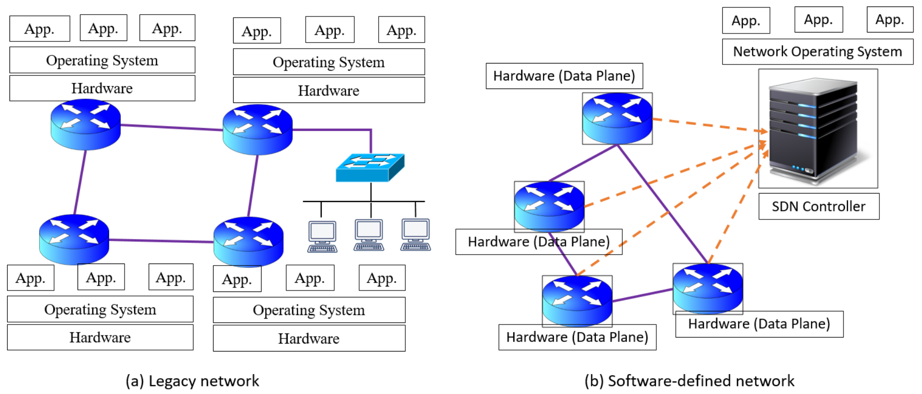


Figure 2.3: Functional architecture of (a) legacy network, and (b) the SDN

through its middleware called northbound and southbound application programming interfaces (APIs). For the controller load balancing with reliability, efficiency, and fault tolerant, additional controllers can be attached via eastbound and westbound APIs. Northbound APIs are RESTful APIs like frenetic, xml, json etc., while OpenFlow is a vendor neutral protocol available in southbound to establish communications between the controller and the data plane devices. Figure 2.4 depicted the overall layered architecture of SDN.

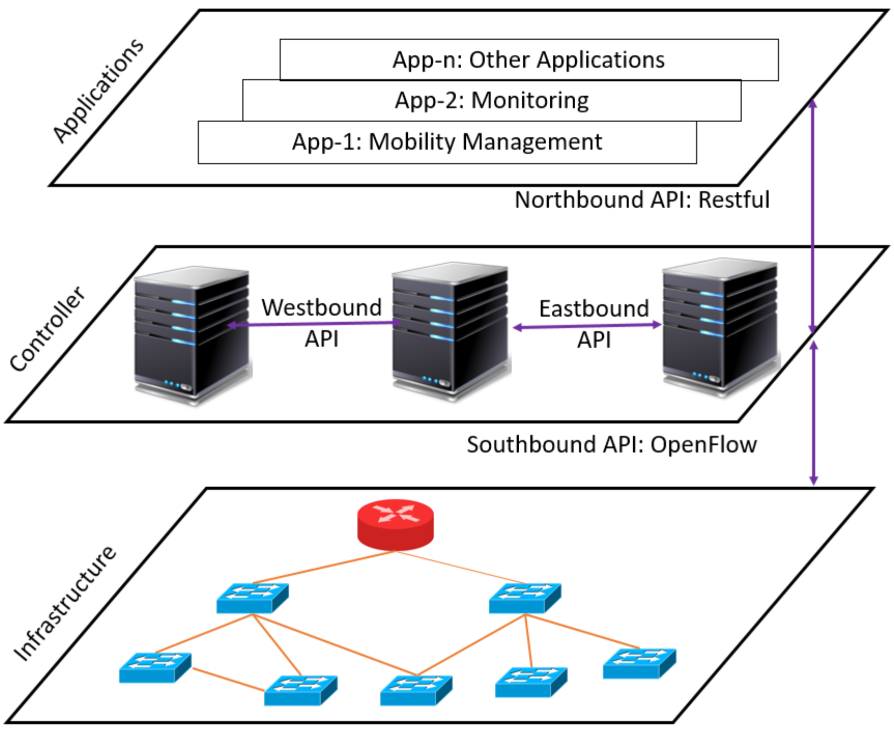


Figure 2.4: SDN layered architecture

Principally, SDN capable switch checks the flow entries of packets incoming and direct the packets to outgoing interface, if the flow entry is matched. Otherwise, the packet header, whose flow entry is not found in the flow table, would be forwarded

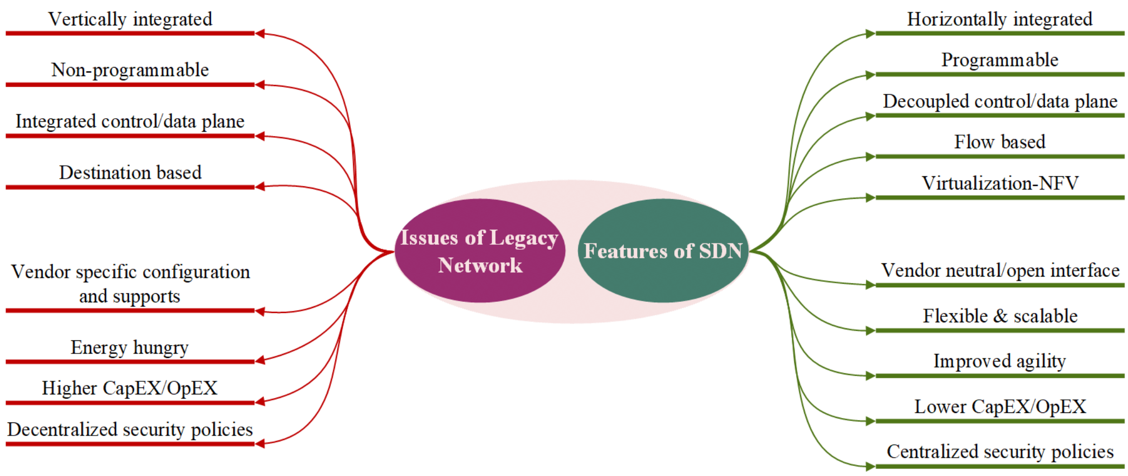


Figure 2.5: Problems of legacy network and features of SDN

to the controller for further decision. The controller provides decision by updating flow tables of the entire switches towards the path of the packet's destination.

2.3.1 Need of SDN migration

SDN allows network operators to manage and operate virtualized resources without deploying additional hardware. This paradigm shift in network operation and management is considered as the advanced networking approach that counters the increasing complexities in the existing legacy networking system and optimize the operational cost. The existing problems of legacy IPv4 networking system and the features of SDN [57] are listed in Figure 2.5.

SDN increases automation in network management and operation with less human intervention that could help to reduce the CapEX and OpEX of the organizations [15, 58, 59]. Hence, it encourages the service providers to search for the better options and attraction towards SDN. Besides the implementation challenges [60], SDN is proven technology towards efficient network management that it solves those existing issues in the legacy IPv4 network and create highly flexible, visible, programmable, scalable, modular, open interface, and abstraction-based networks [61, 62]. Migration to SDN over data center networks are popularly endorsed [63, 64, 65], while ISP networks migration is in the early stages. Similarly, the ongoing research, development, implementation, testing, and verification [61, 66, 65, 67, 68, 69] of SDN and IPv6 implementations in ISP/Telcos network are encouraging activities for service providers to migrate their legacy networks into a phase-wise manner.

2.3.2 SDN migration approaches

The changes in the networking paradigm by detaching control plane form each switch/router and integration into a single controller to manage/control entire network through remote controller is the major technology change endorsed by SDN. This paradigm shift has several benefits as compared with legacy networking. Significant amount of OpEX and CapEX saving can be achieved with the implementation of SDN [58, 70]. But the challenging situation with SDN migration is the issue of network device upgrades or replacement as immediate migration to SDN is not viable same as that of IPv6 network. Smooth transition approaches for SDN migration in ISP and Telcos networks are still an ongoing research and implementation. Three approaches of legacy network migration to SDN proposed by ON.LAB [61] are depicted in Figure 2.6.

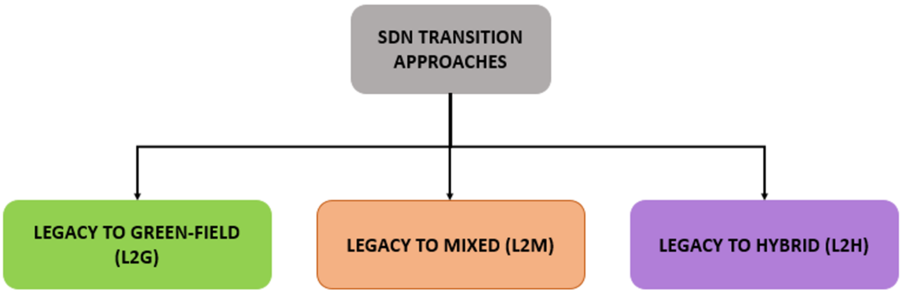


Figure 2.6: SDN migration approaches

The Legacy to Greenfield (L2G) approach enables clean setup of the SDN, in which either only the complete replacement of existing networking infrastructure or expansion of new network is possible. But for the running network infrastructure, the immediate replacement of network devices is not viable for service providers due to many complexities, e.g. higher cost of investments, lack of skilled HR etc. Hence, this approach is applicable for service providers to expand purely new network with possible pilot tests and experimentation.

The Legacy to Mixed (L2M) approach supports a gradual transition to SDN, while the network consists of legacy and SDN enabled devices during migration. Once the interoperability between legacy devices and SDN devices is ensured, this approach is fairly suitable for migration implementation. SDN-IP implementation over ONOS enables integration of legacy networks with SDN for the mixed types of communication in a multi-domain routing environment [71, 70, 72].

Routers in the Legacy to Hybrid (L2H) approach maintains both legacy routing and OpenFlow table. The router in this approach is supposed to be a dual-stack device

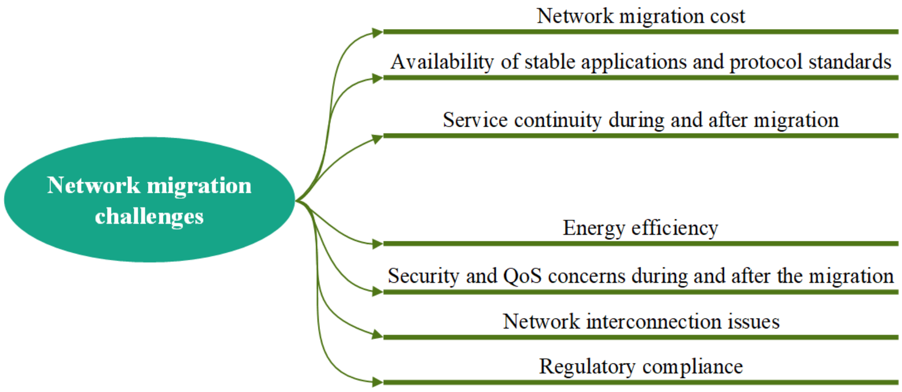


Figure 2.7: Network migration challenges

having the option to forward traffic based on legacy routing or OpenFlow table based on the incoming traffic to be destined. Experiment by ON.LAB [61] and studies by different authors [73, 74, 66] indicated that migration to hybrid network is viable. These days, the terms 'mixed' and 'hybrid' are used interchangeably [75, 76]. Hybrid networks or mixed networks both constitute the existence of SDN and non-SDN devices in the same network. Hybrid switch means it is capable to operate legacy routing and OpenFlow forwarding both.

In summary, network migration using L2G approach is not a viable solution, in which a complete set of new infrastructure can be established using this approach. From the migration perspectives, L2H/L2M approaches are more reasonable to follow for smooth transition. Hence, present study considered Hybrid SDN implementation in the legacy network migration to SoDIP6 network.

2.4 Challenges of Network Migrations

Network migration is a complex process, because the networking infrastructure can't be transformed on-the-fly leading to a delay in the migration [77] due to major challenges [15, 9, 78], which are highlighted in Figure 2.7

1. **Network migration cost**

   The issues of investment and operation cost have many folds. Network infrastructure consists of large number of networking components that are not possible to upgrade or replace on-the-fly. Enterprises should be financially ready, HR ready, application and protocols standards ready, and ready for disaster management as well [79]. For the fairly sustained service providers of developing nations like Nepal, it is hard to migrate their infrastructure into operable latest technologies like SDN and IPv6.

2. **Availability of stable applications and protocol standards**

   Readiness measurement on network and server applications as well as protocol standards and their applicability are important before planning for migration. The World-wide deployment progress of IPv6 shows that the applications and protocol standards are well tested and implemented, while sufficient benchmarking on SDN related network applications and protocols are still an ongoing process. It is required to evaluate all the networking components e.g. hardware, operating system (OS), applications, security systems, and many more for the better continuity of services.

3. **Service continuity during and after the migration**

   The changes on the system may interrupt the overall networking operations. This is one of the major factor that delays the migration. Service providers are always in fear of service interruption, while approaching the new technology in the implementation.

4. **Energy efficiency**

   The expansion of network size including hardware and software increases energy bill annually [4]. Optimization on energy consumption by network equipment focusing to green computing in SoDIP6 network operation is also a major concern for the service providers.

5. **Concerns of security and QoS during the migration**

   Security is another major concern to guarantee that whether the network during or after migration is well secure or not. It is obvious that implementation of new technologies and integrated it with the existing legacy one during the transition can create security risk. The firewalls, servers, and other applications security should also be able to function properly with latest technologies.

6. **Network interconnection issues**

   The World-wide network/internet architecture is a hierarchical tired architecture. Tier-1 ISPs are core network/internet service providers, Tier-2 ISPs are transit service providers, while Tier-3 ISPs are the service providers of end-access customers. The sources of contents in the internet are highly distributed and heterogeneous. ISPs are fully interconnected. They have their own trade agreement and management to exchange the traffic. In this aspect, only migrating of one ISP network does not have meaning and could not provide the latest services to its customer. It is required to have a close coordination with other interconnected ISPs in the same level and in the hierarchy.

7. **Regulatory compliance**

   International regulatory bodies like international telecommunications union (ITU) and Internet corporation for assigned name and numbers (ICANN) have issued standards procedure to IPv6 network migration. Similarly, every country have their own standards and regulatory guideline for network migration [80]. The uneven distribution of IPv4 addresses by the internet registries has created the imbalance on network migration activities World-wide. Asia is the region, where the public IPv4 address exhaustion was announced first time in 2011. ARIN and AFRINIC had lots of IPv4 address block till 2019 leading to delay in exhaustion [81, 82]. The regulatory standards of SDN migration is an ongoing process [83, 82]. Hence, this is an additional challenges for service providers to remain in the boundary of regulatory compliance to migrate their networks.

2.5 Related Work in IPv6 Network Migration

Different transition methods discussed in Section 2.2 are not mutually inclusive. "*Which method is suitable to implement for transition?*" is generally depends on the service provider's network status and their sole decision. For example, if an ISP is in early stage of its IPv6 network migration, but there is customer demand of IPv6 based services, then 6RD technique for quick service delivery would be suitable. Similarly, if ISP backbone network is already IPv6 ready, then DS lite or address family translation like XLAT is suitable. Looking into the world's largest service providers, Google has already migrated its enterprise network into IPv6 [69]. Similarly, AT&T, NTT, and other largest telecom operators have their network operation successfully running with IPv6. In most of the countries, IPv6 network migration is guided by the national regulatory policies [84] that ISPs are migrating their network to IPv6 operable network accordingly. A game theoretic approach of IPv6 network migration was presented by Trinh et al [85]. Nikkhah M [22] performed the mathematical modeling and numerical analysis on incremental adoption of IPv6 network migration from the perspectives of ISPs, content providers, and internet users.

2.6 Related Work in SDN Migration

Being an ongoing research work, development of approaches for SDN migration in Telcos/ISP networks domain have higher priority to the World-wide researchers. There are few contributory works, which are briefly summarized here that attempted to provide the paths for real time transition of legacy networks into SDN.

HARMLESS [86], OSHI [87], Panopticon [73], RouteFlow [88], and Fibbing [74] are some of the approaches proposed for the migration to hybrid IP/SDN. However, the implementation of any approach proposed in the production network is not known. Recently, ONOS/SDN-IP [89] is the dedicated controller and application developed by ON.LAB to dedicate carrier grade network migration of ISP/Telcos networks into SDN. A brief comparison of above approaches are presented in Table 2.1 [71].

A reliable and secure communication between the switch and the controller is the most with minimum flow setup time required to be maintained as a measurement of better quality of service in SDN. It is required to design the best location of controllers with their count to properly handle the communications with switches to be maintained with minimum latency. *How many controllers are required to handle the network?* is dependent on the size of network consisting of number of switches and the distance between controllers and switches. The number of controllers required to be assigned to switches and their proper placement in SDN play important role to achieve considerable flow setup time with better fault handling and effective controller load balancing [90]. Sufficient studies [90, 91, 92, 93, 94] have been carried out regarding the proper placement of controller in data center pure SDN [90, 91]. One major concern in this research is to find proper location of a master controller during network migration. Das T et al. (2018) [95] presented the resilient controllers placement in the hybrid SDN/legacy network and achieved better result by comparing with other controller placement strategies implemented over the pure SDN. For the controller fault handling and resiliency in SoDIP6 network, this approach is applicable to add other controllers after locating master controller in the SoDIP6 networks during and after the migration.

Table 2.1: Hybrid SDN implementation approaches

Migration method	**SDN-IP** [88]	**Fibbing** [72]	**Panopticon** [71]	**OSHI** [85]	**RouteFlow** [14, 86]	**HARMLESS** [84]
Approach	Hybrid network (Traditional + SDN)	Traditional	Hybrid network (Traditional + SDN)	Hybrid switch (Traditional + SDN)	SDN route mapping with traditional routing	Hybrid switch (Traditional + SDN)
Applicable networks	All enterprise and ISP networks	All enterprise and ISP networks	All enterprise and ISP networks	Suitable for large scale experimentation	Small enterprises and data centers	Small enterprises and data centers
Performance	Robust, distributed and scalable	Inherits the benefits (scalability, robustness, fault tolerant) of legacy routing protocols like OSPF, IS-IS	Performance issues at large scale implementation due to tunneling and VLAN tagging. Resource performance tradeoffs	Performance issues at large scale implementation due to tunneling (openVPN, VXLAN)	Operation and configuration complexity for large networks	Not a robust approach over large scale carrier grade network migration
Controller	ONOS	Fibbing controller (own controller)	POX	FloodLight	POX/NOX	OVS controller V2.0.7
Production status	In production and implementation [88, 89, 90, 91, 92]	Not Known	Not in production	Not Known	Not in production	Not in production
Transition support	Yes	Yes	Yes	Yes	No	Yes

2.7 Research Gap and the Proposed Approach

From the literature review, it is clearly seen that SDN and IPv6 are two inter-related future networking paradigms that service providers have to migrate their existing legacy networks to such latest networks for better and efficient services with minimization on operation complexity, organizational CapEX, and OpEX. IPv6 deals with the addressing and routing in the network layer, while SDN added flexibility and programmability to control and manage network layer devices by separating the data and control plane, and logically centralizing the control plane into a controller, which bridges the network applications in the north bound and manage the data plane devices in the south bound. Hence, there is clearly seen the common concerns between SDN and IPv6 that are depicted in Figure 2.8 in terms of network migration.

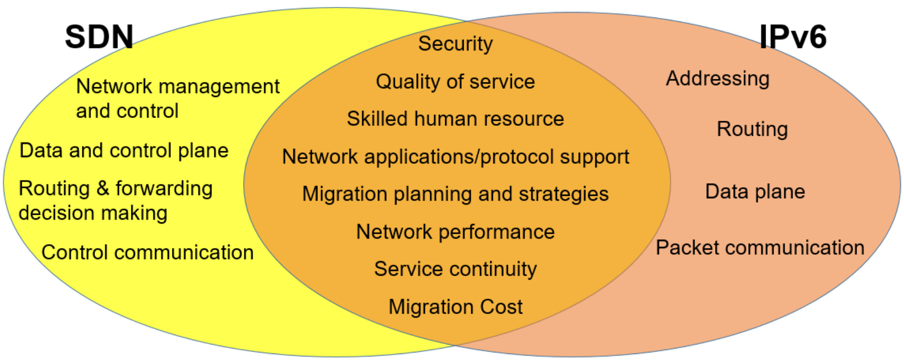


Figure 2.8: Common concerns on migration to SDN and IPv6 networks

IPv6 has better security and quality of service support, while SDN added programmability features leading to better security policy, which can be applied in the future networks. From the service provider point of view, the guarantee of stable networking applications/protocol standards, proper migration planning, technical HR development to operate and maintain the latest system, migration cost estimation and optimization, and strategy development with service continuity in terms of disaster recovery and business continuity planning are the major concerns to be considered in the network migration. IPv6 network migration world-wide is progressive, while the SDN migration in ISPs/Telcos network seem to be still in the early stages. In this context, a joint migration planning would help to have smooth transitioning to future networks with significant optimization in the network migration cost. To the best of author's knowledge, there is limited or no research carried out on the joint migration planning of legacy network migration to SDN and IPv6 network. Hence, SDN enabled IPv6 network, termed as Software-defined IPv6 (SoDIP6) network is introduced as a latest network to be considered for the migration.

For the service providers, those who are in the early stages of their network migration, it is proposed to have research on joint migration planning, migration modeling, and cost optimization so that a sustainable future networks can be established. Figure 2.9 shows the amalgamation of proposed research path, in which to have smooth transitioning methods for ISPs, dual-stack IPv6 and Hybrid SDN are considered.

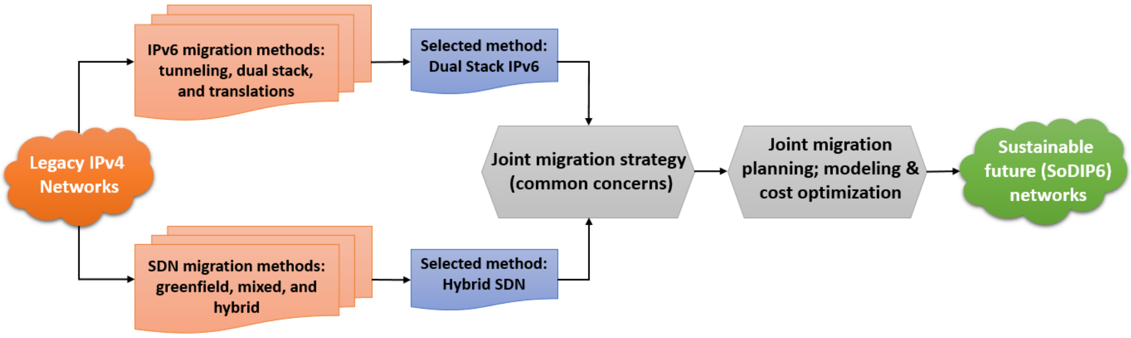


Figure 2.9: Proposed research path

2.8 Chapter Summary

A detailed literature review on IPv6 and SDN migration including World-wide deployment status of those networking paradigms have been carried out. Network migration challenges are identified and proposed joint migration to SDN and IPv6 with the name SoDIP6 network for migration cost optimization, plan and strategy development in joint migration, and energy evaluation of migrated network.

Chapter 3

SoDIP6 Network

As a continuity of literature review done in Chapter 2, Software-defined IPv6 (SoDIP6) network will be introduced with its conceptual definition. The benefits and challenges of SoDIP6 network migration will be discussed. Based on the proposed research directions outlined in Chapter 2, a joint network migration strategy will be presented towards smooth transition planning and migration cost optimization. Problem formulations and algorithms development will be carried out for network device status identification, joint network migration cost optimization, evolutionary dynamics of network migration for service providers, energy efficiency evaluation of SoDIP6 network with CO2 emission reduction practices, and rural broadband network deployment for Nepal in the context of SoDIP6 network implementations.

3.1 Introduction and Definition

One major goal of this research was to investigate "*how does migration of IPv4 based legacy network into SoDIP6 network could provide better efficiency with optimum migration cost?*". IPv6 is an alternate solution to handle many issues of existing legacy IPv4 networks in the context of exponentially increasing networked devices. Furthermore, SDN is regarded as an emerging paradigm that provides better visibility, controllability, and security to the network for better performance and efficiency. IPv6 helps to improve the efficiency of internet protocol including addressing, security, and routing, while SDN helps to improve the manageability of networks by using open protocols and SDN controller. Routers and the switches are the core components of the service networks, which are to be able to operate with the newer technologies. Either upgrade of the software/firmware version or device replacement is required with the investment on CapEX and OpEX for the service providers to migrate their networks. For both networking paradigms, migration concerns the device upgrades or replacement with the need of skilled technical HRs to maintain the network in the long run. Hence, a joint migration to SoDIP6 network as an optimum solution for cost effective migration is proposed. “SoDIP6 network” is defined as: [9].

“The complete network and server systems operated with IPv6 addressing and routing over Software-defined network environment, in which the data plane forwarding devices enabled with IPv6 packet communications, are controlled and managed by the logically centralized SDN controller.”

For the fairly sustained ISPs, it is more important to develop the strategic plan for migration and estimate the cost incurs for total migration of network together with the guarantee of uninterrupted services to their customers. However, IPv6 network migration approaches [17, 24, 20] have been developed and their implementations are in action, the slow pace of adaptation World-wide and the beginning stage of SDN deployment at ISP and Telcos networks encouraged towards joint migration planning and analysis.

3.2 Benefits of SoDIP6 Network Migration

The challenges of network migration including features and issues were discussed in Chapter 2/Section 2.4. In this section, the benefits of migration to SoDIP6 network will be presented. The major reasons that an ISP would be hesitant for migration are the huge cost of investment to migrate, lack of full proof applications and protocol support, lack of technical HRs, lack of clear revenue generation strategies, and lack of confidence that their investments will be returned after the migration.

Legacy IPv4 network is stable based on its protocol standards and applications available. It supports varieties of applications and protocol standards that service providers are currently offering. Additionally, there are many translation and tunneling approaches developed. These are applied with least cost to communicate with remote IPv4 ends as well as communication with IPv6 networks [17]. Although, the IPv4 address is already depleted, the reuse of private addresses and applicable recursive NAT mechanism makes the IPv4 network can sustain longer in the networking world. The network operation, configuration, and management are complex in legacy system, but it has certified technical HRs sufficiently available in the market for management and operations. Network equipment vendors have not closed their support yet for legacy system that leads to easy going for incumbent ISPs to continue with existing legacy IPv4 networking system.

SDN is successfully implemented in the data center networks [61, 67, 69, 68]. Its implementation and migration prospects in the Telcos and ISP networks are popularly under research, development, implementation, and testing. World-wide IPv6 adoption rate is crossing 27%, while its growth in the recent years is exponential [54, 1]. In this regard, being correlated technologies, the joint migration approach is modeled and presented its benefits in migration cost optimization for service providers towards incremental deployment to hybrid SDN and IPv6 network. This establishes the cost effectiveness of migrating existing legacy IPv4 network into SoDIP6 network.

With the growing network size, increasing number of internet users, evolvement of IoT and smart networking, the vertically integrated legacy networking system is becoming more complex in management, operations, and configurations. All the existing issues like address depletion, NAT proliferation, vendor specific configuration and control, and the operation complexities in the existing network system can be avoided only after implementation of SoDIP6 network. However ISPs can sustain longer with continuation of legacy IPv4 system, translations and tunneling approaches are becoming more costly as well as complex in operation and management with the growing network infrastructure and the Internet users. The features of SoDIP6 network that encourages for network migration are shown in Figure 3.1. These are the combination of features of two networking paradigms (IPv6 and SDN) presented in Chapter 2.

1. **Sufficient address space**

   One hundred and twenty eight bit length IPv6 addressing structure using hexadecimal numbers provides higher than the astronomical value to uniquely identify networking devices in this universe. This can create flexible and scalable network, while the implementation of IoT and expansion of WSN will be more convenient to create smart world by using IPv6 addressing.

2. **Efficient addressing and routing infrastructure**

   Internet assigned numbers authority (IANA) has defined the hierarchical distribution of global IPv6 addresses starting with global routing prefix then to regional internet registries, national internet registries, and local ISPs [96, 97]. This creates an efficient, hierarchical, and summarized routing infrastructure.

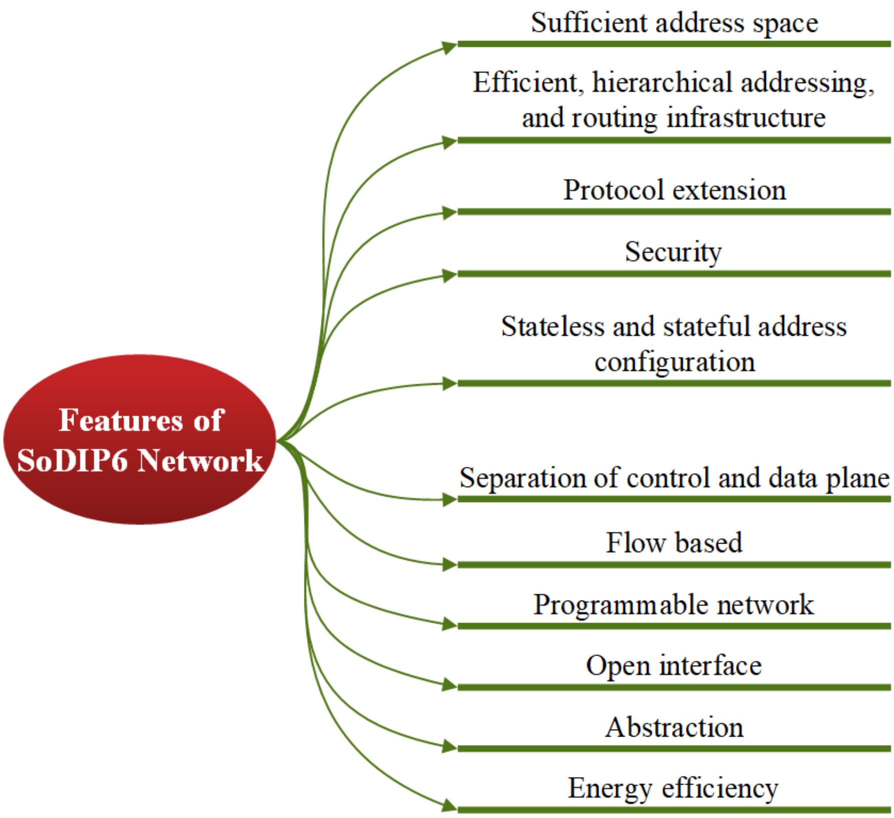


Figure 3.1: Features of SoDIP6 network

3. **Stateless and stateful address auto-configuration**

   Address auto-configuration is the new feature in IPv6 addressing, which supports both stateless and stateful addressing to automatically configure host addresses. In stateless address auto-configuration, IPv6 host automatically configures its link local and global IPv6 address via random assignment by using specific algorithm or by using EUI-64/SEUI-64 address format [98] to define the IPv6 suffix, while prefixes are advertised by local routers. IPv6 supports same concept of IPv4 to use DHCP as a stateful addressing.

4. **Protocol extension**

   IPv4 header is constrained only by 40 bytes optional header fields while IPv6 easily accepts extensions in its header with new features, in which the extension headers are managed in a daisy chain fashion after IPv6 main header.

5. **Separation of control and data plane**

   The control plane of individual devices are removed and centralized into the SDN controller. Data plane of the network device simply acts as a packet forwarding element based on the decision made by the controller. This logical centralization of controller creates opportunities to develop customized applications at its northbound and implement network policies through abstraction. This reduces the complexity of networking functions, applications, and network services making the network more flexible in operation and control.

6. **Flow based**

   Flow based instead of destination based [3] forwarding decisions are made by the SDN controller. A flow in SDN is identified as a set of packet field values acting as a match (filter) criterion. It consists of a set of actions (instructions) on the sequence of packet from source to destination.

7. **Programmable network**

   Programmability feature is the fundamental characteristic of SDN. It is highly programmable, so that customized software applications implemented on the top of SDN controller easily interacts with data plane devices for necessary operation and management of the network.

8. **Open interface**

   Standardization of an open interface with open APIs and communication protocol, like OpenFlow between the devices having control plane (SDN controller) and data plane enables the networking system as a vendor neutral common platform for the network management.

9. **Abstraction**

   To support equipment from different vendors and technologies, and also enable control plane to support varieties of applications, SDN applications are abstracted from its underlying network technologies.

10. **Security**

    IP Security (IPSec) is a default security framework defined under IPv6 protocol suite requirement. IPSec provides set of standards for authentication and encryption with key management framework for network security needs and promotes interoperability between different IPv6 implementations. Similarly, network programmability with centralization of control plane in the network adds more flexibility to apply different security policies to build robust and highly secure network environment.

11. **Energy efficiency**

    Due to the lack of smart controlling features in the legacy IPv4 networking system, energy consumption by network equipment is higher. The energy bill increases with increasing network size as well. SoDIP6 network is more energy efficient, in which energy saving can be achieved algorithmically or through the hardware improvements [4]. Implementing SoDIP6 network has significant OpEX saving with energy optimization and reduction of CO2 emission making the network more energy aware to promote green ICT [4, 10].

Migration to IPv6 network is inevitable and also service providers will be encouraged themselves towards SDN due to its superior features as compared with the legacy IPv4 networking system. The major affecting parameters for a decision maker to take migration decision are the requirement of content providers, other interconnecting ISPs and their migration status, and demand of newer technologies and services by end users and the enterprises. Similarly, regulatory guidelines, government plans, and policies are to be considered for timely address of migration issues.

3.3 Related Work in SoDIP6 Network Migration

Technically viable and economically feasible solutions should be adapted, while considering technology migration. Hence, cost of migration plays a vital role together with the readiness parameters in terms of applications, protocol supports, and technical HRs. Some studies [99, 100] have been discussed on the economic aspects of IPv6 network migration, where some cost benefit analyses have been presented for different stakeholders considering the fundamental principle of the Probit model, ruling that adaptation to newer technologies are viable, if revenue exceeds the expenditure. This applies to all kinds of network, Internet, and content service providers for their sustainability. Measuring the tangible benefits of SoDIP6 network migration is fairly complex because of its focus on efficiency of network operation, management, security, and quality of service, where direct measurement as a source of revenue is difficult. But the benefits of SoDIP6 network that has major contributions in organizational CapEX/OpEX optimization [59, 58] are notably considered.

NIST [101] has presented an economic impact analysis of IPv6 network by doing survey with different stakeholders like service providers, hardware, and software vendors. Csikor et al.(2018) [66] presented a cost effective solution with respect to hardware appliance upgrade in SDN migration. Some researchers [102, 103, 104] have presented the techno-economic aspects of SDN migration.

Backbone network migration with better resource utilization using heuristic solutions like tested with different genetic algorithms (GA) have been presented by Türk et al.(2018) [105]. The author(s) simulated the scenario for a period of five years over ISP backbone networks and claims that crowded DPGA gives better result for optimum cost, and resource utilization. Additionally, Türk S et al. (2014) [106, 107] presented studies based on network migration optimization using meta-heuristics and optimization of network migration cost using memetic algorithm [108]. His study provides solutions to network service providers about migration of network node at suitable time in terms of CapEX, OpEX, and ImpEX optimization. Shayani et al.(2010) [109, 110] presented a service migration cost model using queuing theory and hill climbing optimization for reduced operation cost and optimization of human resource allocation to migrate traditional Telcos networks into next generation networks. A study from the perspective of techno-economic analysis to reduce CapEX/OpEX via SDN and NFV in mobile network operation has been presented by Naudts et al. (2016) [111]. Lähteenmäki et al. (2016) [112] discussed an activity based cost modeling for network service provider cloud platform, in which cost is considered with respect to activities, which generally does not address administrative cost. This is not also the case presented from the perspectives of network migration and it lacks incremental costs during incremental deployment of network devices in the long run.

Most of the previous studies related to cost optimization were focused either on single technology migration or on different telecommunication networks. Das et al. (2015) [103] presented the multi-technology migration using agent based modeling technique, in which joint migration is more benefitted than single technology migration in terms of cost optimization. Hence, sufficient researches can be found with different migration approaches presented for IPv6 and SDN migration separately. But there is limited or no research related to joint network migration including SDN and IPv6. To the best of author's knowledge, present work is the first attempt to develop joint migration of SDN and IPv6 network including migration cost, customer demand, and organization strength in terms of budget and skilled human resources.

Present research has contributed in optimum migration planning of legacy network into SoDIP6 network, which are summarized here. Common cost parameters of both networking paradigms (SDN and IPv6) for migration cost modeling and optimization are identified [14]. Then, established mathematical model for migration cost optimization and developed greedy algorithm for its implementation analysis. It is verified that the joint migration to SoDIP6 network optimizes the total migration cost for service providers [8, 6]. Considering the organizational CapEX and OpEX optimization, an intelligent approach to network device replacement planning is presented for the incremental deployment of SoDIP6 networks [113]. However, SDN implementation in datacenter network is popularly implemented, its implementation at ISP/Telcos networks is not yet realized, because of being several critical challenges discussed before. Open network operating system (ONOS) is a dedicated distributed network operating system designed as an SDN controller to transform carrier grade legacy ISP networks into SDN. SDN-IP is an application run on the top of ONOS to communicate between legacy network and SDN by creating hybrid network during network migration. Multi-domain SoDIP6 networks environment is created and integrated with legacy IPv4 networks using ONOS/SDN-IP, and also proposed the best location for controller placement during network migration [71]. Additionally, current ICT deployment scenario of Nepal is studied including benefits of green networking with respect to SDN and IPv6 as an enabler of energy efficient next generation networking system recommended to be deployed for ICT infrastructure expansion of developing nations like Nepal to develop sustainable future societies [4, 11].

3.4 Joint Network Migration Planning

The sufficiency of IP addresses provisioned by IPv6 allows for everything smart and communicable with the evolvement of IoT and WSN. Similarly, the programmability feature of SDN helps to introduce smartness on every devices. Figure 3.2 shows the amalgamation of networking paradigms and their operations with services into layers. IPv6 and SDN are interrelated, because IPv6 deals with routing and addressing in the IP layer, while SDN deals with the controlling of networking operations as a networking management layer. Those technologies, which are recognized as network operation layer are operated by service providers. The customer services to be provided by ISPs and Telcos are the service layer activities.

The network operators World-wide are migrating their network into IPv6 operable networks. Meanwhile, the emergence of SDN has created additional challenges for network operators to migrate their networks into SDN environment. Being underlying network layer paradigms, some common issues can be clearly seen between IPv6

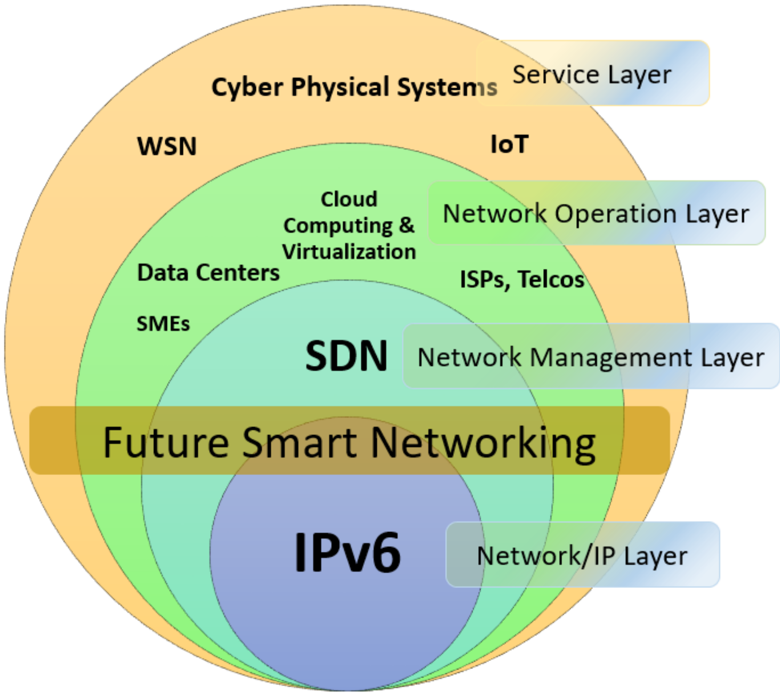


Figure 3.2: Layered view of SoDIP6 network

and the SDN. These are security, quality of service, migration cost, skilled HRs, protocols and application supports, suitable planning and strategies for migration, service continuity and many more [9]. With all those concerns, total cost of investment become the major issue for every service provider, because the cost involved hardware/software upgrade, device replacement, technical HR development, and even to develop the security appliances with service continuity as a part of CapEX and OpEX. In this regard, considering migration planning of two paradigms as a joint migration would help to reduce the organizational costs.

Most of the approaches for the transition to IPv6 and SDN discussed in Chapter 2 are being adapted by different organizations World-wide [67, 68, 114]. The implementations of transition mechanisms depend on the current status of ISP and its interconnection with other ISPs. In the case of new network deployment, L2G approach of SDN migration is preferable, but the existing network migration is only viable either by upgrading the running network devices or replacing it with new devices that are SoDIP6 capable. After investigating through different transition approaches for SDN and IPv6 both, it is considered that dual-stack IPv6 and hybrid SDN [67] are the best choice in the joint migration modeling for smooth transition to SoDIP6 network. Before having a joint network migration planning, it is necessary to understand the basic structure of World-wide ISP network interconnection architecture.

ISP networks consist of the World-wide interconnection of networks of networks by means of which an access to internet is provided to home users and enterprises. Figure 3.3 depicted the scenario of ISP networks interconnection structure. World-wide ISP networks are categorized based on the infrastructure connectivity and the provision of services to clients [115, 116] into Tier-1, Tier-2, and Tier-3 ISPs. Basically tired ISP architecture is managed in a hierarchy in which Tier-1 ISPs are the root source of internet that they own backbone network infrastructure and are able to exchange traffic among the continents and countries, while its major clients are the Tier-2 ISPs. Tier-2 ISPs are generally the regional ISPs that they provide transit services to Tier-3 ISPs. Tier-3 ISPs, being clients of Tier-2 ISPs, are also recognized as national or local level ISPs. They are the last mile internet service providers that they have their home internet users and enterprises as clients. To avoid overloaded traffic flow in the hierarchies, ISPs in the same label can have private, public, transit or donut peering with other ISPs [57], and might have settlement-free interconnection agreement.

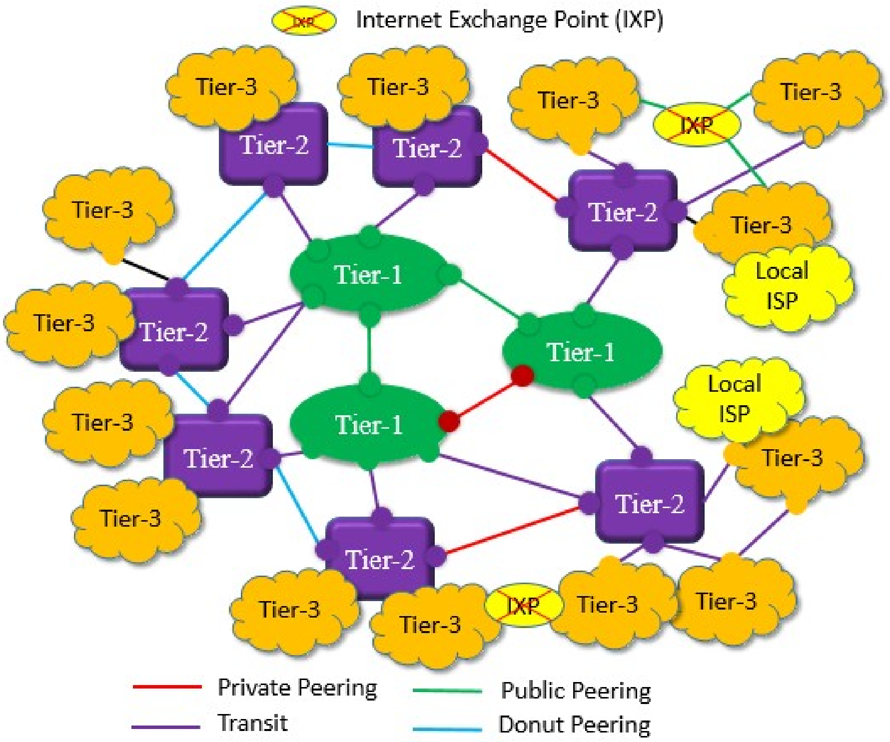


Figure 3.3: World-wide ISP network interconnection architecture

Multiple ISPs can have peering through Internet eXchange Point (IXP) [116, 117, 118]. For example, London Internet Exchange (`http://www.linx.net`, accessed on 26 December 2019) and NetIX (`http://www.netix.net`, accessed on 26 December 2019) are the largest Internet exchange in the World, Toronto Internet exchange (http://www.torix.ca, accessed on 26 December 2019) is the largest Internet exchange in North America. The pre-requisite for every service provider is to maintain the Up to date information of network devices to gain detailed knowledge of existing network devices so that proper migration planning can be achieved. The inventory of hardware and software details help to identify whether any network device can be upgraded or should be replaced with new one to make it capable with newer technologies. Device status identification, budget estimation, plan for upgrade or replacement, and implementation of the plan are the major steps for network migration. It requires service providers to maintain the inventory of network device and infrastructure to monitor the status using suitable management tools [119, 120, 121]. The overall steps for network migration planning are shown in Figure 3.4.

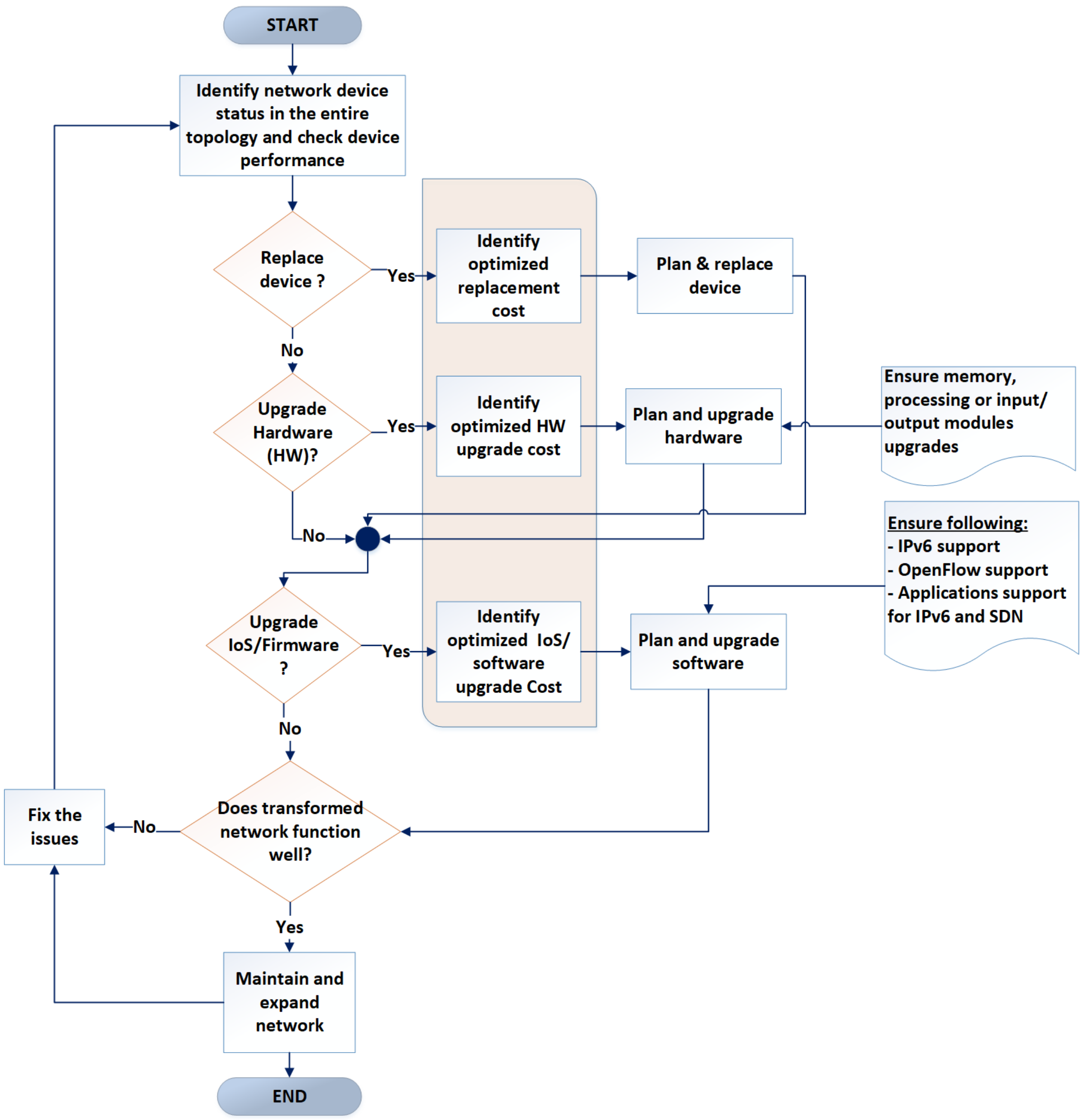


Figure 3.4: SoDIP6 network migration steps for service providers

Service providers first identify the device status, whether the running devices are to be replaced or its firmware/hardware upgrade is sufficient for migration. On the status identification, total number of devices to be replaced or upgraded will be identified, then assessment of human resources with total cost of network migration will be performed. Hardware upgrades generally means increase of memory and processing capacity of the device. In software/firmware upgrade, it is required to ensure the supports of IPv6 routing and forwarding capability, OpenFlow communication, security, and quality of service policy as well as applications and protocol supports by the upgraded device. Migration implementation phase continuously tests and evaluates the functional operation of network, when if successful migration is completed. The same steps from the beginning will be repeated with the network expansion and next phase network migration to other newer technologies.

3.5 Network Device Status Identification

Benchmarking of existing networking devices is required to identify their status before focusing onto joint migration modeling, whether they are upgradable or needs replacement to make them operable with SDN and IPv6 network. So that internet and telecom service providers can have proper planning of their network migration to optimize CapEX and OpEX for their future sustainability. In this study, an adaptive neuro fuzzy inference system (ANFIS) is implemented. ANFIS is a well-known intelligent approach for network device status identification to classify whether a network device is upgradable or requires replacement. Similarly, a knowledge base (KB) system is established to store the information of device IOS/firmware version, its SDN and IPv6 support with end-of-life (EoL) and end-of-support (EoS). Device performance parameters, for example, average CPU usage, throughput, and memory capacity are being extracted in real time using SNMP and mapped with information obtained from KB for input dataset to ANFIS.

Device upgrade is suitable than the replacement to minimize the higher CapEX and OpEX. Because upgrade cost is generally lower than the replacement cost, while considering networking infrastructure migration. However, all networking devices could not be upgradable to newer technologies. Present research is focused to implement intelligent approach to efficient transformation of existing internet infrastructure into SDN enabled IPv6 network with optimum cost and efforts so that future sustainability of service providers against the higher cost of investment can be ensured. Considering the network migration, the major question is – *"are the existing networking infrastructure operating with older technologies migrateable to operate with* *newer technologies?"* Unfortunately, SDN and IPv6 networking paradigms are not backward compatible. Hence, the existing networking devices are either to be replaced or their hardware/software should be upgraded during their active operation to provision with latest technologies and services.

Service providers could have hundreds of thousands of switches/routers running in their network that won't be able to migrate those networking devices at once. Additionally, the major concern is that each service provider has to confirm with their network devices whether they are upgradable or should be replaced to make them operable with newer technologies and applications. Small and medium enterprises (SMEs), and service providers of developing countries run their network devices even after the device EoS due to higher cost of investment. Considering the network migration steps presented at Figure 3.4, an intelligent approach to identify the status of network devices is to be developed before taking the decision for migration to have proper planning and management of budget constraints and human resources required for the migration.

Service providers have to be confident with respect to the following five questions regarding their network devices in the process of migration planning.

1. Is the device inter-network operating system (IOS)/firmware upgradable to enable operation with IPv6 and the SDN?

2. Is the existing memory and processing capacity sufficient to operate with newer technologies, if they are upgraded or does it has extra slot to increase memory/processing capacity?

3. What is the EoL announcement date of the device? How many years does it has to operate?

4. What is the EoS date of the device? Does vendor ready to provide support for next couple of years?

5. What is the device latency/throughput? is it sufficient to operate with upgraded newer technologies and applications?

Set of input parameters can be considered for device status identification from the above questions. Major parameters considered in this study are as follows.

(a) Upgrade on IPv6/OpenFlow enabled IOS/Firmware – binary value (True/False),

(b) Storage capacity – integer (MB),
(c) CPU utilization - float (percentage)
(d) Device throughput – integer (Mbps),
(e) EoL – date (years), and
(f) EoS – date (Years).

To the best of author's knowledge, many researchers have suggested for the phase-wise or incremental deployment of SDN and IPv6 networks for smooth transitioning, but there is a lack of any research that addresses the question raised above. To answer the above question, it is needed to find out the suitable approach that first, determines the device status and recommend the decision maker to proceed for network migration planning.

Most of the parameter values are extracted from technical specification that are to be maintained in the KB system, while some parameters like average of maximum CPU utilization, memory utilization, and throughput are extracted using simple network management protocol (SNMP) agent in real time. Hence, using the KB, set of input data are prepared and those parameter values are input to ANFIS to classify the device for migration planning.

3.5.1 Adaptive neuro fuzzy inference system (ANFIS)

ANFIS is the well-known intelligent approach applicable to solve the problems particularly suitable for classification, estimation, prediction, and forecasting. For network device status identification, whether it is upgradable or replaceable, ANFIS is applied. ANFIS is the combination of artificial neural network and fuzzy inference system. Takagi-Sugeno fuzzy rules are followed and ANFIS is modeled based on its suitability for mathematical analysis and better computational efficiency [122]. The identification of set of input parameters for ANFIS particularly of a network device is a complex problem, as it needs to deal with data of both qualitative and quantitative types. After running series of steps in preprocessing to generate the dataset, input dataset for dependency fuzzy system (DFS) and ANFIS are generated for training, testing, and validation. In ANFIS, system imprecision and uncertainties are accounted by fuzzy logic, while the neural network gives a sense of adaptability. ANFIS first, builds a fuzzy rule base and then tune the parameters of the membership functions from the given trained dataset [123].

ANFIS is principally structured as five layered system. The five layers consist of input, if part, rules and normalization, then part, and output. It might have different nodes in each layer connected with the nodes from the previous level, where the output of previous level is input signals of the consequent next layer. For example, for the Takagi-Sugino rules type [124], the typical common rules with two input and one output variables in the model as depicted in Figure 3.5 can be determined as follows.

if x is A_i and y is B_i, then $f_i = p_i x + q_i y + r_i$ $\qquad rule - i$

Hence, the rules shall be:

if x is A_1 and y is B_1, then $f_1 = p_1 x + q_1 y + r_1$ $\qquad rule - 1$

if x is A_2 and y is B_2, then $f_2 = p_2 x + q_2 y + r_2$ $\qquad rule - 2$

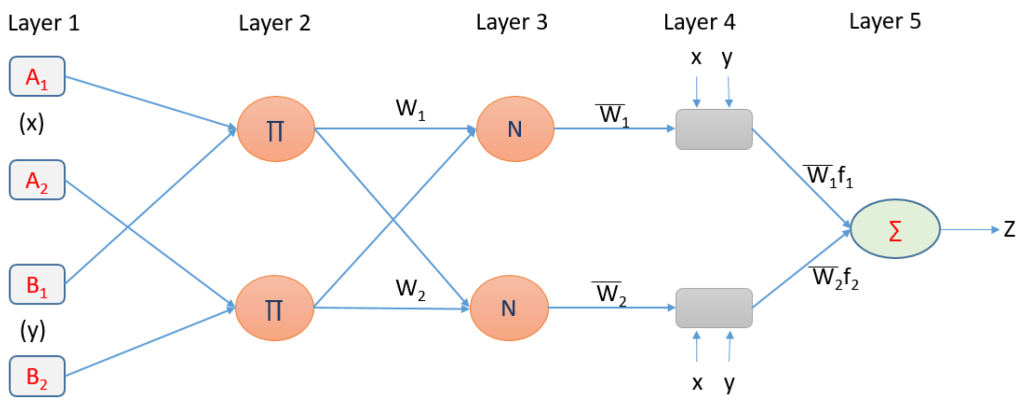


Figure 3.5: ANFIS architecture with two inputs (x, y) and one output (z)

First layer defines the membership function for each i^{th} node. The fuzzification of the input variables are performed with the output shown in equation (3.1).

$$O_i^1 = \mu_{A_{i(x)}} \tag{3.1}$$

'O_i^1' is the output of the i^{th} node and is the membership grade of a fuzzy set (A_1, B_1), where (A_1, B_1) represents the linguistic level associated with node 'i'. The layer 2 nodes are the fixed nodes, which represent the firing strength of the rule and consists of the product (AND) of antecedent part of the fuzzy rules (incoming signals) measures by equation (3.2).

$$O_i^2 = w_i = \mu_{A_{i(x)}} \cdot \mu_{B_{i(y)}}, i \in [1, 2] \tag{3.2}$$

Similarly, the output of the third hidden layer normalizes the membership function and gives the normalized firing strengths. The i_{th} node calculates the i_{th} rule's firing strength to the sum of all rules firing strengths is given by equation (3.3).

$$O_i^3 = \overline{w_i} = \frac{w_i}{w_1 + w_2}, i \in [1,2] \tag{3.3}$$

Layer 4 nodes are the adaptive nodes that provide the de-fuzzification, in which the consequent parameters of the rule are determined with a node function having p_i, q_i, and r_i as the parameter set. Hence, equation (3.4) gives the output of layer 4.

$$O_i^4 = \overline{w_i} f_i = \overline{w_i}(p_i x + q_i y + r_i), i \in [1,2] \tag{3.4}$$

The layer 5 provides the single node output as shown in equation (3.5). It computes the overall output as the summation of all incoming signals.

$$O_i^5 = \sum_i \overline{w}_i f_i = \frac{\sum_i w_i f_i}{\sum_i w_i} \tag{3.5}$$

In ANFIS, premise parameters (to learn the parameters related to membership functions) are determined using back-propagation learning algorithm, while least square estimator is used to determine the consequent parameters. The premise and consequent parameters are determined in the training phase using training dataset, while an error threshold is defined between actual and desired output. ANFIS has two steps procedure to learn the parameters known as forward pass and backward pass. In the forward pass, the input patterns are propagated from input to output to estimate the optimal consequent parameters by an iterative least mean square procedure, while premise parameters are set to be fixed in the concurrent cycle of the training. In the backward pass, the error signals propagate back to adjust the premise parameters, on this epoch by keeping consequent parameters fixed. The output converges towards error threshold defined by propagating back the error and update premise parameters using gradient descent method.

A KB system is established from the device specification and other external sources, while the real time performance parameters like processing, memory, and throughput were collected using SNMP agent. Hence, five input variables and one output binary variable that provides the device status in the ANFIS structure are defined.

3.5.2 Related work in ANFIS implementation

A software effort estimation model was presented by Huang et al. (2009) [125]. His approach combines COCOMO with ANFIS framework. Chabaa et al. (2009) [126] applied ANFIS in forecasting internet traffic time series with set of input and output data provided using statistical indicators and resulted a best fit real network traffic over different time-frames.

An approach for diabetes diagnosis and cancer prediction using ANFIS to achieve better accuracy and effectiveness is presented by Kalaiselvi and Nasira (2014) [127]. Suresh et al. (1994) [128] presented a model describing a fuzzy-set maintenance policy for multi-state equipment. Author implemented the extended model in the equipment maintenance planning. This study was mostly based on the equipment status and its operational life. This approach is useful in equipment replacement planning based on their average life of operation and other performance indicators. To optimize resourc usage considering financial resources, patient safety, and QoS in the medical sector, Rajasekaran et al. (2005) [129] developed a program to classify the equipment needing replacement based on priority assigned for replacement decision.

ANFIS is implemented to classify the medical equipment for replacement planning by Mummolo et al. (2007) [130]. Author first applied scoring system of each input parameter values, then the system provides the decision for replacement of medical equipment based on their downtime ratio, maintenance ratio, age ratio, and redundancy ratio. These kinds of input parameters are also applicable in ISP network device to find its status in the regular maintenance plan. But, for this case, migration of network devices in terms of support for SDN and IPv6 operation is considered.

To the best of author's knowledge, there is limited or no any research works regarding the implementation of ANFIS in SDN and IPv6 networks migration. However, ANFIS has many multidimensional implementations including several applications. ANFIS is also popularly used in communication networks, at which it is mostly used in estimation, prediction, optimization, and forecasting [131, 132, 133, 134, 135, 136, 137, 138, 139, 140, 141, 142, 143, 144]. But none of these studies are particularly related to SDN and IPv6 network migration.

The malicious node detection system in MANET using ANFIS was implemented by Kumaravel et al. (2019) [145]. Author used throughput, average packet loss ratio, energy consumption, and detection ratio as the major parameters used for the input to ANFIS for classification and performance evaluation of the proposed model.

ANFIS is also popularly used to address the classification problems [145, 146, 147]. Proposed research problem was related to the detection of the network device for its upgrade or replacement via ANFIS classification in the domain of new network deployment.

There are limited literature found for the incremental deployment of SDN and IPv6 networks with an overall migration plan for ISPs and Telcos. For example, studies like game theoretic approach on IPv6 network migration [85], incremental adoption to IPv6 networks [22], evolutionary process on SoDIP6 network migration [14], agent based modeling for joint migration to IEEE-PCE and SDN [19], SoDIP6 network migration based on customer priority and optimal path [8], incremental deployment of hybrid SDN in service provider networks [148], and optimal sequence of router replacement using greedy algorithm for SDN migration [149] are those studies, which provide insights on individual and joint network migration. But there is lacking studies particularly to deal with approaches that "*how do service providers decide whether a device is to be replaced or upgraded before planning the migration implementations?*". Hence, ANFIS is implemented to address this issue in this study.

3.5.3 Problem formulations

Every ISP maintains a list of routing devices of their networks with specification details under its network inventory management system. Based on the preliminary survey taken with Nepalese ISPs, the problem is that few of the running legacy routing devices do not support IPv6 addressing and all of the running devices do not support OpenFlow protocol [150]. Objectively, all those routing devices are to be either replaced or upgraded to make it operable with IPv6 addressing and OpenFlow protocol. Regular vendor notifications, available new technologies, and applications as well as other domain specific knowledge are major sources to maintain parameter information of network devices in the KB. With the specified IOS/firmware version, KB maintains the information what exactly the current version supports, like *does it support IPv6 and OpenFlow including information regarding the extra memory slot available, device EoL, and EoS?*

The input parameters and their descriptions are provided in Table 3.1 for the proposed model. The network device can be upgraded, only if it can supports new IOS/firmware, which is SoDIP6 capable. Hence, Boolean variable 'IO' provides the True and False status as an output from dependency fuzzy system (DFS). The decision on prerequisite parameters like IOS/firmware upgrade, extra memory slot available, and new IOS support on SoDIP6 network is provided by DFS. Hence, input to ANFIS is dependent on DFS first. Every network device has active life of operation, beyond that it has to replace. Similarly, vendor support is provided in the specified period as EoS for the designated device. IP routers generally have an operational lifespan of 4-5 years [151], but the currently running technology shall be outdated and demand of efficient services within the lifespan led to the immediate upgrade or replacement of network devices. Generally the lifespan depends on the vendor's quality of production as to be specified by the vendor notifications [152, 153].

Table 3.1: Description of input variables

Variable	Type	Descriptions
IO	Boolean	IPv6 and SDN/OpenFLow supports.
L	Integer	Remaining lifespan in years.
S	Integer	Remaining support period in years.
m	Integer	Average unused memory of device during operation.
M_E	Integer	Extra memory size (MB)
M	Integer	Total memory to be after upgrades (=$m + M_E$).
T	Integer	Average device throughput (Mbps).
C	Float	CPU utilization (%).
E	Integer	Expandable memory size (MB).

Vendors periodically announce the EoS date for their supplied equipment [154]. Hence, a KB maintains the EoL, EoS, and the memory capacity with upgraded version support by the older equipment. The available knowledge is used to decide for the further possibilities on the upgradability identification of the device. Addition of memory or processing capacity without the support for IOS/firmware upgrade is generally meaningless, because the major objective is to make the device operable with IPv6 and the SDN. Hence, the supporting status of IPv6 and SDN is fetched into DFS first, which decides the upgradability of device IOS/firmware and hardware. If the system software does not support new version capable of SoDIP6 network, then a zero value of expandable memory size is set as an output of DFS. This led to the replacement decision by ANFIS. The fuzzy rules (R3.1 – R3.4) for DFS are defined accordingly as follows.

If *device supports system upgrade*, then New-Version = Upgraded-Version (R3.1)

If *Upgraded-Version supports IPv6 and SDN*, then IO = 1 (R3.2)

If *Upgraded-Version do not support IPv6 and SDN*, then IO = 0 (R3.3)

If *device has extra memory slot*, then expandable memory (E) = M_E (R3.4)

Based on the output from DFS, additional data are to be obtained from operational network in real time via the SNMP agent and combined into the input dataset for input to ANFIS. To generate the dataset, remaining lifespan and support period in years and the total unused memory including expandable memory are calculated as follows.

L = (Current Date - EoL Date),
S = (EoS Date – Current Date),
M = (m + E) $\cdot IO$

'm' provides the average unused memory space available in the device during operation. EoL in years is considered based on EoL announcement date. Hardware vendors like CISCO announces EoL notice six months before the effective date of EoL implementation. Only vendor supports are provided after EoL announcement date for five years till EoS date. The device needs to be replaced after EoS.

IP routers have flash memory to run IOS/firmware and DRAM memory for other processing like packet buffering, maintain routing table, security, and QoS implementations. For the faster operation, it requires bigger size IPv6 packet forwarding and maintaining of larger size flow table after upgrades most importantly require higher size DRAM. In this study, only expansion of DRAM as one parameter was considered for device migration. When the device does not support IOS/firmware upgrade or the upgraded version does not support IPv6 and SDN, then the only solution is to replace the device. The system is dependent on the software upgrade to proceed further for identification. Hence, a DFS is implemented before processing to ANFIS. The DFS module decides first the upgradability of system. But the complete upgrade of the system does not only depend on the software upgrade. The overall processing capacity, sufficiency of memory, and throughput of the device are also considered for the final prediction of the device upgradeability. SNMP agent collects the real time data of memory, throughput, and processing capacity. With the device mapping, the relevant data of IO, L, S, and M are determined by DFS getting information from KB. Similarly, other parameters like average CPU usage, memory unused, and throughput are to be obtained from the real network operation.

For the ease of model operation and minimize error margin, input parameters are mapped to scoring system depicted in Table 3.2. As a part of data refinement, based on the sensitivity, EoS is set a bit higher weightage, while most of the CISCO IP routers have expandable memory slot and hence, memory is given with lower weightage value. Lower the overall score value has higher significance to replace the device, while higher the score value is supportive to upgrade. Based on the maximum and minimum value of trained dataset, the range of value is defined in this scoring system.

Table 3.2: Scoring and weight provisioning for data preprocessing

EoL (L) weight=0.2		EoS (S) weight=0.25		Memory (M) weight=0.15		Throughput (T) weight=0.2		CPU usage (C) weight=0.2	
Range	Score	Range	Score	Range	Score	Range	Score	Range	Score
L <1	4	S <1	-16	M <16	-16	T <100	-16	C <40	4
1 ≤ L≤2	3	1≤S≤2	2	16≤M≤48	2	100≤T≤1k	2	40≤C≤60	3
2 <L≤4	2	2 <S≤5	3	48 <M≤128	3	1k≤T≤5k	3	60 <C≤80	2
L >4	-16	S >5	4	M >128	4	T >5k	4	C >80	-16

The device specification details are captured including IOS release versions, IOS upgrade history of the device, and SoDIP6 support with the parameters defined in Table 3.2. Average minimum memory unused, average maximum throughput, and average maximum CPU usage ratio are captured from the real time operational network via simulation. Individual input variables related to upgrade or replacement are interpreted as shown in Figure 3.6. For each input parameter, the score greater than '2' is supposed to be suitable for upgrades. The device operation lifespan shown in Figure 3.6a is five years, while Figures 3.6b,c,d have their usual interpretations. Figure 3.6e provides the score mapping range based on the input data.

If 'δ' is the tuple belonging to any or all input variables and 'Z' is the output variable, the modeled system is mathematically interpreted by equation (3.6).

$$\forall\delta \in [L, S, M, T, C], z = ANFIS(\delta) = \begin{cases} \leq 0 \text{ (Replace)}, \ \delta = -16 \\ > 2 \text{ (Upgrade)}, \ \delta \in [2, 3, 4] \\ \leq 2 \text{ (Replace)}, \ \delta \in [2, 3, 4] \end{cases} \tag{3.6}$$

Equation (3.6) provides the result based on weight value assigned on each input variable with the output (Z) interpreted by equation (3.7).

$$Z = W_1 \cdot L + W_2 \cdot S + W_3 \cdot M + W_4 \cdot T + W_5 \cdot C \tag{3.7}$$

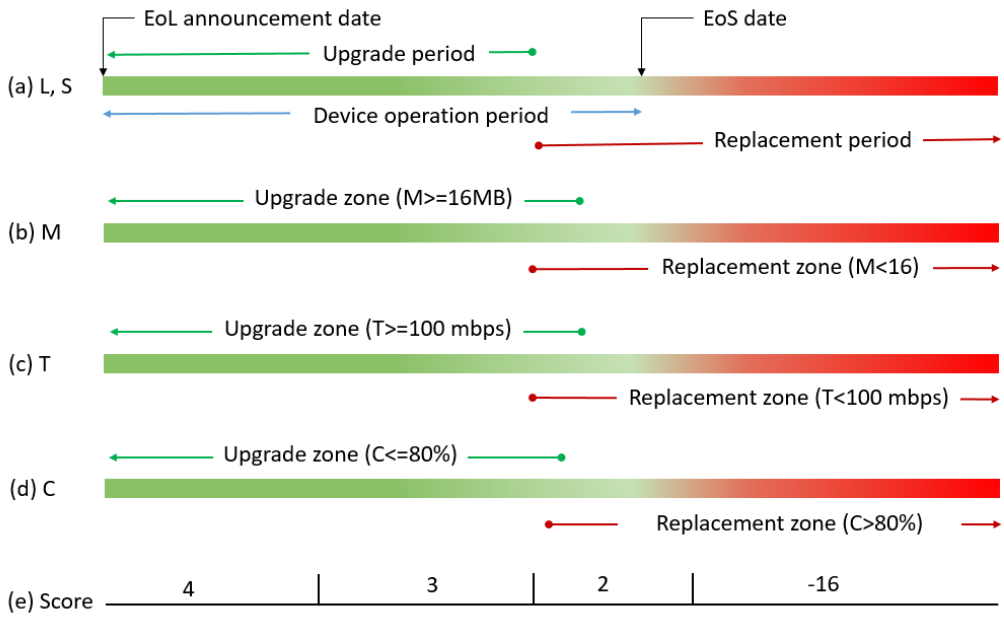


Figure 3.6: Individual parameter value mapping to score for upgrade or replacement

In the worst case, if all input variables have minimum value of -16 or maximum value of 4, then equation (3.7) provides the output ranging from -16 to 4. But, the real data has output classification field of either 0 or 1 to map the result as either replace (0) or upgrade (1). Hence, ANFIS output is interpreted by equation (3.8).

$$\forall \delta \in [L,S,M,T,C], Z = ANFIS(\delta) = \begin{cases} 0(Replace) \\ 1(Upgrade) \end{cases} \quad \text{for } \delta \in [-16,2,3,4] \tag{3.8}$$

The output of ANFIS is a fuzzy value, in which the error value can't be avoided. Hence, the prediction is made based on the threshold defined in equation (3.9).

$$\forall \delta \in [L,S,M,T,C], Z = ANFIS(\delta) = \begin{cases} \leq 0.5(Replace) \\ > 0.5(Upgrade) \end{cases} \quad \text{for } \delta \in [-16,2,3,4] \tag{3.9}$$

Algorithm 3.1 provides the steps for DFS and ANFIS implementation. Function 'DFS ()' returns L, S, and M_E using KB, while value of T, C, and m are obtained from SNMP agent. The dataset for a router is input to ANFIS for status identification.

Algorithm 3.1: ANFIS implementation for device status identification

```
Function DFS(v):
    Input: CD ← today(), E ← 0, [EoS, EoL, M_E, UV] ← KB(v)
    // CD: Current Date, UV: upgraded IOS, get details of router 'v' from KB.
    if Router supports IOS upgrades then
        NV ← UV                                   // NV: New IOS supports SoDIP6.
    else
        NV ← KB(new_IOS)                          // get new IOS information from the KB.
    if UV supports SoDIP6 then
        IO ← 1
    else
        IO ← 0
    if Device has extra memory slot then
        E ← M_E
    L ← (CD − EoL)
    S ← (EoS − CD)
    return L, S, E, IO
Function Main:
    Input: 𝔾 ← (V, E)          // vertices 'V' and edges 'E' to network graph 𝔾.
    for v in 𝔾 do
        [L, S, M_E, IO] ← DFS(v)                  // function call.
        T, C, m ← Snmp(v)                         // SNMP agent of node v.
        M = (m + M_E) · IO                        // calculate total available memory.
        status(v) ← Anfis(L, S, M, T, C)          // API to call ANFIS from MATLAB.
    plot(𝔾)                                       // Visualize the network graph 𝔾.
```

3.6 Joint Network Migration Modeling and Cost Optimization

For the migration modeling, it is assumed that Tier-3 ISPs including local ISPs are interconnected via direct interconnection or through IXP. An economic model of a Tier-3 ISP is established to identify cost metrics for migration cost modeling. Figure 3.7 presents the economic model in terms of income and expenditure for an ISP.

The price of Internet bandwidth provided to end customers as well as dedicated lease services provided to enterprises are the major source of income for an ISP. Similarly, considering Figure 3.3, some ISPs can act as a transit service providers for others based on the interconnection arrangement and agreement made between them. Hence, cost of transit services provided can also be considered as an income, while the same ISP can be the transit service user of another Teir-2 or Tier-3 ISPs. Hence, the cost of transit service use is also an expenditure. The charging models in

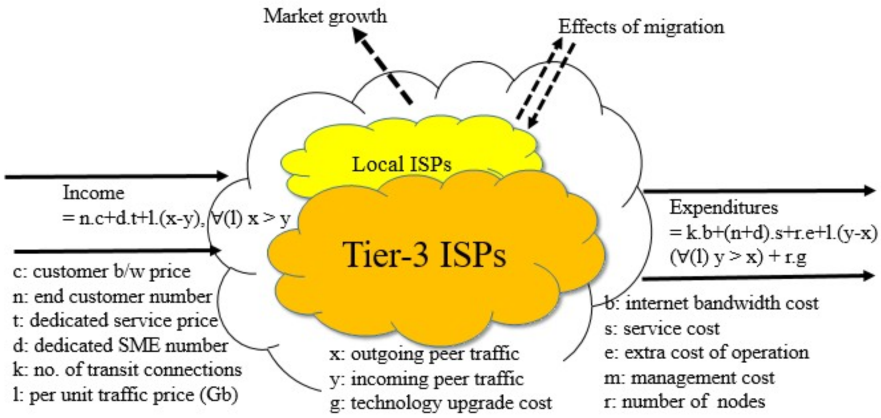


Figure 3.7: Economic model of Tier-3 ISPs

IP based interconnection for the digital packet based communication networks are basically of three types, these are i) per port, ii) per packet, and iii) mixed type. Lower level ISPs in hierarchies like Tier-3 ISPs pay to transit service providers (Tier-2 ISPs) on a per port basis, which amounts by download speed or bandwidth charge. The inter-connected ISPs in the same Tier will charge each other according to the amount of traffic exchanged at the point of interconnection on a settlement basis [155]. This means backbone operators might have zero charging model if the volume of traffic exchanged is same. Otherwise, generally a network receiving a packet should pay under the principle of receiving party network pay (RPNP). RPNP is more applicable in voice communication. However, RPNP applies only to exceeded receiving traffic in packet based communication. In the proposed economic model, for the implementation of evolutionary dynamics in migration, following are the basic considerations.

- The clients of Teir-3 ISPs are mostly the end-users and the enterprises, in which the clients are charged on the basis of bandwidth supplied. An ISP charges other interconnected ISPs (peers) in per port basis, only when the traffic volume outgoing exceeds the incoming in the interconnection point. Similarly, some customers are charged based on dedicated services (e.g. MPLS, VPN etc.) provided.

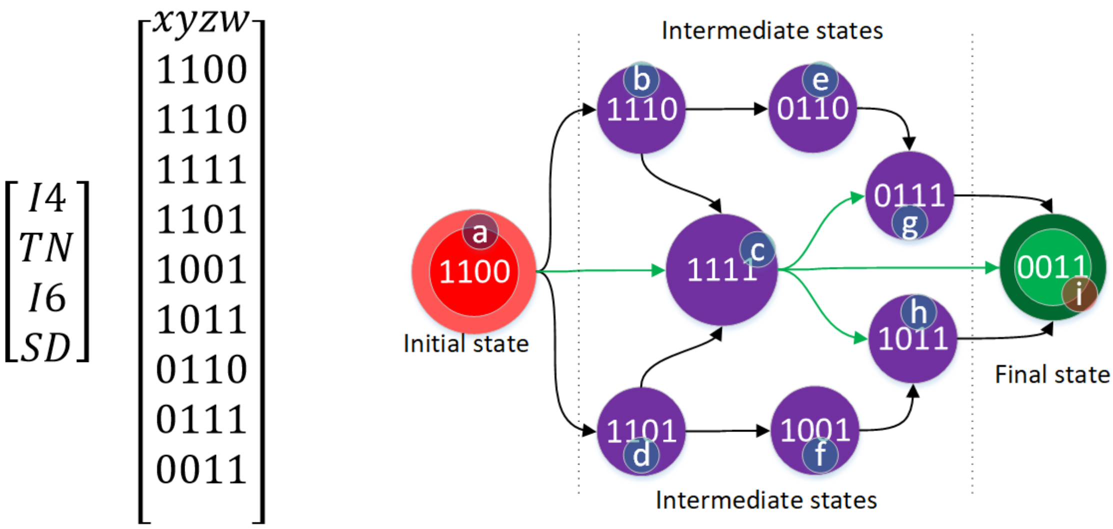
- SoDIP6 networks are dual-stack IPv4 and IPv6 capable under SDN framework, where legacy feature is available for recovery purpose. Hence, SoDIP6 network is a quad-stack (IPv4, IPv6, Legacy, and SDN) capable. Tier-1 and Tier-2 ISPs are SoDIP6 capable.

- Tier-3 ISPs pay to the transit service providers (basically to Tier-2 ISPs) based on per port basis as per bandwidth agreement. Extra cost of operation is considered for ISPs that maintain and operate SoDIP6 network, while migration cost is the one time cost to be invested by ISPs during their network migration.

- In case of Legacy IPv4 only ISPs, the extra cost of operation 'e' holds the cost due to conversion of incoming IPv6 traffic to IPv4 and vice-versa. The border router in the IPv4 edge performs the translation of incoming IPv6 packets. Similarly, for SoDIP6 network, the extra cost holds the cost of dual-stack operation.
- For the joint approach of SDN and IPv6 network migration, planning of service provider's IP routing network is considered, where costs of network migration is more sensitive to the fairly sustained operators.

The possible transition states represented in a matrix and the state transition diagram to migrate legacy IPv4 network as starting state 'a' to the the targeted network state 'i' is shown in Figure 3.8b. Legacy IPv4 network is represented by two variables viz. traditional network as 'TN' and IPv4 as 'I4'. Similarly, targeted SoDIP6 network is represented by two variables viz. IPv6 as "I6" and SDN as "SD". The four variables are mapped in the matrix by binary variables: x, y, z, and w, in which, if the network is legacy IP4, the binary variables x and y are set to '1', while the binary variables z and w are set to '0'.

During the transition, for example, at state 'c', the legacy network is migrated such that it is able to operate with IPv4 and IPv6 packet processing and forwarding as well as support SDN in addition with legacy routing. The legacy routing feature is enabled on the data plane device during migration for the recovery purpose [61]. The IPv6 and SDN features are supposed to be activated from the command line configuration. Figure 3.8 presents only the valid states for migration. The states are: a→[1100], b→[1110], c→[1111], d→[1101], e→[0110], f→[1001], g→[0111], h→[1011], and i→[0011], which are binary representations to switch on or off the technology as per requirement. The path like [a,c,i] is the shortest transition path, in which state 'c' provides the quad-stack SoDIP6 network and switching off the I4 and TN leads directly to final state 'i', which is SDN and IPv6 only capable. As compared with other transition paths e.g. [a,b,e,g,i], [a,d,g,h,i], [a,c,i], [a,c,g,i], and [a,c,h,i] are the effective transition paths. However, Migration is a gradual process; the question of "*which path to follow?*" depends on the readiness status of other interconnected ISPs.



(a) (b)

Figure 3.8: Transition planning, (a) Network migration state matrix, and (b) Network migration state diagram

Every ISP should plan for the migration in such a way that ultimately it has to transform its legacy network i.e. form state ‘a’ to final state ‘i’. To the best of author’s knowledge, it is found that many researches regarding SDN migration have been performed from the perspectives of budget constraints and traffic engineering [104, 156, 157]. In this approach, the cost of transition also depends upon the choice of path in the transition diagram. Paths [a,c,i], [a,c,g,i], and [a,c,h,i] indicate the unified migration. At node ‘c’, the network reached the quad-stack SoDIP6. The other paths [a,b,e,g,i], [a,b,c,i], [a,b,c,h,i], [a,b,c,g,i], [a,d,c,i], [a,d,cg,i], [a,d,c,h,i], and [a,d,f,h,i] show the individual migration sequence to IPv6 and the SDN. The choice of path defines the migration sequence. For example, an ISP chooses path [a,b,e,g,i], then the sequence of migrations would be: (i) enable IPv6 (I6), network becomes dual-stack IPv6 at state ‘b’, (ii) turn off IPv4 stack (I4) at state ’e’, (iii) enable SDN/OpenFlow (SD) in the legacy IPv6 network at state ‘g’, and (iv) turn off legacy network (TN) management at the targeted state ‘i’. At sate ‘i’, the network becomes fully SoDIP6 capable. In the next section, an algorithm with mathematical model will be developed for the migration cost optimization of individual and joint migration considering the transition paths stated.

3.6.1 Migration cost modeling and optimization

Some research studies [102, 103, 158] show that joint transition to correlated technologies is more beneficial than individual migration. Hence, it is expected that joint migration to SDN and IPv6 network is more cost effective than the individual migration. To justify the expectation, two variables viz. shared cost coefficient (μ) and the strength of correlation (ϵ) between SDN and IPv6 are introduced. The shared cost coefficient determines the optimum cost of joint migration. For example, hiring skilled HRs to operate and manage newer technologies incurs higher cost. If a technical HR is trained for SDN operation, then the same HR can be assigned to handle IPv6 network, if resources for both technologies are shared during training. This means, instead of running separate training programs for HR development to handle SDN and IPv6 network, a combined training can be conducted, because the HR of network operation team, as a whole, looks after all the operational and managerial issues of addressing, routing, control, and troubleshooting. OpenFlow version 1.3 and beyond supports IPv6 [159]. This helps to have joint migration to SoDIP6 networks. Under the different categories of cost metrics defined in different literature [59, 58, 160], the cost metrics associated to technology migration are considered, while most of these were obtained from interviews with technical head of enterprises and ISPs. The cost metrics and their symbolic notations are defined in Table 3.3.

Table 3.3: Cost metrics for individual and joint migration to SDN and IPv6.

Cost metrics	**IPv6 migration**	**SDN migration**	**Joint migration (SoDIP6)**
Cost of IOS/firmware upgrade	α_i	α_s	α
Cost of hardware upgrade	β_i	β_s	β
Cost of hardware/router replacement	θ_i	θ_s	θ
Vendor support cost	γ_i	γ_s	γ
HR development cost	δ_i	δ_s	δ
Total cost of migration	τ_i	τ_s	τ
Decision coefficient(x) for IOS upgrade, hardware upgrade	$x_{\alpha i}, x_{\beta i}$	$x_{\alpha s}, x_{\beta s}$	x_α, x_β
Miscellaneous cost	σ_i	σ_s	σ

The IOS/firmware of existing legacy routers can be upgraded unless otherwise there is no performance issues on devices [161, 75]. But lack of IOS/firmware upgrade leads to the decision for device replacement. A decision coefficient $x_{\alpha_i} \in \{0,1\}$ for IPv6 and $x_{\alpha_s} \in \{0,1\}$ for SDN is separately defined for IOS/firmware upgrade, while joint decision coefficient x_α is introduced as $x_\alpha = x_{\alpha_i} \wedge x_{\alpha_s}$. Similarly, if $x_{\beta i}$ and $x_{\beta s}$ are the decision coefficients for hardware replacement for IPv6 and the SDN, then the decision coefficient for SoDIP6 'x_β' for hardware replacement is defined as $x_\beta = x_{\beta_i} \vee x_{\beta_s}$.

This joint migration decision coefficient is derived from the individual migration, such that IOS/firmware upgrade for both technologies should be true, while the hardware upgrade is common for both. Hence, for individual and joint migration, every network router is upgradable or replaceable, is defined by $x_{\alpha_i}, x_{\alpha_s}, x_\alpha \in \{0, 1\}$, where the value '1' means upgrade and '0' means replacement.

ISP network is generally heterogeneous in nature. It mostly contains multi-brand network routers having vendor specific configuration. Due to this dynamic device characteristics, upgrade or replacement cost estimation of individual network router is a complex task. Hence, the total migration cost estimation is simplified based on the individual router migration cost. Total cost estimation is generalized in terms of number of routers set to be migrated in a phase. Here, total migration cost towards IPv6 network of 'N' routers is defined by equation (3.10).

$$\tau_i^r = f(cost\_entities)_{IPv6} = \sum_{i=1}^{N} \{x_{\alpha_i}(\alpha_i + x_{\beta_i}\beta_i) + (\neg x_{\alpha_i})\theta_i + \gamma_i + \delta_i + \sigma_i\} \quad (3.10)$$

Similarly, total router migration cost for SDN of 'N' routers is given by equation (3.11).

$$\tau_s^r = f(cost\_entities)_{IPv6} = \sum_{s=1}^{N} \{x_{\alpha_s}(\alpha_s + x_{\beta_s}\beta_s) + (\neg x_{\alpha_s})\theta_s + \gamma_s + \delta_s + \sigma_s\} \quad (3.11)$$

Additionally, the number of routers to be migrated in an ISP network are considered homogeneous in nature. In the worst case, if two technologies (IPv6 and SDN) are supposed to be fully decoupled, the total cost of migration would double the cost of individual migration. In general, if there is interrelationship between IPv6 and SDN, the total cost of migration is: $(\tau^r) \leq$ cost of IPv6 migration (τ_i^r) + cost of SDN migration (τ_s^r)

By considering interrelated technologies [158, 19] for joint migration, the shared cost coefficient (μ), which is also known as optimization variable, provides the coupling between SDN and IPv6, and the correlation is defined by the strength of correlation (ϵ).

$$\text{i.e. minimize } \left(\frac{1}{\mu}\right)^{\epsilon} (\tau_i^r + \tau_s^r), \text{ subject to } 1 \leq \mu \leq 2, \text{ and } 0 \leq \epsilon \leq 1 \tag{3.12}$$

The detailed interpretations of two optimization variables viz. shared cost coefficient (μ) and strength of correlation (ϵ) are provided at Table 3.4.

Table 3.4: Interpretations of μ and ϵ with different combinations of values.

μ	ϵ	**Interpretations**	**Remarks**
$1 \leq \mu \leq 2$	0	SDN and IPv6 are independent with no correlation. So $\tau = 2\tau^r(\tau_i^r + \tau_s^r)$ is true.	This is not applicable. The literature study demonstrates that SDN and IPv6 are not fully independent.
1	$0 \leq \epsilon \leq 1$	SDN and IPv6 are not coupled. So $\tau = 2\tau^r(\tau_i^r + \tau_s^r)$ is true.	This is not applicable. The literature study demonstrates that SDN and IPv6 are not fully decoupled.
$1 < \mu < 2$	$0 < \epsilon < 1$	SDN and IPv6 are coupled and correlated technologies, where $\tau < 2\tau^r(= \tau_i^r + \tau_s^r)$ is true. This gives the optimization in total migration cost.	This is the most favorable and applicable scenario, because SDN and IPv6 are not a single paradigm and are somehow coupled and correlated.
2	1	SDN and IPv6 are fully coupled and correlated technologies, and $\tau_i^r = \tau_s^r$, where joint migration cost, $\tau = \frac{2\tau^r(=\tau_i^r+\tau_s^r)}{2}$. The total cost is half, meaning that total cost of migration is equivalent to the cost of migration of a single technology.	This is also not an applicable scenario, because SDN and IPv6 are not a single paradigm and are not fully coupled and correlated.

From a migration perspective and considering different cost metrics, SDN and IPv6 are not mutually exclusive. They are correlated, so that the shared cost coefficient (μ) lies between 1 and 2, while strength of correlation (ϵ) lies between 0 and 1. Hence, in normal scenario, joint migration cost (τ) $< \tau^r$ (sum of individual migration cost) holds true. Based on equation (3.12), the individual cost entities can also be modeled as follows:

$$\gamma \leq (\gamma_i + \gamma_s) \cong \left(\frac{1}{\mu}\right)^{\epsilon} (\gamma_i + \gamma_s)$$

$$\delta \leq (\delta_i + \delta_s) \cong \left(\frac{1}{\mu}\right)^{\epsilon} (\delta_i + \delta_s)$$

$\sigma \leq (\sigma_i + \sigma_s) \cong \left(\frac{1}{\mu}\right)^{\epsilon} (\sigma_i + \sigma_s)$

$\alpha \leq (\alpha_i + \alpha_s) \cong \left(\frac{1}{\mu}\right)^{\epsilon} (\alpha_i + \alpha_s), \text{ s.t. } 1 \leq \mu \leq 2$

For $\beta_i = \beta_s = \beta$ (hardware upgrade cost for both technologies is considered as single upgrade). Hence, from the derivation of individual cost metric, equation (3.12) can be revised as shown in equation (3.13).

$$\forall[\alpha, \beta, \gamma, \delta, \sigma] \geq 0, minimize\left(\frac{1}{\mu}\right)^{\epsilon} (\alpha + \beta + \gamma + \delta + \sigma), \text{ s.t. } 1 \leq \mu \leq 2 \qquad (3.13)$$

Router replacement cost indicates the purchase of new router. If replacement is true, then the hardware and software upgrade cost is set to false. Hence, $\neg x_\alpha$ is represented as the complement of x_α. The total joint migration cost is the function of six tuples $(\alpha, \beta, \theta, \gamma, \delta,)$ presented in equation (3.14).

$$\tau = f(\alpha, \beta, \theta, \gamma, \delta, \sigma) = \sum_{k=1}^{N} \{x_\alpha(\alpha + x_\beta \beta) + (\neg x_\alpha)\theta + \gamma + \delta + \sigma\}_k \qquad (3.14)$$

Hence, for the homogeneous network devices, total optimized cost of 'N' routers migration based on equations (3.12), (3.13) and (3.14) is calculated as follows.

$$\tau = \sum_{N} \left(\frac{1}{\mu}\right)^{\epsilon} \{(x_\alpha \alpha + \gamma + \delta + \sigma) + x_\alpha x_\beta \beta + (\neg x_\alpha)\theta\}, \text{ s.t. } 1 \leq \mu \leq 2 \qquad (3.15)$$

Equation (3.15) provides the optimization in joint migration to migrate 'N' routers. Due to budget constraints, migration of all 'N' routers at a time might not be viable for service providers. The criteria for migration planning is the phase-wise migration based on shortest path and customer priority with available budget for migration. Equation (3.16) is modified to fit into the criteria that 'K' numbers of shortest paths are identified based on customer priority. Hence, the entire network can be migrated over 'K' number of phases. If N_i is the number of routers to be migrated in the i^{th} migration phase of K shortest paths, the optimization in total migration cost is achieved by equation (3.16).

$$\tau = \sum_{i=1}^{K}\sum_{j=1}^{i}\left(\frac{1}{\mu}\right)^{\epsilon}\{(x_\alpha\alpha+\gamma+\delta+\sigma)+x_\alpha x_\beta\beta+(\neg x_\alpha)\theta\}_j,\ \text{s.t. } 1\le\mu\le 2 \quad (3.16)$$

Algorithm 3.2 is developed considering the cost modeling with customer priority and optimal path routers replacement. Well known Dijkstras' algorithm is used to find the optimum routers in the optimal path from prioritized customer endpoint routers to the gateway router of an ISP network.

Dijkstra's shortest path algorithm is run for network graph 'G' with 'V' number of vertex and 'E' number of edges with every end-customer in the priority list. Applying the algorithm with binary heap has the time complexity of O(|E|+|V| log |V|) [162]. Hence, for 'N' number of routers attached to priority customers, the complexity of algorithm to measure priority migration path is: N(E+V)logV. For large number of vertices considering tight estimation, since vertices are larger than edges, the time complexity of proposed algorithm is: O(|N||V|log|V|).

3.6.2 Migration modeling with controller placement

This section extends the work of section 3.6.1 in which traffic engineering perspective will be considered for migration modeling and evaluate the functionality of hybrid SoDIP6 network.

Controller is the heart of SDN, in which propagation delay, controller and switch latencies, resiliency, and quality of services are the major and sensitive parameters to be considered in traffic engineering to have minimum flow setup time in SDN. The number of controllers required to be assigned to control switches and their proper placement in SDN play important role to achieve considerable flow setup time with better fault handling and effective controller load balancing [90]. Sufficient studies [90, 91, 92, 93, 94] using different techniques are available regarding the controller placement in the datacenter based pure SDN [90, 91]. One major concern in this study is to find proper location of a master controller during network migration. Das et al. (2018) [95] presented the resilient controllers placement in the hybrid SDN/legacy network and achieved better result by comparing with existing controller placement strategies in the pure SDN. For the controller fault handling and resiliency in SoDIP6 network, this approach is applicable to add other controllers

Algorithm 3.2: Migration to SoDIP6 network based on shortest path routing and customer priority

Input: $\mathbb{G} \leftarrow (V, E), \tau \leftarrow NULL$

`/* vertices 'V' and links 'E' in ISP network graph` $\mathbb{G}$`. total cost of migration at the beginning is set to NULL. */`

Input: $\mathbb{B}_s^e \leftarrow$ Budget

`/* per phase total budget of migration in the optimal path from end router to gateway router S. */`

$\sigma_k^e \leftarrow [\alpha, \beta, \theta, \gamma, \delta, \sigma]$ `/* cost metrics defined in Table 3.3 for estimation and optimization calculation. */`

$\forall e \in E_v : \delta_c$ `// customer priority value (highest).`

$\forall N \in P_e : N$ `/* number of un-migrated paths in the set of all available paths (`P_e`). */`

for $i \leftarrow$ *1 to N* **do**

  `// find optimal path between customer end router and gateway router`

  if *optimal*(P_i) **then**

    $p \leftarrow p_i$ `// retrieve optimal path` p `from set of alternate paths.`

$n \leftarrow$ number of unmigrated nodes in the optimal path p

$\forall \mu_p^e \leftarrow NULL$ `// initialize migration cost to NULL in the optimal path.`

for $k \leftarrow$ *1 to n* **do**

  `// find migration cost of each un-migrated router in optimal path p.`

  if *status*(ρ_k^e) *is 0* **then**

    $\mu_p^e += replace\_cost(\sigma_k^e)$

  else

    upgrade_cost(σ_k^e)

$\tau += \mu_k^e$ `// total cost of migration in optimal path p.`

if $\mu_p^e < \mathbb{B}_s^e$ **then**

  migrate(n) `/* if phased budget` B^e `is sufficient, then migrate all routers (n) in the optimal path p. */`

else

  migrate(m) `// migrate m (<n) number of routers in the optimal path.`

Repeat with next phase migration budget with next priority customer until all network routers are migrated.

Return $\mathcal{T}$, the total optimized migration cost of whole ISP network.

after locating master controller in the SoDIP6 networks during and after migration.

Figure 3.9 presents the glimpses of starting network (Figure 3.9a) migration to targeted network (Figure 3.9f) environment using ONOS/SDN-IP. It is assumed that the ISP network initially consists of multiple autonomous domain, in which few ASes (eg. AS1 and AS2) are already SoDIP6 capable and other ASes are still running with legacy IPv4 (AS0, AS2, and AS3). AS0 is considered as transit AS running legacy IPv4 network. It is interconnected with other ASes.

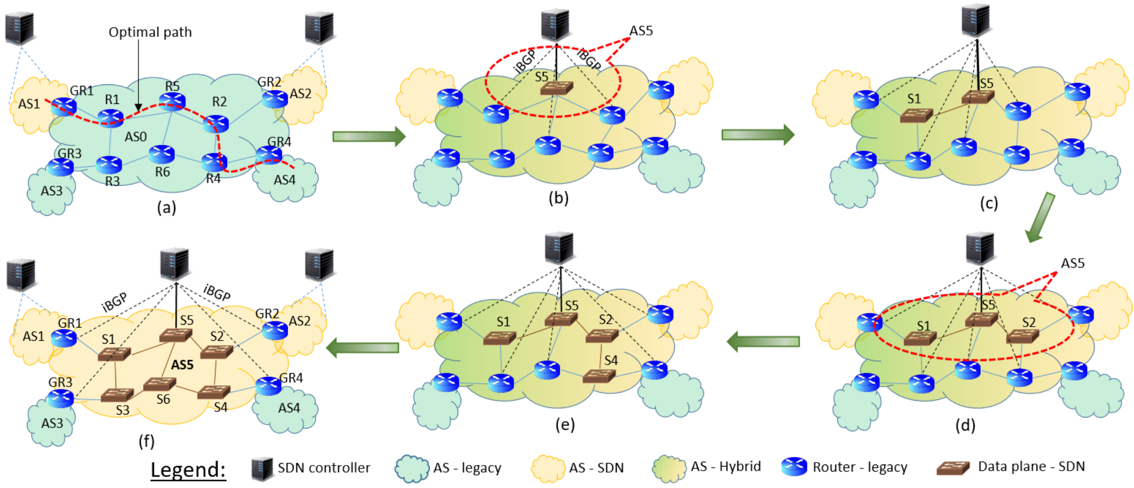


Figure 3.9: Glimpses of AS migration considering one router migration at a time, from source network (a) to target network (f)

The purpose of present study is that the transit AS has to be smoothly migrated to SoDIP6 network and run the multi-domain SoDIP6 networks environment with its legacy network integration. It is considered that gateway router-4 (GR4) in Figure 3.9a is the foreign transit gateway of this ISP. Choice of shortest path (SP) from customer endpoint router to the foreign gateway for router replacement is considered. However, this is the transit network migration, the longest span shortest path (LSSP) between customer gateway (CG) and the foreign gateway (FG) for the migration [71] is considered for migration initiation.

LSSP: *The shortest path consisting of the highest number of nodes between source and destination among the set of other shortest paths obtained from different CGs to the FG is defined as the longest span shortest path (LSSP).*

The gateway routers GR1, GR2, and GR3 are treated as CG routers, while GR4 is FG router. The network during migration in AS0 is a hybrid SDN with dual-stack IPv6 operation. From the implementation principle of SDN-IP, if any one router is migrated to switch and attached to ONOS controller, it needs to separate AS for SDN-based network. Hence, referring Figure 3.9b, router 'R5' is migrated to switch 'S5' and automatically assigned 'AS5' as a separate AS for this switch domain to establish communications with other ASes. At this moment, other directly attached routers with S5 (e.g. R1, R2, and R6) become the iBGP peer gateways. AS0 is replaced by AS5 after migrating all routers in AS0 as shown in Figure 3.9f. To properly locate the controller during migration, minimum control path latency

(MCPL) between switch-controller communications is considered. To achieve this, a median router in the LSSP is identified for the controller attachment.

MCPL: *The shortest path from the switch to the controller with minimum propagation delay for control communication is termed as the minimum control path and the propagation latency over the minimum control path is termed as minimum control path latency (MCPL).*

The migration sequence of other routers in the shortest path was generated using breadth first traversal (BFT) after setting median router, a source for traversal. Proposed approach is mathematically formulated below for migration modeling and controller placement.

The fundamental requirement is that ONOS/SDN-IP should be directly connected with any one SDN switch for its operation. The first migrated switch is supposed to be the root source switch (RSS) that has direct connection to the controller or BGP speaker attached with ONOS controller and the AS of that switch is also set to AS5. The first router selected in the optimal path during migration is the RSS. RSS is determined by the median router amongst the routers in the LSSP. The list of parameters used in the problem formulation of proposed approach is defined in Table 3.5.

The least cost path routers from source to destination are identified by equation (3.17). The shortest path is calculated using the well-known Dijkstra's algorithm.

$$\forall R \in V|A_0, p \in P : p = [R_{s,d}] \leftarrow \Delta_{s,d} \text{ is the least} \tag{3.17}$$

The median router that is best suited to directly connect to the controller for control path latency optimization is determined by equation (3.18).

$$\forall R_{s,d} \in V|p : \mathbb{R} = R_k, \text{where } k = \begin{cases} \frac{n}{2}, & \text{for } n \text{ is even} \\ \frac{n+1}{2}, & \text{for } n \text{ is odd} \end{cases} \tag{3.18}$$

Where 'n' is the number of routers in the shortest path. The sequence of routers to be migrated in the shortest path is identified using BFT, then only the routers, which are not already migrated to switches are set into migration. The median router is migrated first, and then other routers are either upgraded or replaced

Table 3.5: Description of parameters for migration implementation and controller placement.

Parameters	Descriptions
$A_i \in A$	Set of autonomous systems, $A0$ ($AS0$) is the transit AS.
$R_i \leftrightarrow S_i$	Legacy routers and SDN switch mapping during and after migration. Legacy router R_1, once migrated, becomes S_1.
$\Delta_{i,j}$	Optimal path cost from router R_i/S_i to R_j/S_j.
$\forall R_i \in A_0$	Number of legacy routers (R) in the transit AS.
$\forall S_i \in A_0$	Number of SDN switches in the transit AS during and after migration.
$\forall(V_i, E_i) \in A_i$	Number of vertices V and edges E in an AS. $R, S \in V$.
$\forall G_i \in A_0$	Number of gateway routers attached to transit AS ($AS0$)
$\forall A_i \in \mathbb{G}$	Number of ASes in the ISP network graph $\mathbb{G}$.
$\forall p \in P_{i,j}$	Shortest path p in the set of alternate paths $P_{i,j}$ from AS_i to AS_j
$\forall c_i \in C_A^0$	ONOS/SDN-IP controller c in the set of controllers in $AS0$.
$\forall g_i \in R$	iBGP gateway routers directly connected to switch S_i in $AS0$.
ϕ_0^s	Root source switch directly attached to ONOS/SDN-IP controller in transit AS.
τ	Time slot for router migration in the optimal path p.
$T_p \supseteq \tau$	Time stamp to migrate all routers in the shortest path p.
$\mathbb{R}$	Median router in the set of routers' longest span shortest path (LSSP) p.
σ	Controller (ONOS/SDN-IP) processing capacity (intent processing and flow rule generation)
λ_i	Control path latency between switch S_i and controller.
ψ_i	iBGP peering latency between switch gateway (g_i) and controller BGP speaker
γ_i	Average control load generated by switch S_i.
Ψ_i	Average iBGP peering load generated by switch gateway g_i.
x_i	Binary variable set to TRUE if R_i is migrated to S_i.
y_i	Binary variable set to TRUE if R_i is a gateway router attached with SDN switch.
z_i	Binary variable set to TRUE if controller processing capacity exceeds the threshold.

using the BFT approach. Router replacement planning using the BFT approach is termed as the breadth-first router replacement (BFR) mechanism. equation (3.19) defines the median router replacement, while equation (3.20) defines the BFT on other router replacements in the shortest path. Generally a timestamp (T_p) of 6 months is considered to migrate routers in the shortest paths. However, the total time period for whole network migration depends on the size of the network.

$$\forall \mathbb{R}, \phi_0^s = migrate(\mathbb{R}), \text{ if } x_0 = 0 \tag{3.19}$$

$$\forall R_i \in BFT(R_{s,d}, \mathbb{R}) | p, \tau \in (1, ...t \subseteq T_p) : migrate(R_i) \text{ if } x_i = 0 \tag{3.20}$$

The functions "$migrate()$" in equations (3.19) and (3.20) transform the legacy router into a SoDIP6-capable switch. Router migration means either upgrading the device hardware/firmware to make it compatible with SDN/IPv6 or replacing the device with a newer one that is already SoDIP6-capable.

The shortest path routers from GR1 to GR4 are (R1, R5, and R2), if customer endpoint router is considered to be originated from AS1. To replace these routers into SoDIP6-capable switches, the network is drilled in the sequence (GR1, R1, R5, R2, and GR4). Whenever a router is replaced by an SDN switch, the network turns into hybrid SDN, and a controller should directly be attached with that switch to establish the communication as shown in Figure 3.9b. In this drilling, router R5 is selected as the median router for migration. After router R5 is replaced to switch S5, it is now called the RSS. All the traffic to be routed through the RSS are to be managed by the controller, where iBGP peering sessions are to be established between switch gateway routers (R1, R6, and R2) that are directly connected with switch S5. Multiple sessions with multiple paths as BGP multi-homing could be established between the BGP speaker and switch gateway routers (iBGP routers) of AS0, which ensures better failure handling.

The first established controller is the master controller, while other controllers would be established based on control traffic load in the future during the migration of other routers. Increasing the number of SDN switches increases the control path traffic, while iBGP peering traffic varies based on the number of routers attached with the switches. Hence, two latencies are considered, these are: the control path latency (or propagation latency) due to SDN switches, and the gateway latency by iBGP peering gateway routers. It is also considered that after finding the RSS, breadth-first routers are to be replaced/upgraded to SoDIP6-enabled switches in the hierarchy through BFT. In the shortest path, after finding the RSS, the routers are replaced in the sequence provided by BFT. Considering one branch migration via random or depth-first order creates control traffic imbalance in the network. Hence, the choice of BFT with median point router for migration helps to maintain the equilibrium in the control path traffic between switch-controller communications. BFT gives the best choice of control traffic load balancing if it is sliced or clustered the network into different segments for controller placement. The details about the choice of first shortest path, their router migration, and the situation of the network after the first SP routers' migration are depicted in Figure 3.10.

LSSP is identified from the customer endpoint router to the foreign gateway router

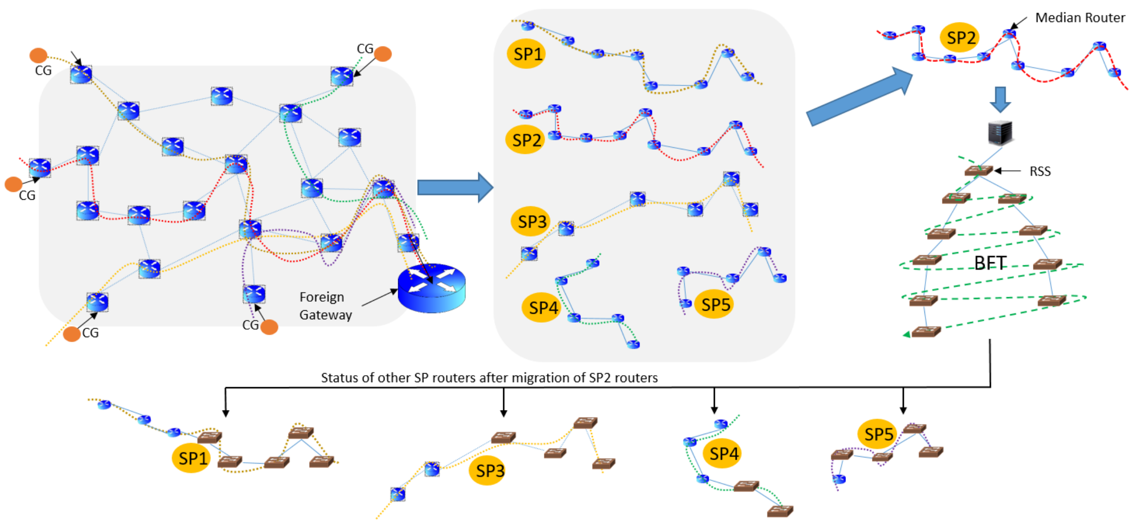


Figure 3.10: Shortest paths (SPs) extraction from CGs to FG and BFT implementation for router upgrades/replacement.

having the higher number of routers in its path as the first shortest path for migration. The steps to identify the LSSP are presented in Algorithm 3.3. The shortest paths are put into order from longest span to shortest span in terms of router numbers and follow migration in the consequent next phases. Hence, among the available alternate shortest paths, SP2 is selected as the LSSP. In the subsequent next migration phases, there might have the chances of some routers that were already migrated to switches in a previous migration. Hence, fewer routers in the path will be set to be migrated in the subsequent next migration phases. The stub routers or backup path routers, if not migrated in all shortest paths migrations, would be migrated in the final phase.

Algorithm 3.3: LSSP identification approach in an AS from network $\mathbb{G}$(V,E).

Function `get_LSSP`($\mathbb{G}, FG$):
  gw ← extract_gateway($\mathbb{G}$,AS_num) `/* extract the list of gateway routers from the provided AS (AS_num) of network` $\mathbb{G}$. `*/`
  for CG *in* gw **do**
    sp_lists ← optimal_path($\mathbb{G}, CG, FG$); `/* this function identifies the number of routers in the shortest path, which are then appended to the shortest path list (sp_lists). */`
  $LSSP$ ← path_highest_count(sp_list)
  `/* this function sorts the sp_lists and returns the highest count shortest path as LSSP. */`
  return $LSSP, sp\_lists$

The average control path latency (λ) [163] due to 'n' number of switches between switch 's' to controller 'c' is defined by equation (3.21).

$$\lambda = \frac{1}{n}\sum_{i=1}^{n}\Delta_{s,c}\cdot x_i \in \{0,1\} \tag{3.21}$$

The binding of the number of switches to the corresponding SDN controller depends on the traffic volume that a controller can process and the requirement of minimum latency. One controller is generally sufficient to handle one AS in a multi-domain ISP network. However, the distance between the controller and the switches matters, such that the minimum round-trip latency is to be considered between the controllers and the switches [163]. For fail-safe operation and controller load balancing, additional controllers could be attached to the east and west bounds of the master controller with at least one backup controller. Finding the approach to locate additional controllers in a large network is not within the scope of this study.

Equation (3.21) considers the minimum path cost (Δ) for the latency calculation. This average value can be considered a generalized value with respect to the number of switches in the network. Instead of averaging, this study considered calculation of actual propagation latency in the shortest path from the switch to the controller by summing up hop-to-hop path cost as a control path latency. In an AS, legacy router runs interior gateway routing protocol (e.g., Routing Information Protocol - RIP, Open Shortest Path First - OSPF). Based on the ONOS/SDN-IP implementation, any router when replaced with an SDN switch needs to configure directly attached routers with BGP and establish an iBGP peering session with the BGP speaker. An automatic Python script enables BGP on those routers attached with the SDN switch; these are identified by equation (3.22).

$$\forall g_i \in R, \exists s_j : hop\_distance(g_i, s_j) = 1 \tag{3.22}$$

The average iBGP peering traffic latency due to 'k' number of switch gateways is defined by equation (3.23).

$$\phi = \frac{1}{k}\sum_{i=1}^{k}\Delta_{g,c}\cdot y_i \in \{0,1\} \tag{3.23}$$

Constraints to trigger addition of new controller in the network under migration is defined by equation (3.24).

$$\forall c_j \in C_A^0, s_j \in c_j, \tau \in (t+1, ..., T) : \sum_{v_j \in S, g_j \in R} (\gamma_{v_j}^t + \Psi_{g_j}^t) \leq \sigma_j \cdot z_j^t \tag{3.24}$$

Algorithm 3.3 identifies the LSSP in an AS of the network, while Algorithm 3.4 implements the network migration and identifies the controller location. The simulation consists of several Python functions. The functions and their major tasks are summarized as comments in the algorithm.

3.7 Evolutionary Dynamics of SoDIP6 Network Migration

The joint network migration model for Tier-3 ISP networks in terms of cost optimization and traffic engineering has been established in section 3.6. In this section, the interconnected Tier-3 ISP networks will be considered, which forms the national network for migration and presents the evolutionary perspective of this network migration.

For the migration modeling, it is assumed that Tier-3 ISPs with local ISPs are interconnected via direct interconnection or through IXP. The interconnection scenario of Tier-3 ISP interconnection network is depicted in Figure 3.11. It represents a particular scenario as a Tier-3 national ISP network interconnection. 16 ISPs are interconnected out of which 5 ISPs were supposed to be already migrated to SoDIP6 networks. A Tier-3 ISP has transit interconnections with Tier-2 or with other Tier-3 ISPs. Some ISPs have private peering and most of the ISPs have public peering interconnection through IXP. This is the scenario can generally be seen on the national ISP network interconnection architecture. In the bi-group game play, it is supposed that Group-1 consists of ISPs having legacy IPv4 networks and Group-2 belongs to ISPs having SoDIP6 networks with backward compatibility and offering services accordingly.

The price of Internet bandwidth provided to end customers as well as dedicated lease services provided to enterprises are the major source of income for an ISP. Similarly, considering Figure 3.11, some ISPs can act as a transit service providers for others based on the interconnection arrangement and agreement made among them. Hence, cost of transit services provided can also be considered as an income, while the same ISP can be the transit service user of another Teir-3 or Tier-2 ISPs. Hence, the cost of transit service use is also an expenditure.

Algorithm 3.4: Network migration and the controller placement using BFR

```
Data: Network topology net_data, Customer gateway records cg_data.
/* Load network data (net_data) also attached customer gateways (CGs).      */
Input: 𝔾 ← net_data, 𝔾 ← cg_data, foreign gateway FG,
       controller_capacity ← 1.1
LSSP, sp_lists ← get_LSSP(𝔾, FG)   // Algorithm 3.3 returns LSSP and their
  routers
𝔾 ← CG_data                        // load customer gateways and attach to 𝔾
ℝ ← median_router(LSSP)   // get median router from LSSP - equation (3.18)
RSS ← migrate(ℝ)  // migrates legacy router ℝ into a SoDIP6-capable switch.
add_link(rss, bgp)                                   // attaches RSS to bgp.
for sp_routers in sp_lists do
    ℝ ← median_router(sp_routers)                // get median router per SP.
    BFT_list ← BFTravel(sp_routers, ℝ) /* function to implement BFT,
      returns the ordered list into BFT_list.                               */
    for router in BFT_list do
        if router is not SoDIP6 capable then
            migrate(router)   // legacy router becomes a SoDIP6-capable switch.
            sdn_switches ← get_switches(𝔾)     // get SoDIP6-capable switches.
            sw_latency ← 0.0                      // initialize switch latency.
            for s in sdn_switches do
                sw_latency+ = Δ_{s,c} /* propagation latency from switch "s" to
                  controller "c" (i.e., bgp) is cumulatively added.        */
                store_switch_latency(sw_file_name) /* this stores the switch
                  numbers and latency records in a data file.              */
            switch_gws ← find_gateways(𝔾)              // Ref. equation (3.22)
            gw_latency ← 0.0                     // initialize gateway latency.
            for g in switch_gws do
                gw_latency+ = Δ_{g,c} /* propagation latency from gateway "g" to
                  controller "c" i.e.,bgp is cumulatively added            */
                store_gateway_latency(gw_file_name) /* records gateway
                  numbers & latency.                                       */
    controller_load ←control_switch_gateway(s, g) /* function to record total
      load to the controller.                                              */
    store_control_load(control_load_file)          // records controller load.
    if controller_load > controller_capacity then
        notify_controller_addition()       // warning at controller overloading.
    for R in 𝔾 do
        migrate(R)   // migrates all stub routers to SoDIP6-capable switches.
    record_latency(S, gw)      // records latency of stub routers and gateways.
```

'K' number of ISPs are assumed to have already migrated to SoDIP6 networks from among 'N' number of ISPs in total. So 'K' number of ISPs are categorized into Group-2 ISPs. It means (N-K) number of ISPs are still running legacy networking system belonging to Group-1 ISPs. It is expected that all ISPs participating in

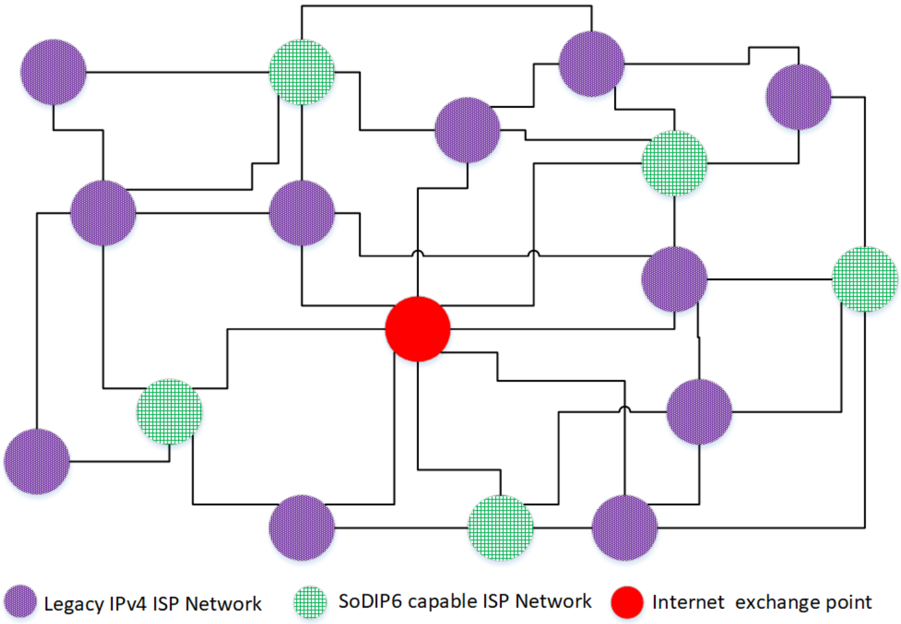


Figure 3.11: Tier-3 ISP network interconnection architecture

the evolutionary game play will migrate to SoDIP6 network with probability that suitable time for migration decision making could be determined by the migration strength presented as adaptation variable in equation (3.27) and the fitness value provided by equation (3.28). Migration is not a one-step solution that a network can switch to adaptable newer technologies on-the-fly. It has to pass series of transition periods and ISPs play with different strategies for proper migration. Hence, during the game play, ISPs are migrating to SoDIP6 network by setting the strategies based on the evaluation of different parameters and their results provided by equation (3.27) and the fitness value provided by equation (3.28). When considering all 'N' ISPs running with legacy IPv4 system in the beginning of the game play, then the utility (μ_k^4) for a Group-1 ISP is:

$$\mu_k^4 = p_k^4 - c_k^4 \tag{3.25}$$

The symbols with their usual meaning are defined in Table 3.6. If anyone ISP at a moment decided to migrate to SoDIP6 network, then the utility for that ISP migrated to SoDIP6 network can be expressed as:

$$\mu_k^{s6} = p_k^{s6} - c_k^{s6} \tag{3.26}$$

Table 3.6: Symbols and their descriptions for migration modelling

Symbols	Descriptions
μ_k^4	Utility of k^{th} ISP in legacy IPv4 network.
p_k^4	Profit of K^{th} ISP in legacy IPv4 network.
c_k^4	Cost of K^{th} ISP operating legacy IPv4 network.
c_k^{s6}	Cost of K^{th} ISP operating IPv4 with SDN and IPv6.
μ_k^{s6}	Utility of k^{th} ISP operating IPv4 with SDN and IPv6.
p_k^{s6}	Profit of k^{th} ISP operating IPv4 with SDN and IPv6 network.
γ_k	Expected utility of K^{th} group of ISPs.
$X_{4 \leftarrow 6}^6$	Number of ISPs having SoDIP6 network
$\cup_k$	Obtained utility of K^{th} group of ISPs.
N_k	Number of ISPs in K^{th} group.
K_k	Number of SoDIP6 ISPs in k^{th} group of ISPs such that $K_k \leq \mathrm{N}_k$.
$ipv6_{in}$	Average volume of incoming IPv6 traffic.
B_t	Per time step organization budget available.
HR_{s6}	Total human resources capable for SoDIP6 network operation.
σ_{4t} or σ	Overall adaptation variable at time step t.
σ_c	Sub-Adaptation variable based on number of customers and demand of SoDIP6 based services.
σ_p	Sub-Adaptation variable based on peer ISPs and traffic volume exchanging the network.
σ_s	Sub-Adaptation variable based on human resources, budget and migration cost.
n_t	Total customers of an ISP at time step t.
n_{kt}	Number of customers demanding SoDIP6 services at time step t.
n_{t-1}	Total customers at consequent previous time step $(t-1)$.
f_{4t}	Fitness function of Legacy IPv4 network at time step t.
f_{s6t}	Fitness function of SoDIP6 network at time step t.
n_p	Total number of interconnected peer ISPs.
n_{p4}	Number of Peer ISPs having Legacy IPv4 only network.
$ipv4_{in}$	Average volume of incoming IPv4 traffic.
B_c	Per time step expected migration cost.
HR_{all}	Total technical human resources of an ISP.

Hybrid SoDIP6 network is considered so that it has interoperability with legacy network. Hence, the utility due to its legacy networking capability is an added benefits. Many literature show that the operational cost of SDN and IPv6 network is comparatively lesser than the existing legacy networking system [59, 8, 15, 70]. It means SDN enabled IPv6 network will have higher payoffs as well as lower operation cost. equation (3.27) provides a calculation of strength of migration i.e. called adaptation variable (σ_{4t}) for a legacy IPv4 ISP in terms of customer demand, incoming and outgoing IPv4/IPv6 traffic based on interconnection settlement made between ISPs, and human resources with organizational budget. Hence, adaptation strength is the function of 3-tuples recognized as sub-adaptation parameters i.e. $\sigma_{4t} = f(\sigma_c, \sigma_p, \sigma_s)$ such that $\sigma_c = \frac{n_{kt}}{n_t} \cdot e^{\frac{(n_{t-1}-n_t)}{n_t}}$, $\sigma_p = \frac{(n_p - n_{p4}) \cdot ipv6_{in}}{n_p \cdot (ipv4_{in} + ipv6_{in})}$, and $\sigma_s = \frac{HR_{s6t} \cdot B_t}{HR_{all} \cdot c_m}$. Finally, summing all three sub adaptation parameters to calculate overall adaptation strength (σ_{4t}) is given by equation 3.27:

$$\begin{aligned} \sigma_{4t} &= |\sigma_c + \sigma_p + \sigma_s| \\ &= \left| \frac{n_{kt}}{n_t} \cdot e^{\frac{(n_{t-1}-n_t)}{n_t}} + \frac{(n_p - n_{p4}) \cdot ipv6_{in}}{n_p \cdot (ipv4_{in} + ipv6_{in})} + \frac{HR_{s6t} \cdot B_t}{HR_{all} \cdot c_m} \right| \end{aligned} \tag{3.27}$$

Here, σ_c measures the strength in terms of customer number and demands of SoDIP6 based services. σ_p measures the strength in terms of IPv4/IPv6 traffic incoming and outgoing from the ISP network. σ_s measures the strength in terms of organizational budget and technical HRs available for migration. Those mathematical parameters are derived based on the Tier-3 network interconnection architecture presented in Figure 3.11 and the economic models referred from the literature [85, 164, 165].

Sixteen ISPs are supposed to be operating in legacy IPv4 network that will migrate in six years so that timestamp for migration decision making is divided into 24. Each timestamp consists of three months i.e. on every three months period, legacy IPv4 ISPs (Group-1 ISPs) calculate the strength of adaptation (σ_{4t}), and compare the strength with subsequent previous measurements. The choice of three months' time step over a period of 6 years was based on the interview with major Nepalese ISPs, while most of the ISPs have maintenance plan of 3 to 6 months. Here, σ_c is the sub-adaptation parameter that measures the migration strength in terms of customer demand of SoDIP6 network based services and change in customer numbers between current and previous timestamp. Decreasing number of customer indicates that the ISP is unable to offer SoDIP6 network based services to its customer as per their demands. However, this only is not the cause of customer loss for an ISP as there are other factors like quality of service, reliability, efficient customer support, cost of services, and many more. Another sub-adaptation parameter σ_p measures the strength of migration from the perspective of traffic engineering, where measurement is based on the number of interconnected ISPs capable of SoDIP6 network and the exchange of IPv4/IPv6 traffic of the candidate ISP supposed to be decided for migration. This provides the external interference in network migration. Migration cost, available budget, and the technical HRs of candidate ISP are the major indicators to evaluate another sub-adaptation variable σ_s. Sufficiency of budget and increasing number of technical human resources capable to operate SoDIP6 network constitute to increasing value of σ_p. Strategically, candidate ISP evaluates the adaptation strength on every timestamp and compare the results with previous evaluation. The patterns of adaptation strength for example, if σ_{4t} is found to be increasing in the subsequent previous timestamps i.e. $\sigma_{(4t-2)} < \sigma_{(4t-1)} < \sigma_{4t}$, then the candidate ISP can change its strategy and take a decision for migration.

Sixteen (N=16) number of ISPs transitioning to SoDIP6 capable ISPs are modeled as an evolutionary process in which an ISP migrated to SoDIP6 network is supposed to be dead from legacy IPv4 networking (i.e. dead from Group-1) and born as SoDIP6 network capable ISP (i.e. birth on Group-2). Moran's birth-death process [166] is considered, where there is fixed number of populations (i.e. N number of ISPs) remains the same. The relative fitness to be calculated with fitness function measures in terms of strength of adaptation and the utilities given by equation (3.30). The higher the fitness value is more likely to migrate to SoDIP6 network. When the game starts and migration populations are randomly selected form the Group-1 ISPs i.e. at the beginning, for example $X^s_{4\to6}(\leq N1)$ ISPs decided to move to Group-2 ISPs, i.e. $(N1 - X^s_{4\to6})$ ISPs of Group-1 do not have SoDIP6 network capability. Then, Group-1 and Group-2 ISPs both have expected payoffs calculated as below.

$$\gamma_1 = \frac{\sum_{k=1}^{N1-X^s_{4\to6}} \mu^4_k}{N1-X^s_{4\to6}}, \text{ and } \gamma_2 = \left\{ \frac{\sum_{k=1}^{N2} \mu^{s6}_k}{N2} + \frac{\sum_{k=1}^{X^s_{4\to6}} \mu^{4s6}_k}{X^s_{4\to6}} \right\}$$

Based on the expected payoffs, the Group-1 and Group-2 will have fitness values [167] calculated as:

$$f_{4t} = 1 - \delta + \delta \cdot \gamma_1, \text{ and } f_{s6t} = 1 - \delta + \delta \cdot \gamma_2$$
$$\text{where, } \delta = \left(\frac{1}{1 + e^{-\sigma_{4t}}} \right) \cdot \eta \tag{3.28}$$

δ measures the migration strength modeled in terms of migration constant η as a coupling coefficient between two networking paradigms (SDN and IPv6) [8] and the logistic regression with σ_{4t} in the range from 0 to 1, and hence, $0 \leq \delta \leq 1$ is true. When $\delta = 0$, the fitness does not depend with payoffs and the migration strength. This discourages the decision making for migration. Similarly, at $\delta = 1$, fitness for both groups is evaluated in terms of payoffs only. Considering $\delta \geq 0.6$ is contributory for migration decision making with increasing payoffs. An ISP, when transformed from Group-1 to Group-2 i.e. migrated to SoDIP6 network leads to higher utilities and so maximizes the profit of Group-2. This increase the populations in Group-2 and decrease the population in Group 1 provided that 'N' remains the same. From the principle of evolutionary dynamics [166, 168], this is simply the birth-death process, in which same ISP is reproduced after its death, i.e. transformed from legacy system to SoDIP6 network provided with the probability that the number of SoDIP6 capable ISPs in Group-2 increases or remains same are calculated using the fitness values; if K out of N ISPs have SoDIP6 network capability at timestamp t:

$$P_{K,K+1} = \frac{K \cdot f_{s6t}}{K \cdot f_{s6t} + (N-K) \cdot f_{4t}} \frac{N-K}{K} \text{ and } P_{K,K} = 1 - P_{K,K+1} \tag{3.29}$$

In absorption states, i. e. at $P_{0,0} = P_{N,N} = 1$, all ISPs apply same strategy. The fixation probability (P_{s6t}) [85, 167] determines the scenario that migration to SoDIP6 favors, only if $P_{s6t} > \frac{1}{N}$, where $P_{s6t} = \frac{1}{1+\sum_{K=1}^{N-1}\prod_{i=1}^{k}\frac{f_{4t}(i)}{f_{s6t}(i)}}$.

At the end of the game play, when all ISPs are SoDIP6 network capable, then equation (3.25) gives zero payoff. Hence, in an initial random setting, the game is formulated for 'N' ISPs with two groups one with 'N1' legacy IPv4 networks (Group-1) and another with 'N2' SoDIP6 networks (Group-2). The size and number of customers for each ISP may vary. Group-1 and Group-2 utilities are calculated as:

$$\begin{aligned} \gamma_1 &= \sum_{k=1}^{(N1-X^s_{4\to 6})} \mu_k^4, \text{ and} \\ \gamma_2 &= \sum_{k1}^{(N2+X^s_{4\to 6})} \mu_k^{4s6} \text{ , s.t. } 0 \le X^s_{4\to 6} \le N1 \text{ and } N1+N2 = N. \end{aligned} \tag{3.30}$$

ISPs of Group-1 are supposed to be migrating to SoDIP6 only networks, i.e. to Group-2. Then for group k (capable of SoDIP6 network) has the utility $\cup_k = \log(\sigma_k + \gamma_k)$, k∈[1,2] and for typical value of σ_k is 1, $\log(\sigma_k + \gamma_k)$ is a generic convex function of γ_k for each group k. Without loss of generality, all group members are rewarded equally participating in a group mission. Hence, the utilities of two groups are:

$$\cup_1 = \log(1 + (N1 - X^s_{4\to6}) \cdot \mu^4_k), \text{ and } \cup_2 = \log(1 + (N2 + X^{4s6}_{4\to6}) \cdot \mu^{4s6}_k$$
$$\text{S.t. } 0 \le X^s_{4\to6} \le N1 \text{ and } N1 + N2 = N. \tag{3.31}$$

The evolutionary process of multi-ISP networks migration based on the defined concept and constraints is presented in Algorithm 3.5. The algorithm can be run with different values of η to measure the effects, while changing the migration constant value to evaluate δ for decision making.

Algorithm 3.5: Evolutionary process of multi-ISP network migration

```
Input: G1 ← list of legacy ISPs, G2 ← list of SoDIP6 capable ISPs, η ← 0.7,
       {σ_{4t−2}, σ_{4t−1}, σ_{4t}} ← NULL
1  @every 3 months,
2  for n ∈ G1 do
3      γ1, γ2 ← calculate utilities                 // Ref. equation 3.30.
4      σ^n_{4t} ← calculate value of σ_{4t}          // Ref. equation 3.27.
5      δ^n_{4t} ← calculate value of δ               // Ref. equation 3.28.
6      if (σ^n_{4t−2} < σ^n_{4t−1} < σ^n_{4t}) and (δ^n_{4t} ≥ 0.6) then
7          proceed_migration(n)     // Migrate this ISP 'n' using Algorithm 3.4.
8          G1.remove(n)             // remove migrated ISP form n1 list.
9          G2.add(n)                // add migrated ISP into n2 list.
10     σ^n_{4t−2} = σ^n_{4t−1}
11     σ^n_{4t−1} = σ^n_{4t}
12 Repeat from step-1 to measure strength of unmigrated ISPs for next phase
   migration.
```

3.8 Energy Efficiency Evaluation of SoDIP6 Network

One of the major challenge of ICT service providers is to optimize the energy consumption by ICT equipment by transforming the infrastructure into energy aware system. Greening ICT is expected to help reduce the negative impact caused by powering ICT infrastructure. The way of reducing the energy consumption by the ICT equipment and reducing CO2 emission by properly managing the ICT equipment to consume less power is regarded as green ICT. Use of green technologies for ICT infrastructure helps to reduce CO2 emission than that of produced by using traditional technology based equipment. For example, tele-computing and virtual meetings are expected to reduce 68 MtCO2 by 2030 [169]. Similarly, according to WWF, 100 MtCO2 emission could be reduced if 5% cars were operated with tele-computer and 15% airplane trips were substituted by virtual meeting. It is understood that ICT is not only the part of environmental problem, but also greening ICT could reduce negative impact in the environment. Reliable ICT infrastructure could help to reduce third-party energy wastes and achieve higher level of efficiency, for instance, video conferencing could replace in-person meetings through virtual meetings that leads to reduction of travelling behavior, smart electrical grid could help to utilize electricity optimally, and so on. The major motivation behind greening of ICT infrastructure is to reduce energy consumption and CO2 emission in the delivery networks, minimize operational cost in wireless networks, minimize the service provider operational cost, and improve the quality of service [170].

3.8.1 Green networking with SDN and IPv6

Energy consumption by the network equipment and the link utilization vary with respect to network traffic load and pattern. This variation is less in case of legacy IPv4 devices. The legacy IPv4 devices always have peak energy consumption even if devices are in idle condition. The integration of control and data plane within the individual devices of the legacy networking system needs heavy processing that leads to higher energy consumption as compared to SDN. Hence, legacy IPv4 network has greater energy waste problem, because of its complexity in management, control, and operation [171]. Several studies have been done for the energy aware routing scheme to minimize the energy consumption and carbon footprint reduction to show that IPv6 and SDN have greater flexibility towards green networking [172, 173, 174, 175, 176, 177, 178, 179, 180, 181]. SDN devices are programmable and controllable. network switches and links can enter into low power state in the sleep mode. The device architecture can be designed to have actual load based proportional energy consumption [182]. Hence, energy saving in SDN is viable algorithmically or through hardware improvements [183, 184, 185, 186, 187].

Many organizations World-wide have been maintaining their networking infrastructure (servers, routers, switches, and computers) in their own organizational premises. This scenario is more prominent in case of developing countries like Nepal. With the emergence of cloud computing, the network infrastructure is migrating to data centers. The Internet/Intranet services are provided as utilities from remote datacenters with higher bandwidth and lower latency. Hiroshi (2015) [188] estimated that moving the legacy infrastructure into cloud data centers could reduce CO2 emission by 40% and energy saving by 15%. Hence, individual management of network infrastructure like allocation of separate HRs, applications, security solutions, servers, switches, and cooling system etc. in small enterprises result into higher

OpEX in terms of operation and management with higher energy consumption and CO_2 emissions.

Radio Frequency (RF) and WSN enable smart devices or things in this planet are connected, controlled, and managed. IPv6 over low power personal area network (6LowPAN) [189] is specially designed for energy efficiency in IoT implementations. The amount of energy consumption is proportional to the amount of traffic condition flowing through the link. Hence, link pruning or making low traffic link into sleep mode and getting alternate routes according to traffic condition could help to reduce the energy consumption by the link. Feature for adjustment of link capacity with dynamic traffic condition is not available in legacy networks. For example, 10 Mbps port consumes less energy than 100/1000 Mbps port/link. 10Mbps links at real time consume 4 watts lower than that of 1Gbps link [184]. SDN has the capability to dynamically adjust the network parameters (speed of port/link, sleep/wake-up mode based on link activity) on-the-fly.

The power consumption by a network switch including link utilization has been studied by Zhu et al. (2016) [176]. Power consumption by a switch is static and dynamic type. Static power consists of chassis, fabric etc. while dynamic power is the power consumed by interfaces with traffic across it. Assuming this, better energy saving with IPv6 router can be achieved as compared to IPv4 router since, IPv6 router doesn't fragment the oversize packets. Due to bigger size transmission unit and support for jumbo-gram packet transmission, IPv6 network is faster leading to reduction of energy consumption with the reduced transmission period. With the migration of organizational network infrastructure into Data Centers (DC), the energy consumption and CO_2 emission by individual organization is transferring to DC.

3.8.2 Energy evaluation approach and formulations

There are major three energy saving approaches in ICT network [190], these are: re-engineering, smart sleeping, and dynamic adaption. Re-engineering focuses to the design of ICT equipment with complementary metal oxide semiconductor (CMOS) technology for energy saving as well as the refinement on the memory technology like ternary content addressable memory (TCAM) compression for packet processing. Dynamic scaling can be achieved by means of performance scaling i.e. reducing the CMOS applied voltage, changing clock frequency and turning off the sub components of equipment during the idle condition. In smart sleeping, idle device or link from where no traffic is passing, can be put into sleep mode.

Network function virtualization (NFV) and server virtualization help to reduce the energy consumption in the network. The software and network operations previously run in the separate commodity hardware are moved to single hardware with virtualization technologies. It means, number of computers are integrated into a single computer leading to energy optimization. There can be a single platform and multiple applications that improve scalability and reduce energy consumption.

Resource monitoring and its optimum utilization according to traffic condition has leading role in the reduction of energy usage and carbon footprint. SoDIP6 network is flexible and programmable, so that intelligent traffic analysis and bandwidth monitoring help to maintain the quality of service with proper resource utilization.

Present study evaluates the energy consumption by SoDIP6 network by considering a typical ISP that extends wired/wireless services to enterprises and individual home users. The experimental SoDIP6 network only at the end-user access network is considered as an use case for the energy evaluation as shown in Figure 3.12. The assumption of the end-access technologies that are almost heterogeneous in nature and their power consumption model considering the legacy IPv4 system to provide Internet services to rural area is almost similar in the study of [191, 192]. The experimental test-bed depicted in Figure 3.12 consisting of 14 switches, 8 CPEs, and 24 links, in which switches are categorized as S0 to S5 are access switches, and E0 to E5 are end-user switches. Similarly, A1 to A3 are base station access points. Additional researches are referred [192, 193, 194] to consider average power consumption of network devices and links in this works. The feasibility of SoDIP6 network for a service provider is investigated taking this case and studied how SDN enabled IPv6 network could reduce energy consumption and carbon footprint emission, while providing reliable and fast internet/network services. Based on the current infrastructure deployment initiation for Nepal, the network infrastructure is considered rural networks as the home/access networks under the hierarchy of Telcos/ISP networks in the experimental analysis. Total power consumption in ISP network is: $P_{total} = P_{access} + P_{metro} + P_{core} = \sum P_{node} + \sum P_{link}$.

Here, power consumption by CPE or switch is represented by P_{node} and power consumption by link is represented by P_{link} in the access, metro, and core network. Considering access network only, the nodes represent the CPEs and end access switches, while link represents wireless and wired links both. The power of switch in the active mode varies due to changes in its active ports and load proportional traffic demand [195]. Hence, considering the basic formulation of power consumption in

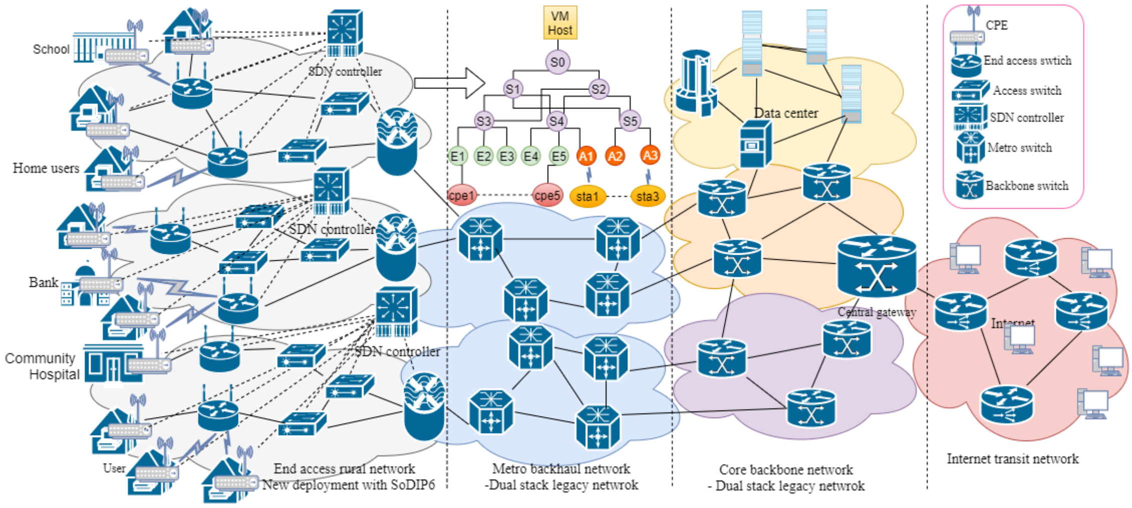


Figure 3.12: SoDIP6 capable end-access rural network in the hierarchy of nation wide ISP networks

ISP network by Chiaraviglio et al [196], the total power consumption by an ISP end-access network having two modes (active and sleep) of operation can be formulated as:

$$(P_{total})_{access} = \sum_{i=1}^{ns} \{P_{sleep_i} + x_i(P_{active i} - P_{sleep_i}) \cdot \sum_{j=1}^{ks} (f_{tr j} \cdot P_{pc_j})\} + \sum_{k=1}^{nl} x_k \cdot P_{link k} \quad (3.32)$$

Here, 'ns' represents the number of nodes, 'ks' represents the number of active ports of that node, 'nl' represents the number of links, 'f_{tr}' represents per active-port load proportional traffic demand, and 'P_{pc}' represents the port power coefficient. Binary variables $x_i, x_k \in \{0, 1\}$ have the value of '1' if the node or link is active, '0' otherwise.

Legacy IPv4 networking devices like switches and links run 24hrs a day with peak energy consumption and so resulted in a higher energy bill annually. The beauty of an SoDIP6 network is that energy consumption can be optimized using dynamic scaling, adaptive link rate, and smart sleeping [175]. Smart sleeping and traffic load-based energy variance are considered in this study to evaluate the energy efficiency of the proposed test-bed. The overall steps of experimental activities are shown in Figure 3.13. Custom end-access network topology as mentioned in Figure 3.12 are loaded and executed in the Mininet emulator after starting the Open Daylight SDN controller. The network hosts generate random IPv6 traffic in a periodic manner. The traffic with power consumption status of data plane devices are being continuously monitored via a power monitoring daemon. Similarly, the sleep/wake-up daemon instructs data plane devices based on traffic status to sleep or wake-up accordingly.

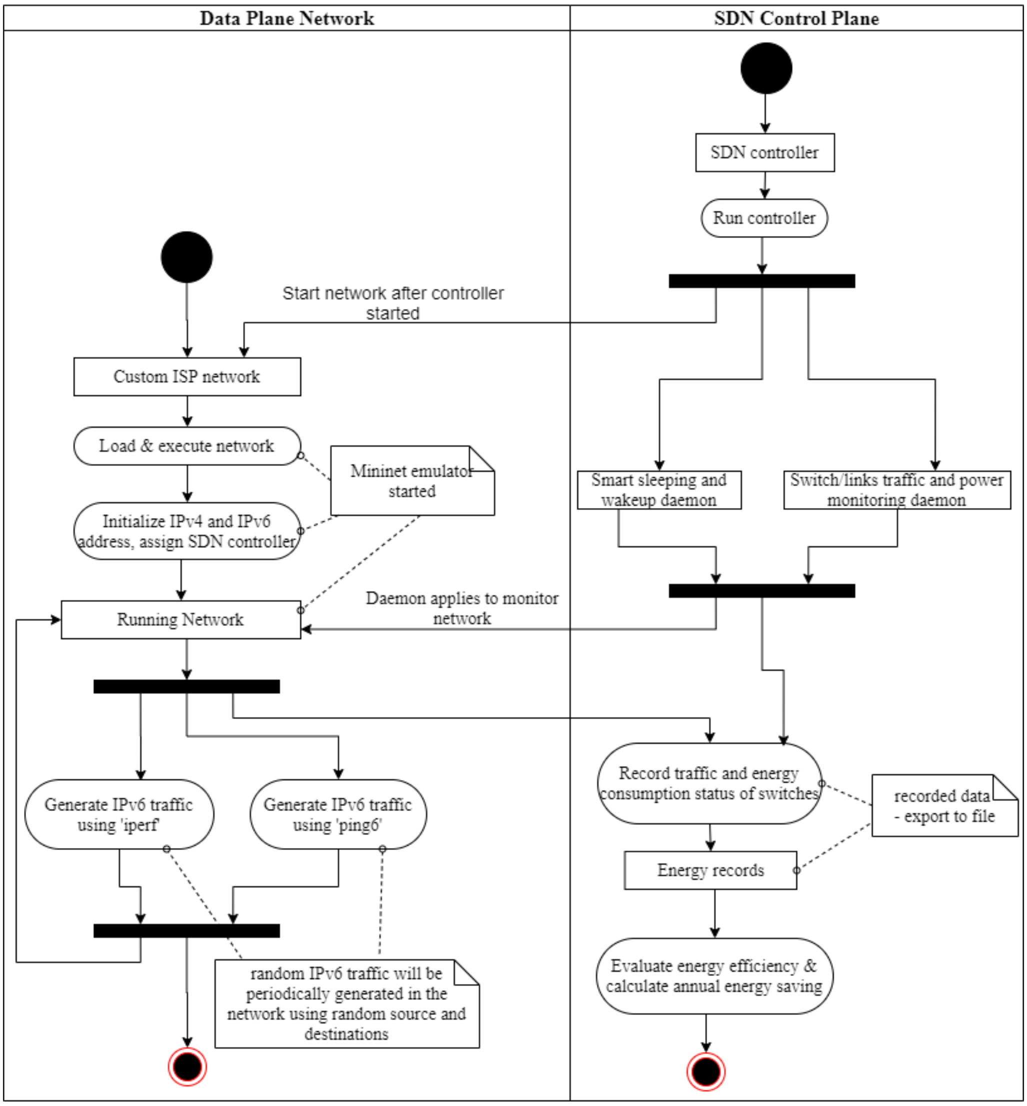


Figure 3.13: Activity diagram showing the steps of power monitoring and evaluation at simulation environment.

The pattern of energy consumption recording during 24hrs of monitoring is presented in Algorithm 3.6. During the running of the SoDIP6 network, at the beginning, a list of source hosts and destination hosts are randomly generated to establish IPv6 traffic exchange using a traffic generator tool like ‘iperf’ and ‘ping6’. Source hosts periodically generates IPv6 traffic to the destination, while the ‘iperf’ tool generates traffic on every two minutes and the ping6 tool generates traffic on every three minutes. This situation creates continuous traffic flow in the network. The device and link power monitoring daemon continuously monitor the IPv6 traffic status at the switch and links; then activates the smart sleeping and wake-up daemon accordingly.

Algorithm 3.6: SoDIP6 network traffic and power monitoring

```
Input: 𝔾 ← (V, E)
                                   // vertices 'V' and links 'E' in network graph 𝔾.
run_network(𝔾)      // initialize network, assign IPv6 address, set remote
  controller.
src_list = random(V) /* V belongs to CPEs.  This identify source hosts for
   random ipv6 traffic generation.                                        */
dst_list = random(V) /* V belongs to CPEs.  This identify destination hosts
   to send IPv6 traffic generated form source hosts.                      */
while running_network(𝔾) do
    @every 2 minutes, Generate_IPv6_iperf(src_list) /* generate IPv6 traffic
       every 2 minutes using iperf.                                       */
    @every 3 minutes, Generate_IPv6_ping6(src_list) /* generate IPv6
       traffic every 3 minutes using ping6.                               */
    @every 2 to 3 minutes, for node in V do
        if node is active then
            record_active_power(node) /* record active power of each switch
               with average traffic volume passing through it.            */
        else
            record idle/sleep mode power of node
        if no_traffic(node) then
            sleep_node(node)/* if node is idle then the node is signaled to
               enter into sleep mode.                                     */
    @every 2 to 3 minutes, /* record power of links, record power of active
       and sleep switch on every 2-3 minutes.                             */
    for link in E do
        if link is active then
            record_link_power(link)            // record power of each link.
    @10PM to 6AM, sleep_all_node() /* sleep the node during the night from
       10 PM to 6AM.                                                      */
    @6AM, wakeup_all_node()              // wake-up nodes if in sleep mode.
```

While implementing Algorithm 3.6, the activities to be carried out in the simulation environment are presented as an activity diagram as shown in Figure 3.13. The activities are associated with data plane and control plane both. Controller is to be started first to make it ready to listen the traffic from the data plane devices. Once the SoDIP6 network is started, smart sleeping, wake up daemon, and power monitoring daemons would be started with traffic generation daemon. Power monitoring daemon continuously monitors the SoDIP6 traffic and evaluates the total power consumption.

3.8.3 Sustainable network deployment: context of Nepal

Most of the rural areas of developing countries have limited resources for ICT accessibility. For example, there is lack of public libraries, skilled HRs, and ICT infrastructure. In 2019, the government regulatory body of Nepal had proposed a progressive plan to expand ICT infrastructure throughout the country [197]. This is, after implementation, is considered as the next milestone for Nepal to improve people's life style with the proper use of ICT in different sectors e.g. healthcare, agriculture, industry, governance, and many more. Almost 49% of the total population of Nepal live in the hilly zone including high altitude, which covers almost 70% of the total land. The major issues for rural communities are the diverse geography and demography leading to lack of accessibility, literacy, affordability, and sustainability. Although, ICT can play a remarkable role in uplifting people's living status, the prerequisites to provide broadband service as basic service in rural Nepal are reliable Internet connectivity, reliable power supply, affordable education to improve literacy rate, efficient management and delivery of local products, encouragement of private sectors to expand services with the latest technologies to rural communities, effective policies and implementation, subsidization for infrastructure expansion, content delivery, and quality of services to the end-users.

Nepal has adapted a liberal policy in ICT sector development with the promulgation of the Telecommunications Act, 2003 and the Telecommunications Policy, 2004. The policy and act encouraged involvement of private sectors in ICT service expansion. Private industries are being attracted in the ICT sector with sufficient investment for ICT service provisioning. This helped to reduce the digital divide and considerably increase the ICT penetration rate. The increase in penetration rate is not contributing to rural communities, because more services are available in urban areas. However, ICT infrastructure is perceived as the lynch-pin for sustainable economies of rural communities [198].

A nation-wide broadband deployment project including district level optical fiber network connectivity through the Mid-Hill Highway, establishment/erection of mobile base transceiver stations including operation and maintenance of shelter and power, connecting schools and connecting communities, and making ICT accessible to people with disabilities are the major initiative by Nepal Telecommunications Authority (NTA) utilizing the rural telecommunication disbursement fund (RTDF) that supports the policy actions irrespective of the time of target defined. With the deployment of nation-wide ICT infrastructure, the government has to come up with additional measures to reduce the digital divide and gap in the internet access, and utilization between groups [199]. Hence, the increase in ICT accessibility to rural areas becomes the basic requirement that these projects are trying to address. Additionally, content creation, delivery, and security are becoming other concerns together with the greening of network infrastructure for the ecofriendly environment towards long term sustainability of service providers and the societies [11].

The effect of global warming is alarming with the increasing network connectivity to rural Nepal covering the hilly areas. Similarly, the increasing ICT infrastructure and users led the sector consumes more energy leading to a higher volume of CO2 emission. Hence, this scenario is expected to increase rapidly; if no mitigation approaches via greening techniques are adopted. Greening of networks such as the use of renewable energy technologies to power the network equipment and the use of the latest energy efficient networking technologies like SDN enabled IPv6 networks, while deploying the connection would help to create sustainable societies as well as to provide support to service providers' sustainability. Significant amounts of energy savings in an ISP network would help to reduce the annual energy bill as a part of organizational OpEX [10] reduction.

Considering the greening approach by newer networking paradigms viz SDN and IPv6, there are several studies that contribute to green ICT with an energy aware routing scheme for energy saving and carbon footprint reduction to show that IPv6 and SDN have greater flexibility towards green networking [180, 177, 181, 174, 172, 178, 179, 173, 176]. The rapidly changing global scenarios with the latest cutting-edge technologies, such as advancement in hardware, software, applications, and protocols, service providers must be well adapted to provide efficient, reliable, and well performed faster services to customers. The latest technologies developed will be more robust, efficient, cost effective, and more operation friendly. Hence, encouragement to service providers towards timely migration of their networks based on SDN and IPv6, wireless virtualization, and the use of OpenBTS and OpenCellular technologies are required for sustainable services.

3.9 Chapter Summary

SoDIP6 network with its features and migration challenges are introduced in this chapter. Similarly, the joint migration modeling and analysis is conceptualized dividing the whole process into sub-tasks. These sub-tasks are: (a) status identification of legacy routers, which are to be investigated to measure their strength for their upgradability, (b) Migration cost optimization modelling and implementation process, (c) realization of migration implementation in carrier grade ISP networks using ONOS/SDN-IP, multiple ISP networks migration following evolutionary gaming approach, and (d) energy efficiency evaluation of SoDIP6 network including network deployment in the context of rural Nepal. This chapter further elaborated the literature review on SoDIP6 network with respect to above tasks and formulated the problem for its implementation.

Chapter 4

Methodology

Present research work by its objectives are focused on the issues and challenges of legacy IPv4 networking system, finding of suitable solutions for joint migration to two networking paradigms viz. IPv6 and the SDN. Similarly, migration planning, modeling and cost optimization, implementation, and evaluations in terms of energy efficiency including possible recommendations for broadband deployment with latest networking in the Nepalese context are considered. This chapter covers the overall research design including conceptual frameworks of research studies, experimental tools and techniques used, data collection, and assumptions made for simulation and analysis.

4.1 Overall Design and Framework

The overall conceptual research framework is presented in Figure 4.1. The overall research was designed in the modules contributing to journal papers (JP) to address the research questions outlined and as per the objectives defined. Legacy IPv4 network is considered as a research use case.

Qualitative as well as quantitative data were collected via ISP survey. Mathematical models are developed and performed numerical as well as empirical analysis with number of simulation activities to test and validate the research outcomes. The details of the concept formulations, data samples used, experimental tools used, and necessary assumptions made in the simulation works are presented in the below sections.

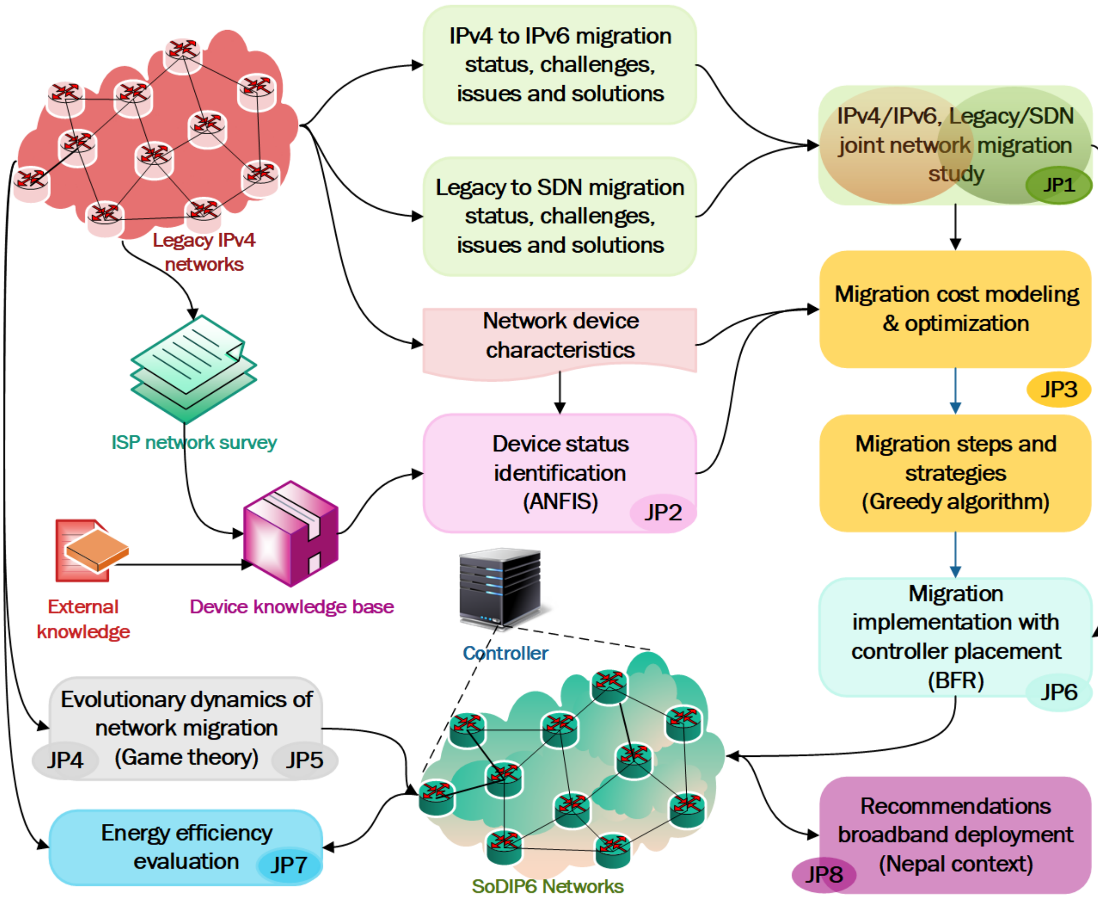


Figure 4.1: Overall conceptual framework

4.2 Technical Implementation Framework

4.2.1 Joint network migration study

As a part of literature review, the study on SDN and IPv6 network migration approaches were carried out in Chapter 2. Individual study on migration to SDN and IPv6 were carried out with their current status of deployment, migration challenges, and suitable approaches for migration. Common issues of SDN and IPv6 networks migration are identified with suitable approach for joint migration. For the real time network migration, dual-stack IP6 and hybrid SDN migration are the major choice for joint network migration.

4.2.2 Network device status identification

To enable latest networking technologies and services in the service provider network, a benchmarking is needed to measure the device status, whether it supports the projected newer technologies or not. A KB system is proposed for each networking devices by considering its dynamic device characteristics and implemented ANFIS for the status identification. The necessary parameters considered for status measures are defined in Table 3.1, while the overall framework for network device status prediction is depicted in Figure 4.2. Using KB, the DFS module measure the upgradability of device and then generate dataset by capturing certain parameter data using SNMP agent from the operational network for five inputs and one output ANFIS model.

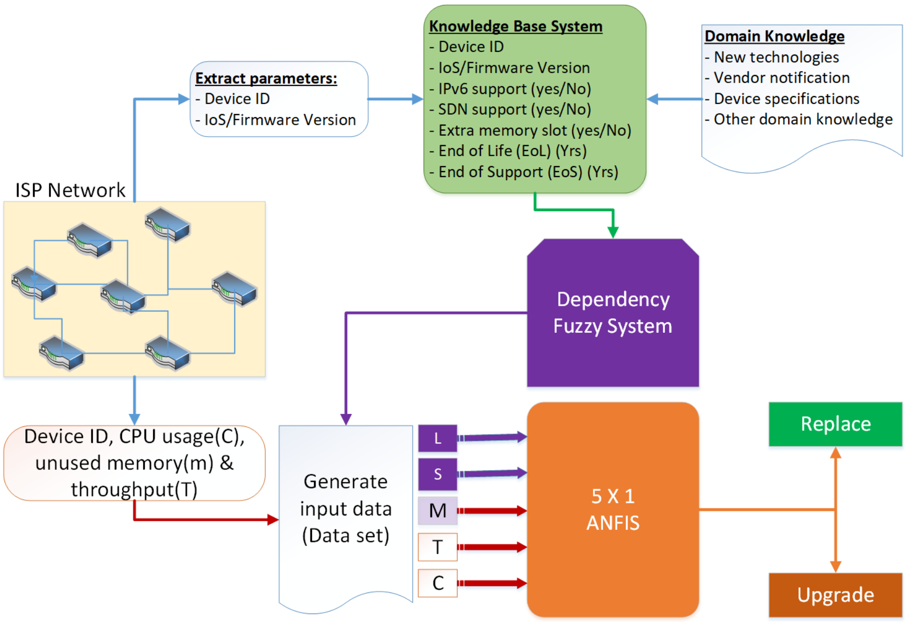


Figure 4.2: Device status identification implementation framework

4.2.3 Joint migration cost modeling and optimization

Once the device status is identified, the next task is to optimize the upgrade or replacement cost with proper migration planning so that overall cost of migration can be optimized. Figure 4.3 presents the overall implementation framework in which the developed system takes the network topology as input to create a use case scenario of network operation by attaching customers in the end-access routers. Customer priority and optimal path routing are the basic criteria set for phase-wise migration. The routers in the priority optimal path are migrated/replaced first and then consequently other optimal path routers are set into migration based on budget constraints in a specified period of time. Cost metrics for individual technology (SDN and IPv6) are identified. The joint cost model for migration cost optimization is developed. The cost metrics and their value assumptions are defined in Table 3.3.

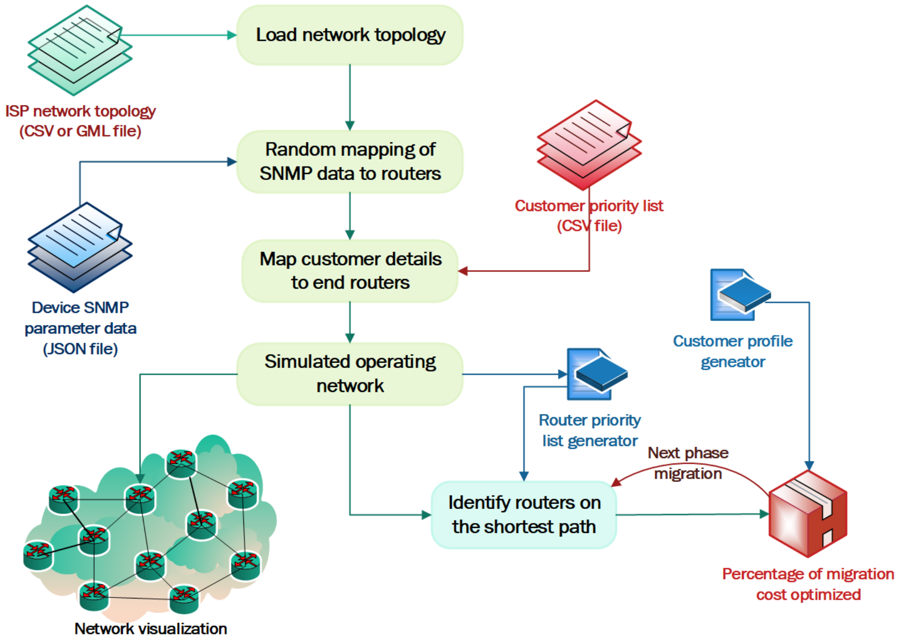


Figure 4.3: System model simulation environment

4.2.4 SoDIP6 network implementation with controller placement

As a continuation of the proposed concept presented in Section 4.2.3, a network use case of a multi-domain SoDIP6 network environment is created and evaluated the functionality of SoDIP6 network. Figure 4.4 presents the overall framework for multi-domain SoDIP6 network implementation using ONOS/SDN-IP. Starting from the multi-domain legacy IPv4 network, optimal path routers are upgraded/replaced using BFR technique. LSSP routers are extracted from among all shortest paths between customer endpoint routers and the foreign gateway. With the routers migration, proper placement of controller has major concern. Hence, ONOS controller is set to be attached to the median router as a source in the BFR after considering the MCPL between the switches and the controller. All SP routers are migrated in a phase-wise manner considering the order of SPs in terms of their number of routers. During the migration, the increase of SDN switches lead to the increased load to the controller. A constraint is defined to trigger addition of controller for load balancing, while study on placement of other controllers is not in the scope of present study.

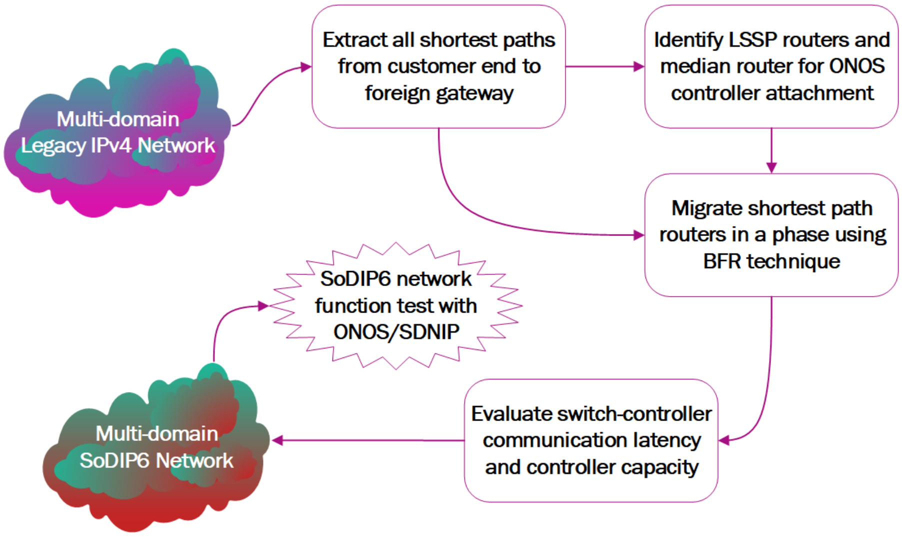


Figure 4.4: Framework for multi-domain SoDIP6 network implementation

4.2.5 Evolutionary dynamics of ISP networks migration

Previous sub-sections presented frameworks as shown in Figure 4.3 for joint migration of a single ISP network. This section considers migration of multiple interconnected ISP networks as a nation-wide Tier-3 ISP networks from the perspective of evolutionary gaming by realizing the transition through utility measurement via numerical analysis. Figure 4.5 presents the scenario of migration modeling, in which migration is an evolutionary process such that any ISP transitioned form legacy IPv4 to SoDIP6 network follow the Moran's birth-death process. So that death of legacy network and birth of SoDIP6 network creates several opportunities and benefits for service providers such that future sustainability can be ensured. Different parameters are defined, for example, customers and their demand of newer technology/services, volume of IPv4/IPv6 traffic exchanged by the ISPs in the interconnected network, organizational budget available for network migration, and availability of technical HR to handle migrated network to develop economic model and calculate adaptation strength for migration decision making. The utilities in terms of profit and loss are evaluated with the migrated network.

4.2.6 Energy efficiency evaluation of SoDIP6 network

The increase of energy consumption and CO2 emission by ICT equipment with the increase of network infrastructure is alarming for the World to minimize climate change impacts. Less energy consumption by SoDIP6 network as compared to legacy IPv4 network is one of the encouraging feature that attract service providers to migrate their network to minimize organizational OpEX. Present study evaluates

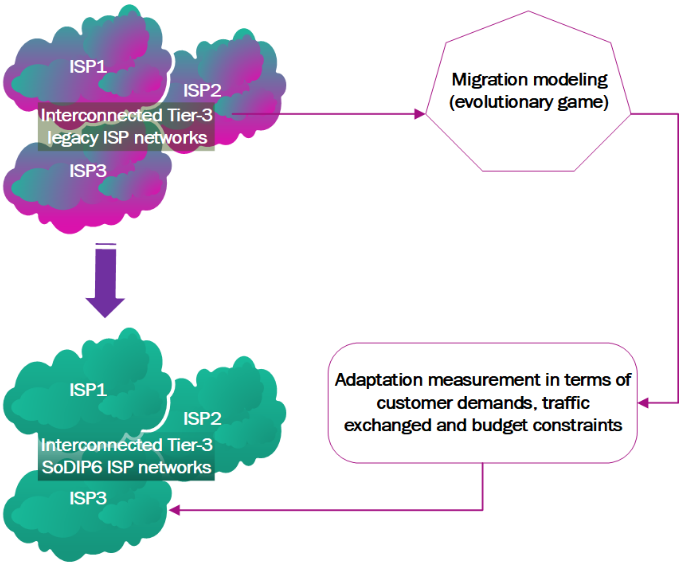


Figure 4.5: Framework for evolutionary approach of ISP networks migration

the energy consumption by SoDIP6 network through emulation considering end-access ISP network using the approach of smart sleeping in SoDIP6 network. The framework for overall energy efficiency evaluation by SoDIP6 network is depicted in Figure 4.6.

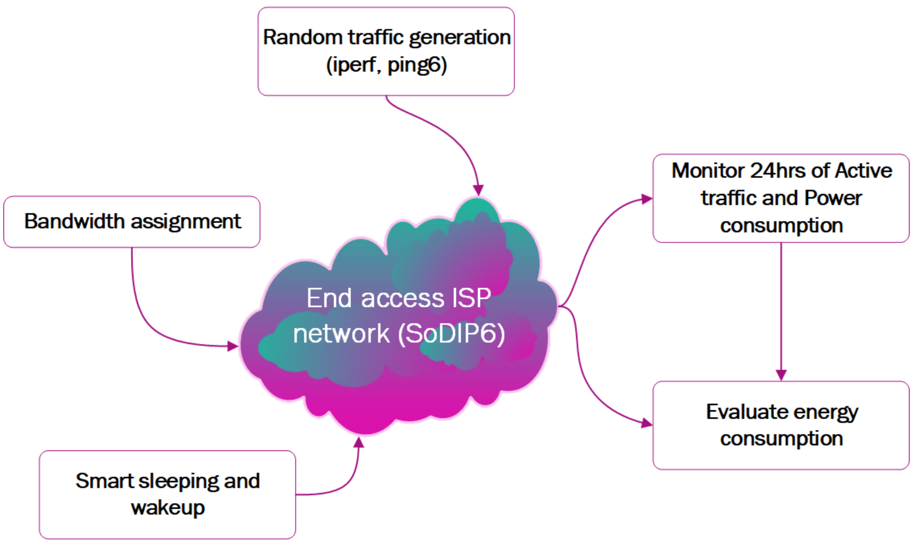


Figure 4.6: Framework for energy efficiency evaluation of SoDIP6 network

Link bandwidths are randomly assigned, IPv6 traffic are generated using *Iperf* and *ping6* tools. Traffic are monitored for a period of 24hrs. Energy consumed by switches and links are calculated. Energy efficiency is evaluated by comparing energy consumption by legacy IPv4 networks considering the same topology defined.

4.2.7 SoDIP6 network implementation: context of Nepal

The ICT and broadband network expansion throughout rural Nepal is still in the early stages. A preliminary surveys with the ISPs, Telcos, and Data-Center service providers of Nepal have been carried out to understand the current status regarding IPv6 and SDN migration. In this context, a framework for SoDIP6 network expansion in the early stage broadband expansion for Nepal has been recommended with ample suggestions for sustainable ICT expansion throughout Nepal for service providers and the communities. The framework for the broadband expansion with SoDIP6 network is shown in Figure 4.7. Qualitative and quantitative data analysis were performed after obtaining the data from survey and study from the secondary sources. Then, possible solutions are recommended to establish green ICT with sustainability of service providers and the communities by the implementation of SoDIP6 networks in the nation-wide broadband infrastructure development.

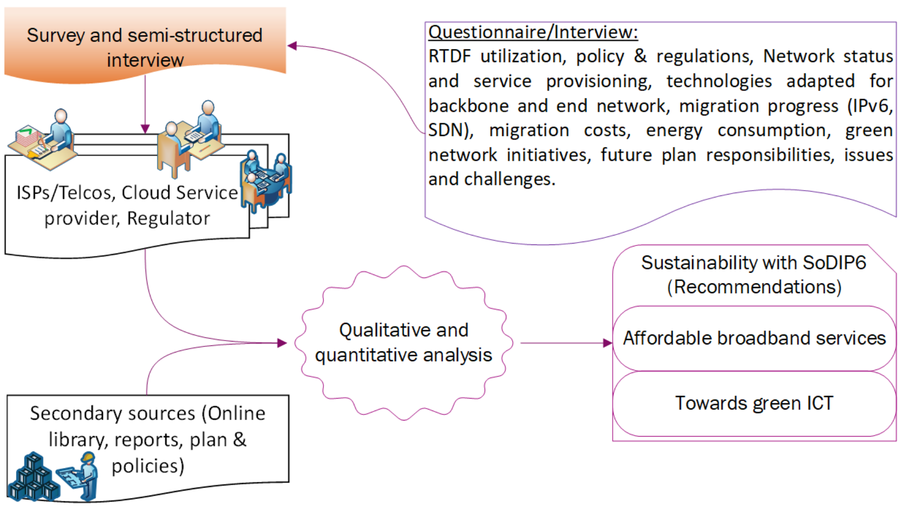


Figure 4.7: Framework for sustainable SoDIP6 network implementation: context of Nepal

4.3 Dataset Preparations, Sampling, Testing, and Validations

Present study was started with the findings of the current status of network migration in Nepalese service providers and enterprises. A survey was conducted with stakeholders of Nepal to capture certain parameters presented in Table 4.1. The set of questions designed for questionnaire survey are listed in Appendix D. Researches related to Nepalese ICT and the digital economies are very limited. Secondary sources of data were obtained for analysis from the online research libraries, regular reports published by ministries, regulator, and planning commission of Nepal. Most of the data obtained from questionnaire survey and interviews are qualitative in nature. Some facts are lacking regarding network equipment upgrade/replacement cost and the cost of energy consumption by network devices to be obtained from the stakeholders due to cause of proprietary data that they could not share. The qualitative nature of data obtained are almost sufficient to carry out the analysis and discussions presented in this study with the defined scope of works.

As a requirement to capture data from the techno-economic perspectives, judgmental sampling was followed for the survey and interview. A set of 38 questions for ISPs and Telcos, 14 questions for regulator, and 22 questions for cloud service providers were prepared. Although, Nepal has more than 40 ISPs, four major Nepalese ISPs were chosen out of six major ISPs. Most of the other ISPs are the secondary ISPs, who purchase internet bandwidth from major ISPs and provide services to customers. Among the emerging cloud service providers in Nepal, three were chosen for the questionnaire survey. Basically head of technical operations were interviewed. Answers of the questionnaire survey were mostly collected from email communications.

More than 900 data samples were generated to assess network device status for its migration by referring more than 40 different CISCO product models viz. CISCO 800, 1700, 1800, 1900, 2600, and 2900 series routers. CISCO products are popularly used World-wide in service provider networks. Comparing to other vendor products, specification details with relevant notices and information are easily available with CISCO products online. CISCO's periodic announcement on EoL and EoS of their products [152] led to refer to the most popular CISCO routers to test and validate the proposed model. Taking the reference from CISCO IP routers, the dataset were generated via augmentation by considering the minimum and maximum value of each parameter of the train dataset as confidence interval to generate random dataset for testing and validation. 60% dataset were used for training, 20% for testing, and 20% dataset were used for validation. Most of the router models used in this evaluation support IPv6, but does not support OpenFlow. It is assumed that the upgraded version of the IOS release is fully SoDIP6 capable.

Input parameters are mapped to scoring system presented in Table 3.2 for the ease of model operation and minimize error margin with higher error tolerance. CPU over-utilization in switch/router is generally less significant because data processing is generally done by interface processor. Most of the CISCO IP routers have expandable memory slot. Hence, memory is given with lower weightage value. As a part of data refinement, based on the sensitivity, EoS is given a bit higher weight. Lower

Table 4.1: Domain knowledge captured by the questionnaire survey

Stakeholders	Samples	Captured domain knowledge
Major Nepalese ISPs	4(66%)	- Current network infrastructure and its energy consumption scenarios. - Readiness status for network migration (Skilled human resources, network migration/deployment cost, future plan etc.) - Expectations from government and regulatory bodies. - Latest network deployment challenges and sustainability issues. - Corporate social responsibilities. - Annual energy consumption by network. - Cost metrics contributed to organization OpEX and CaPEX.
cloud service providers	3(66%)	- Same as above.
Telecom operators	2(33%)	- Broadband expansion plan. - Legacy network energy consumption scenarios. - Readiness status for network migration (Skilled human resources, network migration/deployment cost, sustainability plan etc.) - Existing issues and challenges. - Corporate social responsibilities. - Cost metrics contributed to organization OpEX and CaPEX.
Telecom regulator	1(100%)	- RTDF utilization. - Broadband project and its expected impacts. - Policy initiatives regarding broadband expansion and network migration. - Policy issues and implementation challenges.

the overall score value has higher significance to replace the device, while higher the score value is supportive to upgrade. Based on the maximum and minimum value of trained dataset, the range of value is defined in this scoring system.

The major information captured are device specification details including IoS release versions, IoS upgrade history of the device, and SoDIP6 supports with the parameters defined in Table 3.1. Average minimum memory unused, average maximum throughput, and average maximum CPU usage ratio are captured via simulations.

In the migration modeling and cost optimization, the analysis of survey data has contributed to identify the cost metrics for joint migration and planning. An Integer linear program (ILP) problem is formulated including identified cost metrics for migration cost modeling and optimization. The common cost metrics identified, and assumptions for simulations and analysis made are presented in Table 4.2.

Table 4.2: Individual node migration cost assumptions

Cost metrics	Cost per node (USD)	Descriptions
IoS upgrade cost	$275	Per node average IoS upgrade license cost.
Hardware upgrade cost	$700	Addition of memory or extra ports.
Device replacement cost	$7000	Average purchase price of SoDIP6 capable L2/L3 device.
Support cost	$140	Vendor support per router license cost.
HR development cost	$250	Assume cost is $2500 per HR, where one person handles/manages 10 routers.
Miscellaneous cost	$75	Extra cost per router during the migration. This may include configuration, testing, verification, transportation etc.

Extensive simulations were carried out with the proposed heuristic algorithm to measure the percentage of cost optimized in joint network migration using the standard network topology (Abilene, BTAsiaPAC and Xeex) obtained from the internet topology zoo (http://www.topolozy-zoo.org). The implemented heuristic is extended to evaluate the real-life implementation of multi-domain SoDIP6 networks using SDN-IP over ONOS controller. Optimal path routers are replaced/upgraded using BFR approach so that suitable placement of controllers during network migration could be achieved with optimization in controller load balancing. The functionality of SoDIP6 network was validated by configuring a network use case. Similarly, additional simulations and empirical analysis have been carried out to identify the proper location of master controller based on MCPL.

The migration of nation-wide interconnected ISP networks is considered from the evolutionary perspectives after analyzing an ISP legacy network migration to SoDIP6 network. The evolutionary process of network migration is mathematically modeled and evaluated with extensive simulations. Sensitivity analysis on network migration are carried out with the six round of simulations and numerical analysis. Assumptions of economic parameters on rate of change of customer demands, traffic, and organizational budget for this analysis are provided in Table 4.3.

Table 4.3: Simulation parameter setting and assumptions

-Total customers of an ISP= 1200 -Total migration period of 6 years -Time steps to evaluate adaptation value and migration strength = every 3 months -Expected utility of group-1 ISP = 500 -Expected utility of group-2 ISP =700 -Incoming IPv4 traffic to group-1 ISP = 900 TB	-Incoming IPv6 traffic on a group-1 ISP = 300 TB -Number of tier-3 ISPs interconnected=16 -Peer ISPs migration ratio (per time step) = 2/3 -Total technical human resources per ISP=120	-SoDIP6 capable human resources per group-1 ISP =2 -Migration budget per ISP = 30,000 USD. -Allocated migration cost per ISP = 45,000 USD.

	σ_c		σ_p		σ_s	
Simulation Rounds	Customer Demand	Total customers	Incoming IPv6 traffic	Incoming IPv4 traffic	Org. budget	Migration cost
	0%↑	-0.5%↓	2%↑	0.5%↑	3%↑	1%↑
1st	1%↑	-0.5%↓	3%↑	-0.5%↓	3%↑	2%↑
	1.5%↑	-1%↓	4%↑	1%↑	2%↑	1.5%↑
	2%↑	0.5%↑	6%↑	-2%↓	2%↑	3%↑
	1%↑	-1%↓	2%↑	0.5%↑	2%á	2%↑
2nd	2%↑	-2%↓	3%↑	-1%↓	2%↑	3%↑
	3%↑	-2%↓	5%↑	2%↑	3%↑	3%↑
	6%↑	0.5%↑	8%↑	-4%↓	3%↑	2%↑
	2%↑	-1%↓	3%↑	-2%↓	2%↑	2%↑
3rd	4%↑	-4%↓	6%↑	-3%↓	-1%↓	2%↑
	7%↑	-6%↓	8%↑	-4%↓	1.5%↑	4%↑
	10%↑	-10%↓	10%↑	-6%↓	3%↑	6%↑
			2%↑	0.5%↑	3%↑	1%↑
4th	1%↑	-0.5%↓	3%↑	-0.5%↓	3%↑	2%↑
			4%↑	1%↑	2%↑	1.5%↑
			6%↑	-2%↓	2%↑	3%↑
	1%↑	-1%↓			2%↑	2%↑
5th	2%↑	-2%↓	3%↑	-1%↓	2%↑	3%↑
	3%↑	-2%↓			3%↑	3%↑
	6%↑	0.5%↑			3%↑	2%↑
	2%↑	-1%↓	3%↑	-2%↓		
6th	4%↑	-4%↓	6%↑	-3%↓	1.5%↑	4%↑
	7%↑	-6%↓	8%↑	-4%↓		
	10%↑	-10%↓	10%↑	-6%↑		

The assumptions are made with the information obtained from ISP survey and other literature, while multiple round of simulations were carried out to measure the stability and validate the migration model with sensitivity analysis. The interpretation of simulations and analysis are provided in Chapter 5.

For the energy efficiency evaluation of SoDIP6 network, IPv6 traffic were generated periodically and monitored the traffic for a period of 24 hrs with power consumption status by SoDIP6 network created over Mininet using python programming.

4.4 Experimental Setup and Tools Used

Multiple experiments were executed over the virtual environment using different tools based on the research framework designed depicted in Figure 4.1. The major input to the system for analysis is a network topology, while set of network information were captured by SNMP trap. The tools used during the experiments are listed in Figure 4.8, which also shows the overall technical implementation framework of this research study.

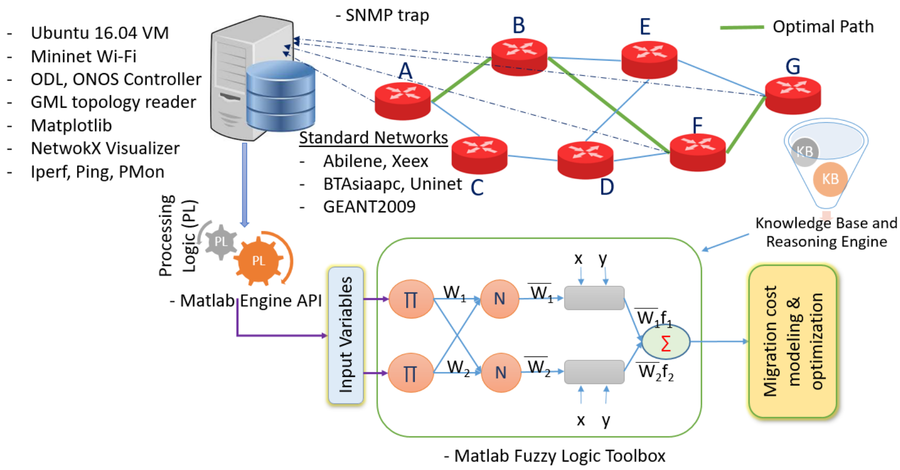


Figure 4.8: Technical implementation framework with tools used during the experimental analysis

ANFIS model is trained using MATLAB programming with fuzzy logic tool box to identify the network device migration status, while the trained ANFIS model is integrated with python interface through the application programming interface (API) called MATLAB engine API in python. The python program to implement proposed heuristic algorithm for joint migration cost modeling integrates the ANFIS model via a middleware API and simulate the scenario of phased network migration with cost optimization using standard network topology. Throughout the study, Abilene, BTAsiapac, Xeex, GEANT2009, and UNINET are the standard backbone/customer-end network topologies used for experimental test and analysis using python NetworkX module.

The joint migration modeling with the implementation of ONOS/SDNIP towards multi-domain SoDIP6 network operation is carried out over Ubuntu 16.04 virtual machine with python Mininet programming. Similarly, the evolutionary process of network migration is implemented with extensive simulations using python programming.

As a preliminary analysis, the tools used were OpenDaylight Controller, Kill a Watt, NEC's OpenFlow PF5240-ProgrammableFlow Switch, and Mininet to perform energy consumption evaluation of proposed SoDIP6 network taking the use-case of an university campus network. The test-bed was setup over two Ubuntu Virtual Machines (VM), i.e. one for Open Daylight Controller and another to run the network topology was the Mininet-WiFi VM, each having 8GB RAM over an windows server host with 2.1GHz octa-core processor and 32GB of RAM. Link bandwidth between switches is set to 1000Mbps and between switch to CPE is set to 5Mbps. Daemons are developed for random IPv6 traffic generation, power consumption recording, per port traffic measurement in switches and links, sleep the switch based on controller's traffic status evaluation in the entire network, and auto wake-up. Random IPv6 traffic has been generated on every 2 minutes using 'iperf' tool and 'ping6' on every minute. Active traffic on the switches and their ports were measured using 'vnstat' traffic monitoring tool, while the SDN controller signals the switches into sleep mode, if it is in idle state. Power consumption of each switch and links were monitored periodically over a span of 24hrs. Wake on LAN (WoL) concept is used to auto wake-up the switch and activate links.

All the program source code for experimental test and analysis are available at GitHub link – `http://www.github.com/baburd/SoDIP6`, while software interface snapshots are provided in Appendix B.

4.5 Algorithm of Overall Research Work

Different algorithms are developed to complete specific tasks formulated in Chapter 3. Algorithm 4.1 provides the abstract view of overall research studies.

Algorithm 4.1: Overall steps of research studies

Input: $G \leftarrow (V, E), \Phi \leftarrow$ customer priority Data, $\phi \leftarrow$ gateway list data
/* vertices 'V' and links 'E' in ISP network graph $\mathbb{G}$, customer details to be mapped to network graph, customer priority dataset and AS gateway dataset are listed in Appendix A. */
Input: $\psi \leftarrow [L, S, M, T, C]$
// Dataset generated by function DFS() and SNMP() according to Algorithm 3.1.
Input: $\Upsilon \leftarrow [\alpha, \beta, \gamma, \delta, \sigma, \theta], \tau \leftarrow$ migration_budget
/* cost metrics for device migration based on Table 3.3 and network migration budget. */

1 @every 6 months,
2 $\sigma_{4t}, \delta_{4t} = get\_strength(\mathbb{G})$ // get migration strength. Ref. Algorithm 3.5.
3 **if** $\sigma_{4t}, \delta_{4t} \geq 0.6$ **then**
4     $\rho \leftarrow list\_SP(\mathbb{G}, \Phi, \phi)$ /* returns list of shortest paths in the order form longest to shortest span. Ref. Algorithm 3.3. */
5     $\mathbb{R} = \text{RSS}(\rho_1)$ /* identify median router as RSS from LSSP and migrate to switch. */
6   add_link($\mathbb{R}, bgp$) // attach ONOS/BGP speaker to RSS.
7     $\mathbb{S}_U, = NULL$ // set NULL for unmigrated routers in the previous phase.
8   **for** $P \in \rho$ **do**
9         $\xi_P = BFR(P)$ // BFR implementation Ref. Algorithm 3.4.
10         $\mathbb{S}_P \leftarrow Anfis\_status(\xi)$ /* returns router status in the shortest path. Ref. Algorithm 3.1. */
11         $\xi_P + = \mathbb{S}_U$
12         $N_1, N_2 + = status\_count(\mathbb{S}_P)$ /* get number of routers to be upgraded or replaced. */
13         $\omega = optimum\_migration\_cost(\mathbb{S}_\rho, \Upsilon)$
14   **if** $\omega \leq \tau$ **then**
15   migrate($\xi_P, \mathbb{S}_P, \tau_P$) // migrate all routers. Ref. Algorithm 3.2.
16   **else**
17   upgrade($\xi_P, \mathbb{S}_P, N_1$)
18   replace($\xi_P, \mathbb{S}_P, n_2 \leq N_2$)
19             $\mathbb{S}_U = get\_unmigrated(\mathbb{S}_P)$ /* transfer non migrated routers to next phase migration. */
20 **else**
21   continue from step-1 // evaluate migration strength on every 6 months.
22 evaluate_energy($\mathbb{G}$) // SoDIP6 network energy evaluation. (3.6).

4.6 Chapter Summary

This chapter outlined the overall research design works with single methodological framework. A technical implementation framework for each tasks viz. joint migration modeling, device status identification, migration implementation with controller placement, evolutionary process of migration, and energy evaluation of SoDIP6 network are briefly discussed by considering the conceptual works formulated in Chapter 3. Similarly, dataset preparation, necessary assumptions for simulations and analysis, tools and techniques used in the whole research have been presented with the overall steps of research work.

Chapter 5

Analysis, Results, and Findings

Research concepts and problem formulations were discussed in Chapter 3, while the conceptual research frameworks based on the objectives defined were presented in Chapter 4. The outcome of ISP survey, experimental outputs, and empirical/numerical analysis with findings and contributions will be discussed in this chapter.

5.1 Joint Network Migration Study

Individual network migration study of SDN and IPv6 provided the current status of network deployment with their common concerns. Being underlying network layer paradigms, the common issues in network migration clearly shows the opportunity for migration cost optimization, while following joint network migration. The overall research direction presented in Figure 2.9 first enables the choice of migration technology and then identify the suitable strategy for joint migration modeling. The basic steps defined for joint migration implementations are listed below.

1. Identify the common issues/concerns of SDN and IPv6 network migration.

2. Measure the status of existing networking devices in terms of their performance and available technologies for their upgrades or replacement.

3. Identify the common cost metrics to formulate the problems for migration cost estimation and optimization.

4. Prioritize the customers with their service demands and list all the network routers to be migrated in the optimal path form customer endpoints to foreign transit gateway.

5. Develop algorithm and plan for phased network migration with budget constraints for an ISP.

6. Implement the migration with multi-domain ISP network in terms of their profit and losses through evolutionary process.

7. Evaluate the production level implementation of SoDIP6 networks using ONOS/SDN-IP.

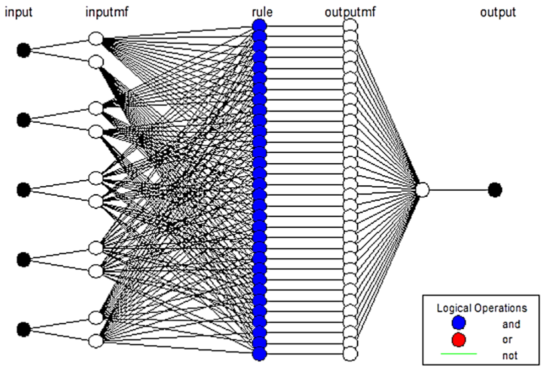
8. Evaluate the energy efficiency of SoDIP6 networks with its contribution in Green ICT, and

9. Recommend possible deployment solution of SoDIP6 network to establish nationwide broadband network in the context of Nepal.

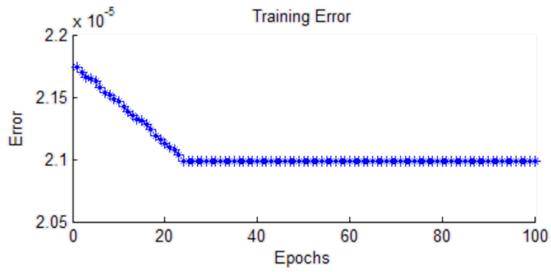
5.2 Network Device Migration Planning

The first step in the migration planning is to identify the status of existing running network device, which is supposed to be upgraded its hardware/software or to be replaced to make the network compatible with SDN and IPv6 operation.

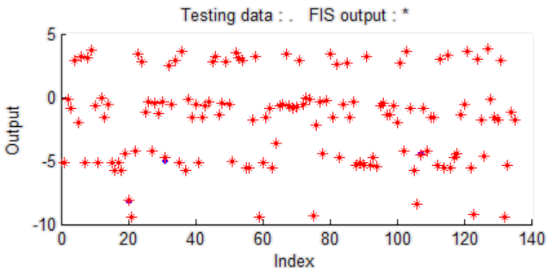
Five inputs and one output ANFIS model is developed and trained using MATLAB fuzzy logic toolbox by choosing hybrid learning algorithm with different membership functions (MF) and types at different number of epochs. At first, primarily refined data samples without applying scoring in the preprocessing are used to train the model. While applying different MFs (e.g. trapezoidal, triangular, Gaussian, and gbell), GBell MF gave the minimum test root mean square error (RMSE) value of 0.7503. Then, the data samples were further processed and applied scoring and weight provisioning to minimize noise in the data samples. The trained model gave the minimum testing RMSE value of 0.031169 at 100 epochs with MF 'gbellmf' value at [2 2 2 2 2] as a best result over 450 data samples. Figure 5.1a,b present the ANFIS structure and RMSE plot while training. Similarly, Figures 5.1c,d provide the plots of testing and validation as FIS outputs during training, while Figure 5.1e shows the model input and output fuzzy system. In the worst case, if all input variables are high, the total score is 20, while to neutralize to zero output, minimum value of a variable is set to -16. Setting a 50% threshold in an average gives the decision point at 2. This means, output threshold value '2' is defined for the decision making. Output value greater than 2 indicates the device upgrade, otherwise the device should be replaced. Input at L=2, S=-16, M=3, T=2, and C=4 give status output of -1.95, which indicates device replacement.



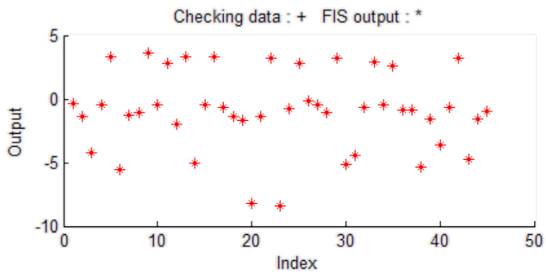
(a) Modeled ANFIS (32 rules, 92 nodes)



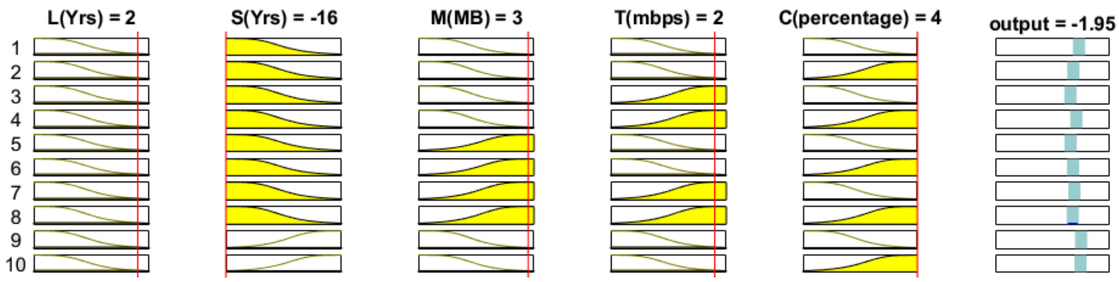
(b) Training error stabilized at RMSE = $2.09e^{-5}$)



(c) Model output against testing data (epochs=100, test RMSE=0.031169)



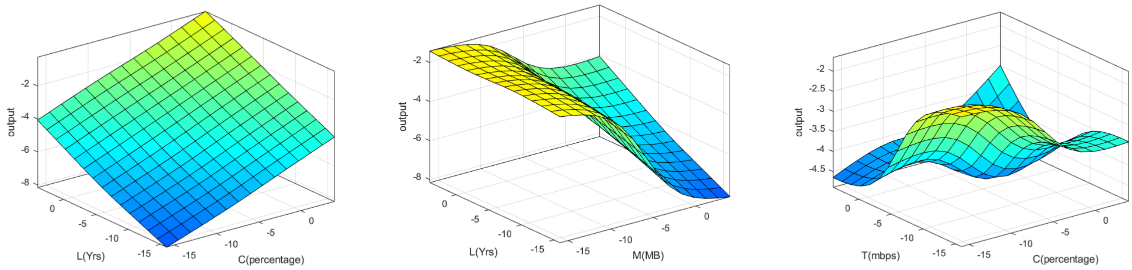
(d) Model output against check data (epochs=100, check RMSE=0.04459)



(e) Model output evaluation window (input=[2 -16 3 2 4], output = -1.95)

Figure 5.1: Training, testing, and validation results

Surface view graphs of some parameters are shown in Figure 5.2. Figure 5.2a presents the mapping from C and L to output, while setting other parameters [M, T, C] to constant value at [3, 4, -16]. Similarly, Figure 5.2b presents the surface view mapping of M and L to output with constant value of [L, T, C] = [3, -16, -16] and Figure 5.2c provides surface view mapping of C and T to output at constant value of [L, S, M] = [-16, 4, -16]. The three-dimensional surface view provides the patterns of two input parameters with respects to corresponding output. For example, in Figure 5.2a, for the defined reference inputs, the patterns of C and L almost have linear mapping. Similarly, in Figure 5.2b, the output mapping of C looks almost exponential, but with respect to L, the output changes from linear to constant. Figure 5.2c presents the complex mapping of inputs C and T at defined reference inputs of L, S, and M.



(a) Surface view of C and L at ref. input: M,S,T=[3,4,-16]

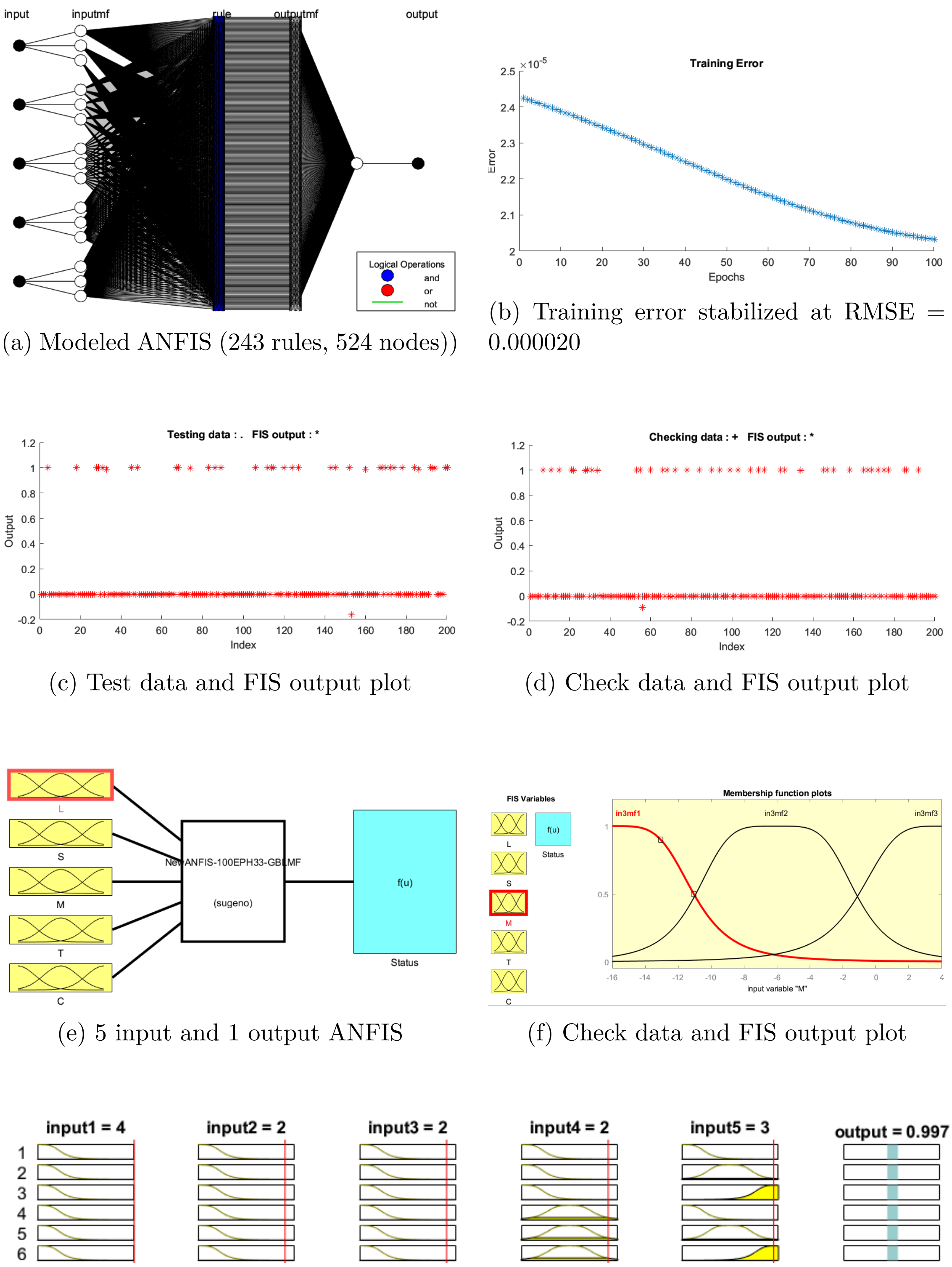
(b) Surface view of M and L at ref. input: S,T,C=[3,-16,-16]

(c) Surface view of C and T at ref. input: L,S,M=[-16,4,-16]

Figure 5.2: Surface view of input parameters for ANFIS model at different reference inputs

An additional experiment was executed with MF type 'gbellmf' and MF value at [3 3 3 3 3] over the dataset of more than 900 samples. The dataset have output classification value of 0 and 1. The ANFIS structure (having 524 nodes and 243 rules) was generated at best result, which is shown in Figure 5.3a. Figure 5.3b shows the error plot during training at 100 epochs. The experiment was run up to 100 epochs with training error tolerance of almost zero value. Figures 5.3c,d display the FIS output with test and validation data during training, in which the predicted output is almost overlapped with FIS output showing best results of the model. Figure 5.3e presents the trained ANFIS model at 100 epochs having five input variables and one output (status) variable, while Figure 5.3f shows the membership function plot of input variable 'T', where the threshold of 0.5 was considered for decision making based on ANFIS output. Figure 5.3g shows the model input and output fuzzy system. Input at L=4, S=2, M=2, T=2, and C=3 give status output of 0.997 (almost closed to 1, >0.5), this indicates device upgrades.

The three-dimensional surface view provides the patterns of two input parameters with respect to corresponding output. For example, the contour view plot in Figure 5.4a shows that output status goes maximum value of 0.04, even if the reference input of S and L both are highest value of 4. This implies the device replacement based on constraints defined in equation 3.9. Similarly, the same cases can be seen in Figure 5.4b about the distribution plot of T and L for given reference input at [S, M, C] = [4, -16, 2]. In Figure 5.4c, the reference input are all positive value,



(a) Modeled ANFIS (243 rules, 524 nodes))

(b) Training error stabilized at RMSE = 0.000020

(c) Test data and FIS output plot

(d) Check data and FIS output plot

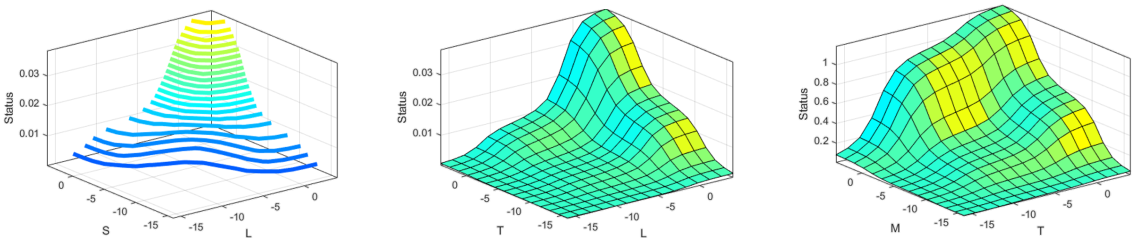
(e) 5 input and 1 output ANFIS

(f) Check data and FIS output plot

(g) Model output evaluation window at input=[4, 2, 3, 2, 3] and output = 0.997

Figure 5.3: ANFIS training, testing and validation with binary decision

i.e. [L, S, C] = [2, 4, 4]. Based on these reference inputs, it can be seen that the distribution of M and T have values varying from 0.5 to 1 with error tolerance at the positive distribution area from 2 to 4.



(a) Contour view of S and L at ref. inputs: M,T,C=[-16,4,2]

(b) Surface view of T and L at ref. input: S,M,C=[4,-16,2]

(c) Surface view of M and T at ref. inputs: L,S,C=[2,4,4]

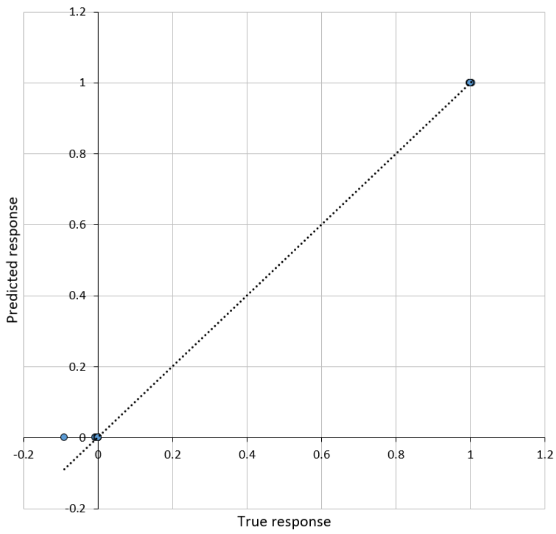
Figure 5.4: Surface view of input parameters for ANFIS model at different reference inputs for binary output

5.2.1 Performance comparison

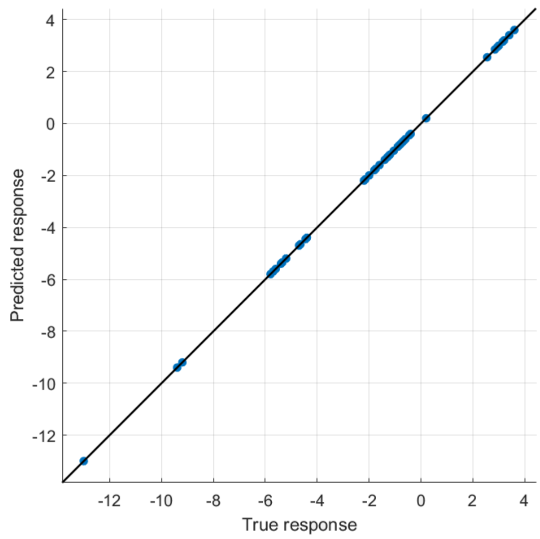
The trained ANFIS model gives the best fitting result in both experiments with data samples 450 and 900. Those data samples for training is sufficient and the obtained minimum test RMSE is justifiable to perfectly classify the router status [125]. For the cross verification of the model performance, additional experiments were executed with other recent classification methods. The proposed model has only five input variables, which is suitable for hybrid learning in ANFIS. The performance of the model is evaluated in terms of error parameters. Other algorithms, for example, linear regression, fine tree, optimizable SVM, linear SVM, and ensemble tree (boosted and optimizable) were used for the evaluation. The training of ANFIS considered 30 epochs.

Figure 5.5 shows the regression plot of observed vs. predicted result with check data for three methods viz. ANFIS, liner regression, and linear SVM. Figure 5.5a is based on binary results defined by equations (3.8) and (3.9). To cross verify the mathematical model proposed, Figures 5.5a,b,c are plotted based on the output classification fuzzy value of [0 to 1] and [-16 to 4] defined by equations (3.6 and 3.8). Almost all plots provided good fitting linear model. This indicates no false positive result in device classification using these models. It can also be seen that the mathematical model gives the best fit as implemented with linear regression and SVM.

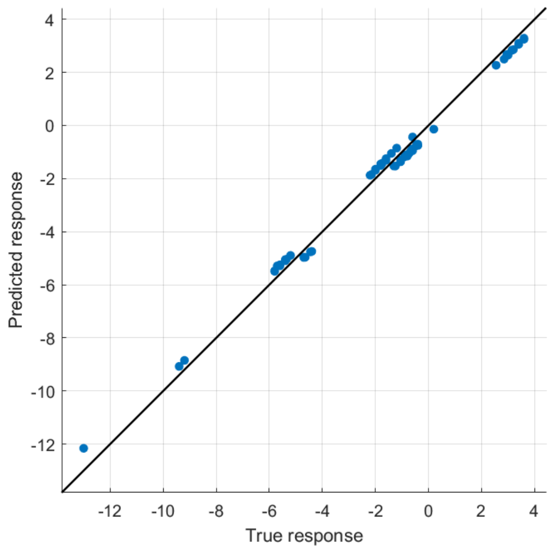
Table 5.1 shows the values of different error and performance parameters during training, testing, and validation of ANFIS. RMSE value is the least, coefficient of determination (R^2) and correlation factor is almost 100%, and mean absolute error (MAE) is also the least for ANFIS.



(a) Regression plot based on equations 3.8 and 3.9



(b) Liner regression plot based on equation 3.6



(c) Liner SVM plot based on equation 3.6

Figure 5.5: Regression plot of check data observed vs. predicted output

Table 5.1: ANFIS performance evaluation

	RMSE	R^2	Correlation	Standard deviation	MAE
Training	0.00002	0.99999	0.99999	0.30503	0.0000044
Testing	0.01167	0.99912	0.99956	0.39254	0.0021872
Checking	0.00643	0.99974	0.99987	0.40029	0.0012512

The standard deviation values are also not significantly varied among training, testing, and checking data. This indicates the best fit model with ANFIS. Similarly,

Table 5.2 shows the comparative results of error values with other different classification methods. Other methods were evaluated at 10-fold cross validations and 30 iterations. The least value is obtained using ANFIS except the time of training, which is comparatively higher than other methods. Since, training time is a one-time task, which is less significant than other performance parameters.

Table 5.2: Comparison of training error measurement with different classification methods

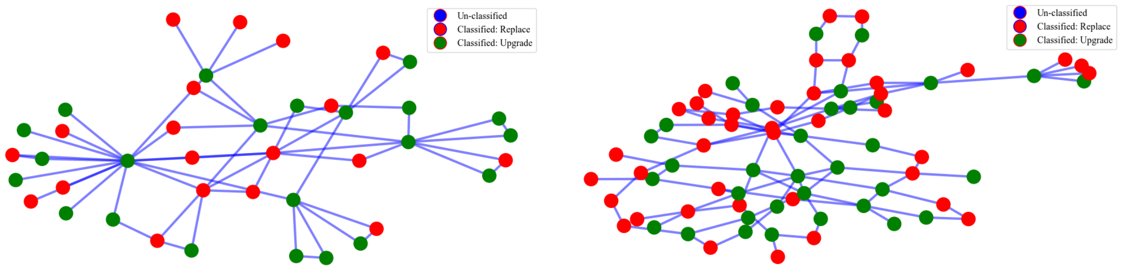
	Linear regression	Fine tree	SVM optimizable	Linear SVM	Ensemble tree (Boosted)	Ensemble tree (Optimizable)	ANFIS
RMSE	0.22953	0.05244	0.27915	0.26639	0.06098	0.00081	0.0000203
R^2	0.44000	0.97000	0.17000	0.24000	0.96000	1.00000	0.9999999
MAE	0.18071	0.00364	0.26297	0.15123	0.01270	0.00026	0.0000044
Trainin time (sec)	1.73070	1.59820	436.210	1.66740	2.37680	72.63100	>600

5.2.2 Model implementations

The trained model was applied with two standard IP network topologies - UNINET and CERNET. The networks were simulated using python NetworkX module. Router details were extracted using SNMP agent and mapped with the information obtained in the KB system to generate input dataset of IP routers to fetch into the developed ANFIS model for their classification.

The plots of classified IP routers are shown in Figure 5.6. Nodes with red color are supposed to be replaced, while nodes with green color legend are classified to be upgraded. Nodes with blue color legend are left unclassified. with this implementations, the ANFIS model is able to classify all the routers in the topology. For the phase wise migration planning considering shortest path and customer priority [8], the status of routers in the optimal path can be identified with this model. Then, ISPs can plan for necessary resources like budget, human resource etc. for the migration.

Figures 5.6a,b indicate that there are number of routers classified into upgrades and replacement. Following the incremental deployment approach based on optimal path and customer priority, proposed ANFIS model is introduced to detect the device migration status instead of random assignment via simulation in author's previous work [8] to achieve more realistic results.



(a) CERNET network (b) UNINET network

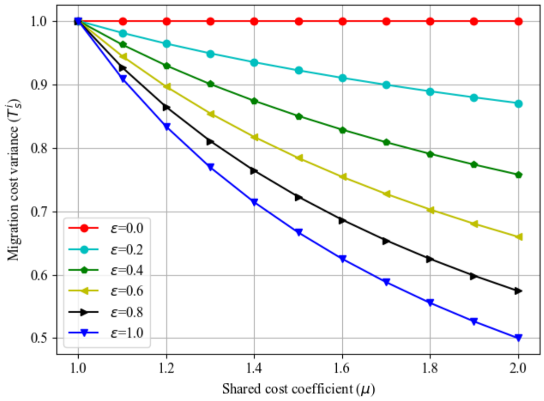
Figure 5.6: Classification results of IP routers by the proposed ANFIS model for migration

5.3 Migration modeling and cost optimization

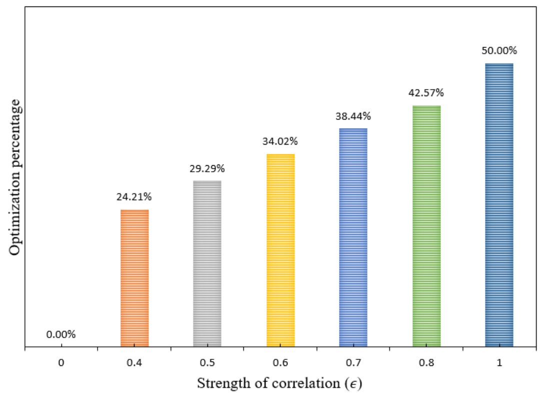
Experimental analysis for migration modeling and cost optimization is based on the concepts formulated in section 3.6 with assumptions for simulation presented on Table 4.2 and Algorithm 3.2.

The algorithm was implemented with three network topology models (Abilene, BTAsiapac, and Xeex). A cost profile was generated with respect to varying shared cost coefficient (μ) and the strength of correlation (ϵ). The choice of two variables (μ and ϵ) for migration cost optimization with different combinations of their values are depicted in Table 3.4. Figure 5.7a presents the cost profile varying μ from 1 to 2 and ϵ from 0.0 to 1.0. μ at 1 indicates a single technology migration, at which strength of correlation has no meaning. For two technologies viz. SDN and IPv6, μ is 2, at which setting the correlation strength (ϵ) value from 0.4 to 0.7 and ϵ greater than 0.6 gives the more realistic estimations in reality. Since, SDN and IPv6 are not fully coupled technologies. Hence, Figure 5.7d presents migration cost optimization of 21.59% at μ=1.5 and ϵ=0.6. Similarly, Figure 5.7c shows the graphs at μ=1.8 with cost optimization of about 29.72% at ϵ=0.6 and 34% cost optimization at μ= 2 and ϵ=0.6 as shown in Figure 5.7b . In reality, total migration cost optimization of about 24.21% to 38.44% could be achieved, while considering ϵ value from 0.4 to 0.7 and μ at 2.

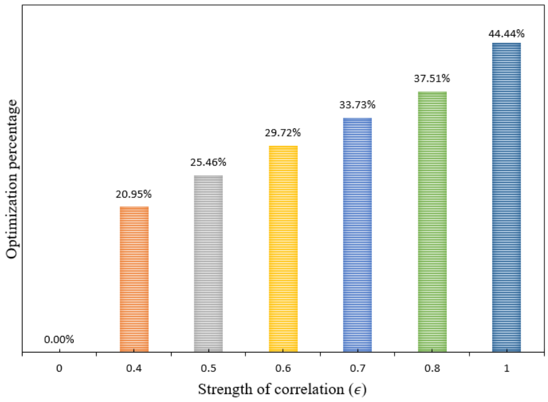
While implementing the Algorithm 3.2 with different types of standard network topologies, the graph of Figure 5.8a shows that 8 nodes in random network were migrated in 3 phases, in which 3 routers were identified to be migrated in the first phase shortest path. Similarly, the routers once migrated, consequently list of other routers to be migrated in the second and third phases were identified. Similarly, Figures 5.9a, 5.10a, 5.11a, and 5.12a show the number of routers to be migrated



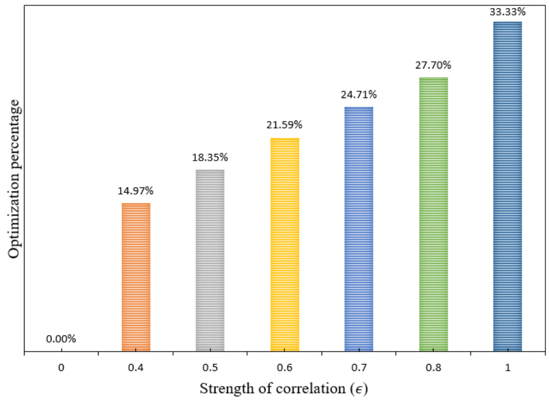
(a) Migration cost profiles with respect to μ and ϵ



(b) Percentage of total joint migration cost optimization at $\mu = 2$ (SDN + IPv6)



(c) Percentage of total joint migration cost optimization at $\mu = 1.8$



(d) Percentage of total joint migration cost optimization at $\mu = 1.5$

Figure 5.7: Migration cost variances with different values of ϵ and percentage of migration cost optimized at $\mu = [2,1.8,1.5]$

in the set of corresponding phases and its shortest path, while Figures 5.8b, 5.9b, 5.10b, 5.11b, and 5.12b show the distributions of budget required to migrate those routers with percentage of total cost expected to be optimized, while following joint migration. It also shows that the migration cost per phase migration are generally found to be decreasing. This creates the favorable situation for ISPs according to budget constraints in the migration planning.

The simulations considered 11 nodes in Abilene, 24 nodes in XeeX, 20 nodes in BtAsiapac, and 34 nodes in GEANT2009 networks set to be migrated at 4, 13, 14, and 12 phases respectively. The number of routers to be migrated in a phase depends upon the choice of ISP gateway router. Similarly, the number of phases identified were based on the customer numbers with their priorities. Changing the gateway changes the shortest path from customer endpoint router to the gateway. Hence, it directly affects the number of phases, at which the network is to be migrated.

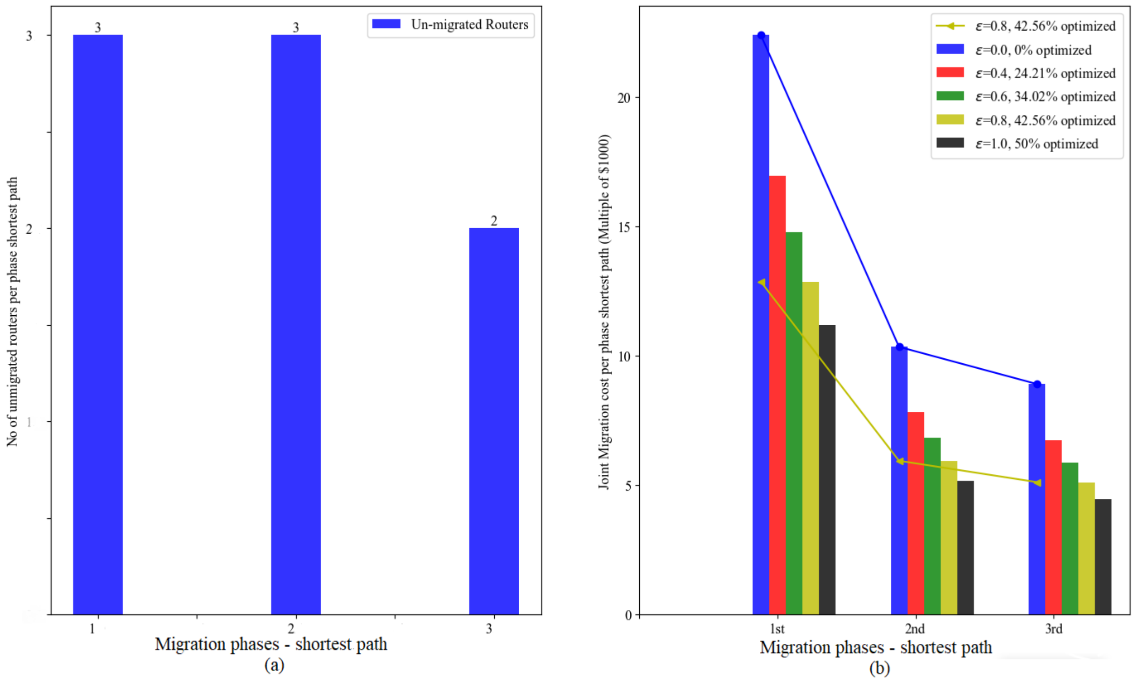


Figure 5.8: Number of routers identified to be migrated per phase shortest path – (a), and optimum cost of migration per phase shortest path – (b) for Random Network (8 nodes)

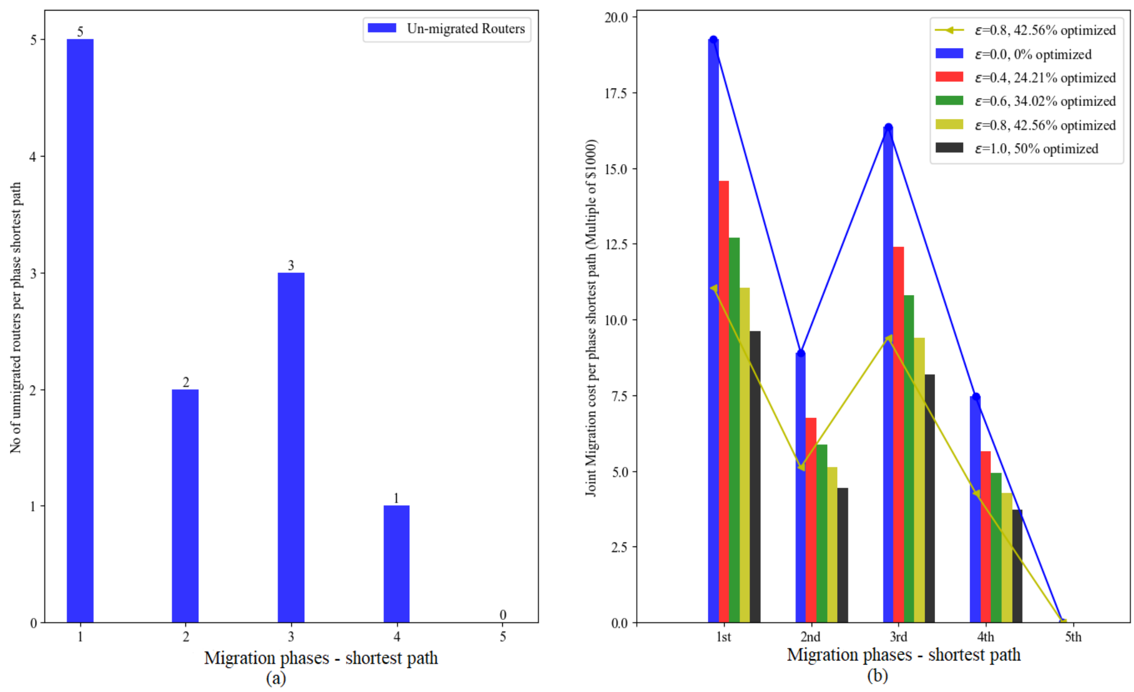


Figure 5.9: Number of routers identified to be migrated per phase shortest path – (a), and optimum cost of migration per phase shortest path – (b) for Abilene Network (11 nodes)

The gateway routers assumed were: 'Chicago' 'Chicago', 'Singapore', and 'DE' for Abilene, Xeex, BtAsiapac, and GEANT2009 network respectively.

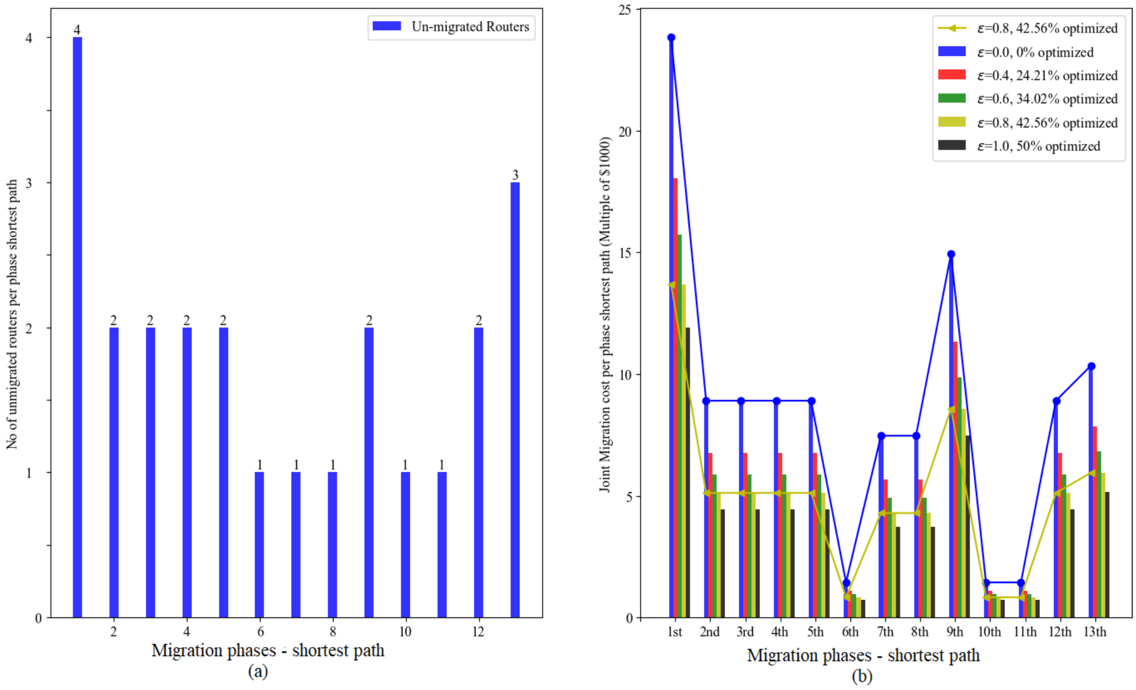


Figure 5.10: No. of routers identified to be migrated per phase shortest path – (a), and optimum cost of migration per phase shortest path – (b) for XeeX Network (24 nodes)

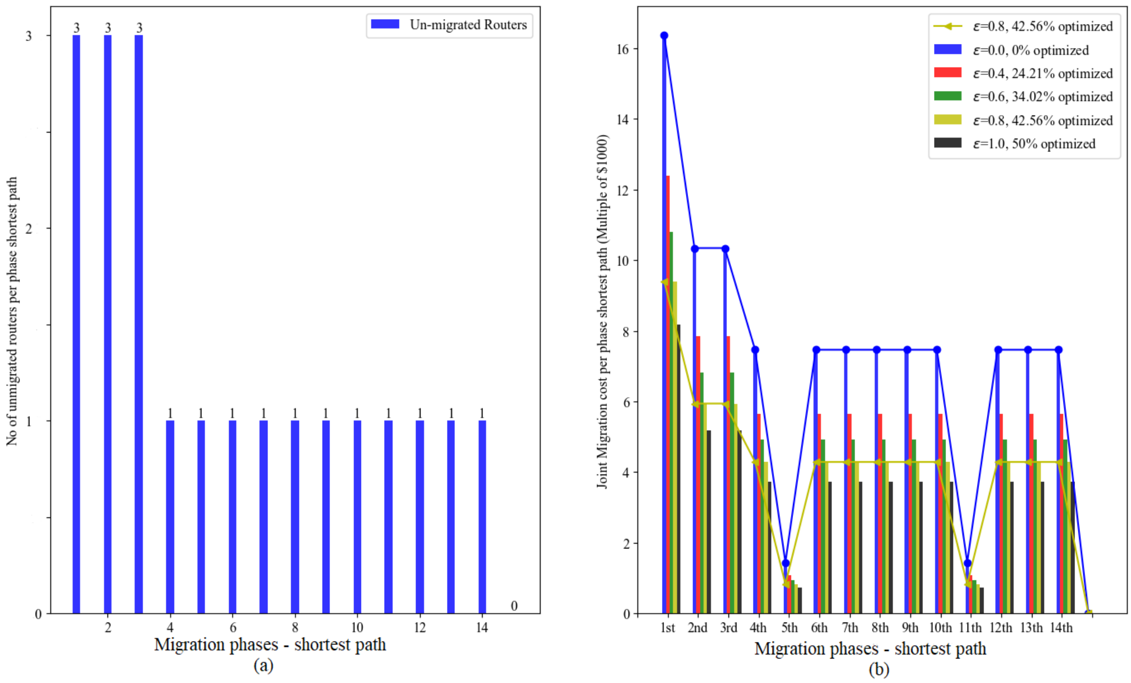


Figure 5.11: No. of routers identified to be migrated per phase shortest path – (a), and optimum cost of migration per phase shortest path – (b) for BtAisapac Network (20 nodes)

Because of random assignment in the simulations, some routers were set as upgradable, while some were set as replaceable. Hence, cost of migration in the initial phases might be high because of higher number of routers could be identified for migration. On the other hand, the migration cost optimization graphs (Figures 5.8b, 5.9b, 5.10b, 5.11b, and 5.12b) show that each phase migration budget might be different, even if the number of routers to be migrated are same. For example, in Figure 5.10a, the number of migrant routers in 9th and 12th phase shortest paths are same, but Figure 5.10b shows that 12th phase migration incurs lower cost as compared to 9th phase migration cost against same number of routers are migrated. This indicates that routers in the 12th phase migration were identified as upgradable. Similarly, in Figure 5.11, 5th and 11th phase routers were identified as upgradable so that the cost of migration in the graph (Figure 5.11b) is seen less as compared to other routers in the subsequent migration phases.

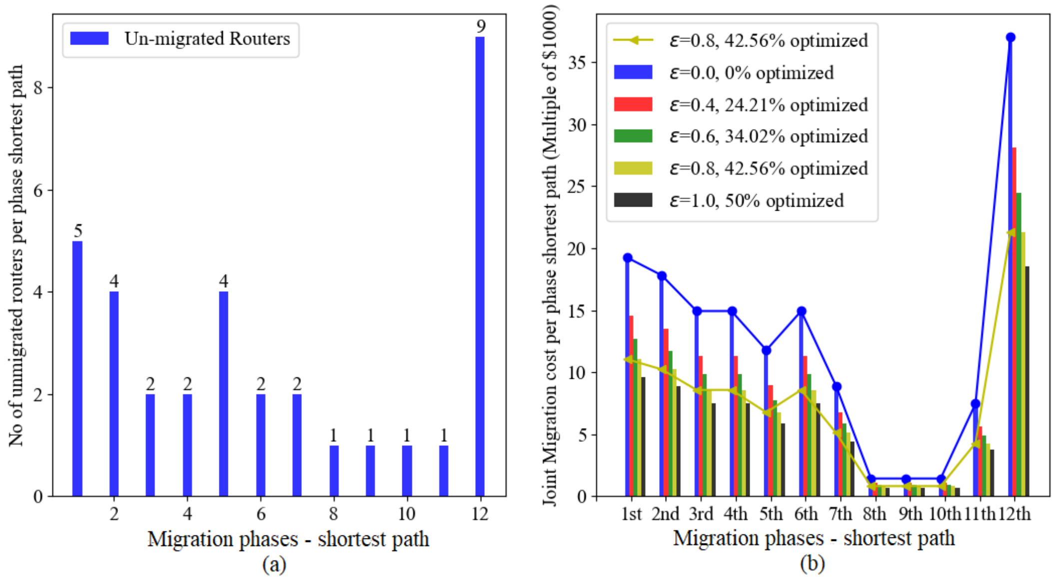


Figure 5.12: No. of routers identified to be migrated per phase shortest path – (a) and optimum cost of migration per phase shortest path – (b) for GEANT2009 Network (34 nodes)

Presented approach of migration planning helps service providers to properly maintain the budget and technical HRs required for routers migration. Similarly, routers in the shortest path of highest priority customers could be migrated first so that legacy and SoDIP6 traffic can be maintained well in the network.

5.4 Multi-ISP Networks Migration: Evolutionary Gaming Approach

An approach for migration modeling of a single ISP network was analyzed in section 5.3. This section considers analyzing a nation-wide interconnected ISP networks and their migration into SoDIP6 networks. Migration of an ISP network affects the other interconnected networks from both business and technical perspectives. An ISP can't independently decide for migration, because of its agreement with other ISPs dealing about the traffic exchange and technology use, where the protocols and standards should be inter-operable to achieve the communications. Considering the use case model presented with the economic model in Figures 3.3 and 3.7, a scenario for multiple interconnected ISP network migration was modeled as an evolutionary process with concept formulated in section 3.7.

At the beginning, legacy IPv4 (i.e. Group-1) ISP(s) were randomly selected for migration. However, in the subsequent next timestamp of the game play, ISP(s) with higher σ_{4t} would be selected for migration. It is considered that an ISP, when migrated to Group-2 would never migrate back to Group-1. Hence, at every timestamp, only Group-1 ISP would be chosen to evaluate the strength of migration. The sub-adaptation parameters and their effects in migration decision making are individually visualized in Figures 5.13, 5.14, and 5.15 respectively. Figure 5.13a shows the plot of adaptation strengths based on number of customers demanding the services, Figure 5.14b presents the strength based on IPv4/IPv6 traffic entering the network, and Figure 5.15c presents the strength with respect to available HRs, migration cost, and the organization budget. A detailed explanation with interpretation for 1^{st} round of simulations is provided. The visualizations of subsequent round of simulations simply depicted the measures of sub-adaptation parameters with different random value setting according to interpretations.

The interpretations of simulation parameter setting and their results in the visualizations are briefly discussed here. For example, σ_c at (2%↑, -4%↓) means the customer demand of SoDIP6 based services is increased by 2% and total customer number is decreased by 4%. This indicates that ISP is losing its customers, while demand of new technology services is increasing. The resulting graph of Figure 5.13a depicts higher alarm to ISP indicating migration decision to be taken in the earliest. Similarly, σ_p at (4%↑, -1%↓) means that incoming IPv6 traffic to an ISP is increased by 4%, while incoming IPv4 traffic is decreased by 1%. This indicates that interconnecting ISPs are migrating to SoDIP6 network leading to higher IPv6 traffic and lower IPv4 traffic reported in the interconnection point. This increase the cost of ISP to install translator device in the border. The ultimate choice for an ISP is either migrate to SoDIP6 network or use translator for IPv4 to IPv6 traffic and vice versa. This affects the internal operation of ISP and services to be provided to its customers.

Considering a scenario of Figure 3.3, each ISP has mesh interconnection with other 15 ISPs. The strength of that migration is plotted over 24 time steps as shown in Figure 5.13b, 5.14b, and 5.15b respectively. For an ISP migration ratio of 2/3 (i.e. =16/24, 16 ISPs in Group-1 are supposed to be transformed to Group-2 ISPs over 24 time steps), and also expected that higher budget accumulates annually for an ISP and the migration cost will increase with the delay in migration decision making. Hence, Figure 5.13c, 5.14c, and 5.15c show the plots on changing budget and also changing migration cost, while SoDIP6 network operation capable HRs are increased by 4.16% (1/24) of the existing capable HRs. σ_s at (2%↑, 4%↑) indicates that organizational budget is increased by 2% and migration cost is increased by 4%. This means, inflation is higher, so that expenditure would be higher than the income. This also creates alarming situation to ISPs to take early decision for migration. The 2nd and 3rd round of simulations present more analytical results with random values. Plots (a) and (b) of Figures 5.16, 5.17, and 5.18 show the overall strength of adaptation variable (σ_{4t}) results of sum of all three sub-adaptation variable values at different combinations of their values plotted in Figure 5.13, 5.14, and 5.15 respectively. Similarly, Figures 5.19, 5.20, and 5.21 show sensitivity results of the cumulative plots keeping the sub-adaptation variable constant at a time during multiple round of simulations.

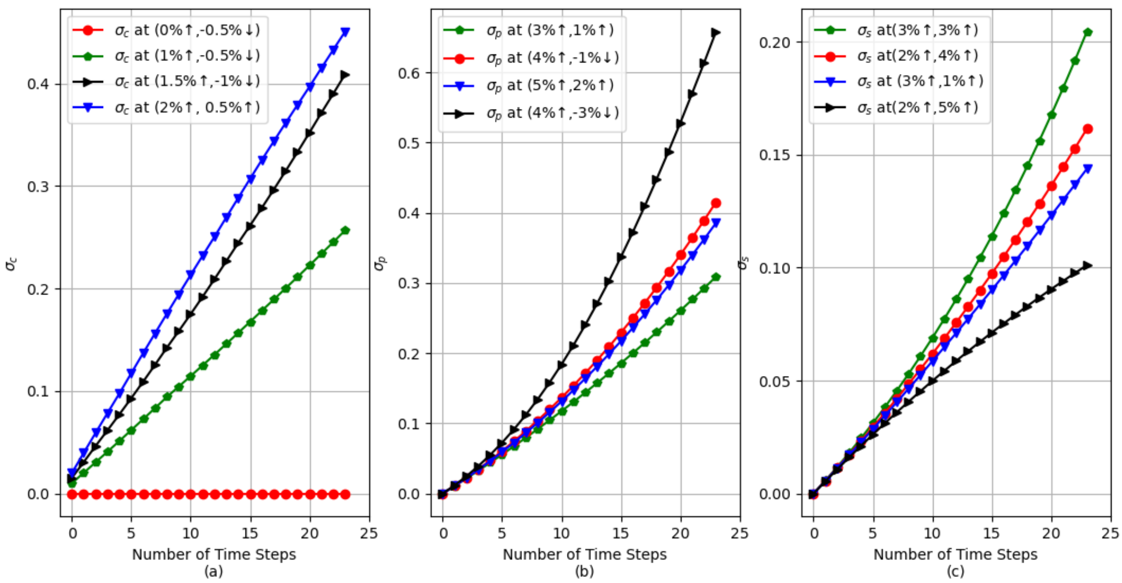


Figure 5.13: First round plot of sub-adaptation parameters $\sigma_c, \sigma_p,$ and σ_s

The plot of adaptation variable (σ_{4t}) at σ_c (2%↑, -4%↓), σ_p at (4%↑, -1%↓), σ_s (2%↑, 5%↑)] presented in Figure 5.16a indicates the most likely scenario to take decision for migration, because the customer demand of SoDIP6 services has been increased by 3% and total customer number has been decreased by 1%, while IPv6 incoming

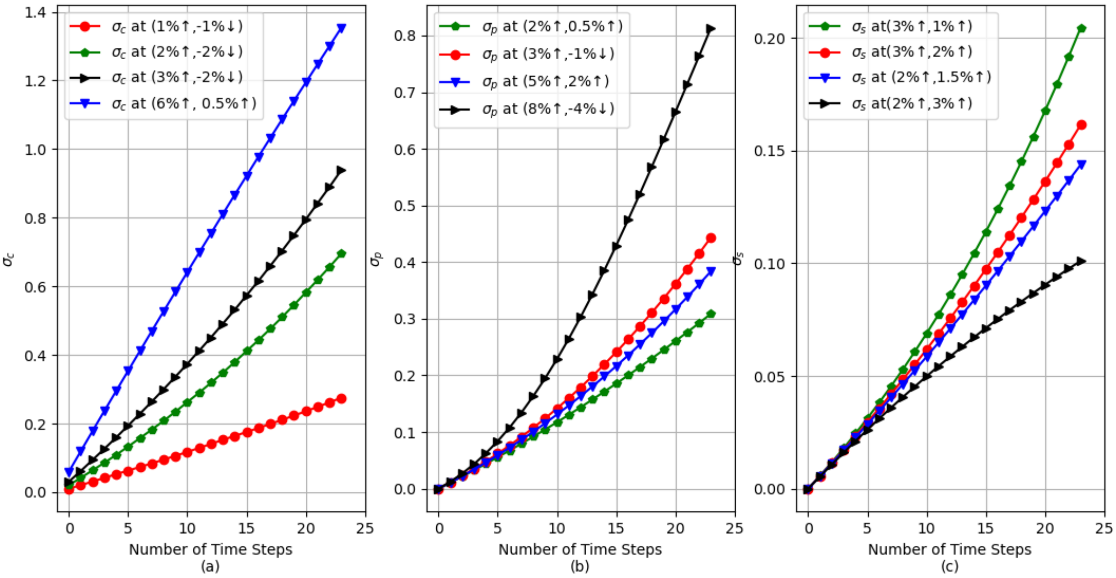


Figure 5.14: Second round plot of sub-adaptation parameters σ_c, σ_p, and σ_s

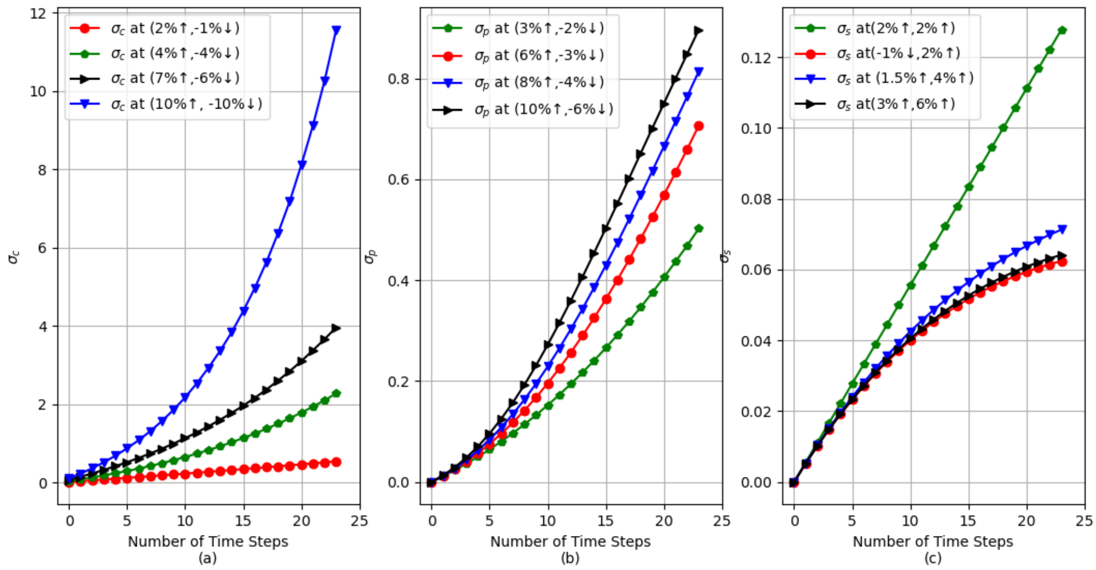


Figure 5.15: Third round plot of sub-adaptation parameters σ_c, σ_p, and σ_s

traffic has been increased by 4% and IPv4 incoming traffic has been decreased by 1%. Similarly, organizational budget has been increased by 2% and cost of migration has been increased by 5%.

The measurement of adaptation variable (σ_{4t}) on every time step, when recorded increasing value leads to migration decision making, while the strength of migration (δ) normalizes the value of adaptation variable between 0 to 1. The choice of suitable value for migration constant (η) increase confidence level to the decision maker to take migration decision. Hence, Figure 5.22 shows that at η and δ both values above

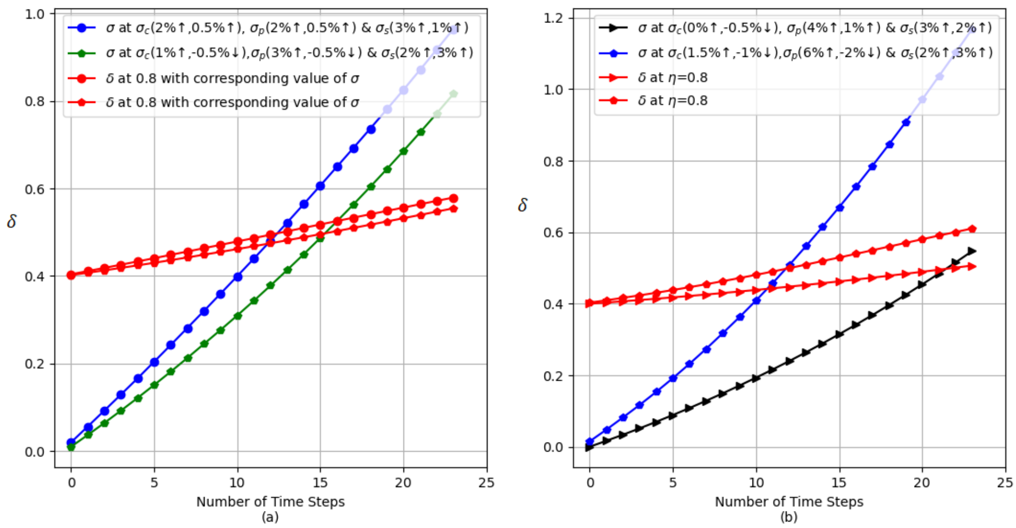


Figure 5.16: First round plot of $\sigma_{4t}(\sigma)$ at different combinations of σ_c, σ_p, and σ_s

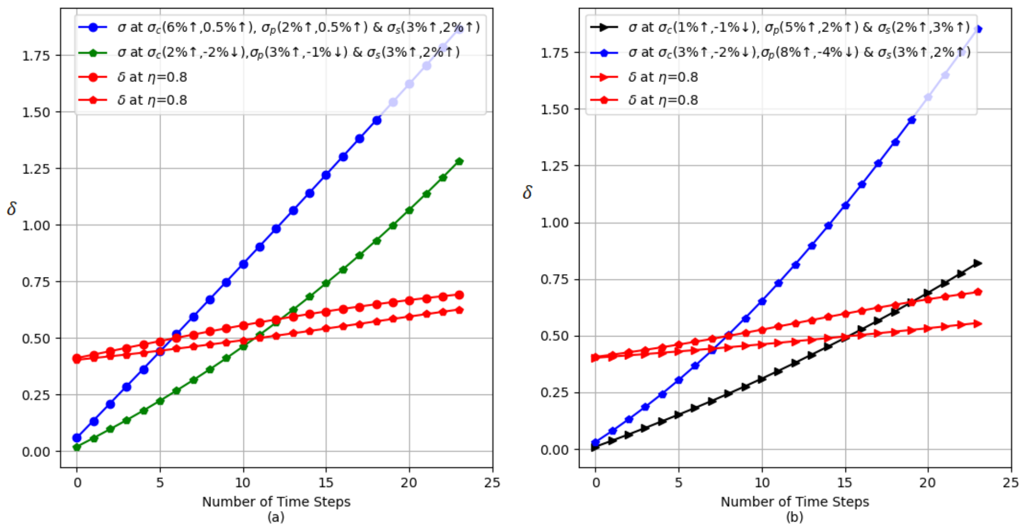


Figure 5.17: Second round plot of σ_{4t} (σ) at different combinations of σ_c, σ_p, and σ_s

0.6 give the better result for an ISP to make a migration decision.

Figure 5.23 shows the numerical results of evolutionary process starting with twelve ISPs in Group-1 and four ISPs in Group-2 at (a), eight ISPs in Group-1 and eight ISPs in Group-2 at (b), four ISPs in Group-1 and twelve ISPs in Group-2 at (c), and no ISPs in Group-1 and all 16 ISPs in Group-2 at (d). The simulations were carried out considering migration of single ISP at a time. When all Group-1 ISPs have migrated to SoDIP6 networks i.e. to Group-2, then utility for Group-1 would be zero, at which all Group-2 ISPs are SoDIP6 capable with higher utilities as shown in Figure 5.23d.

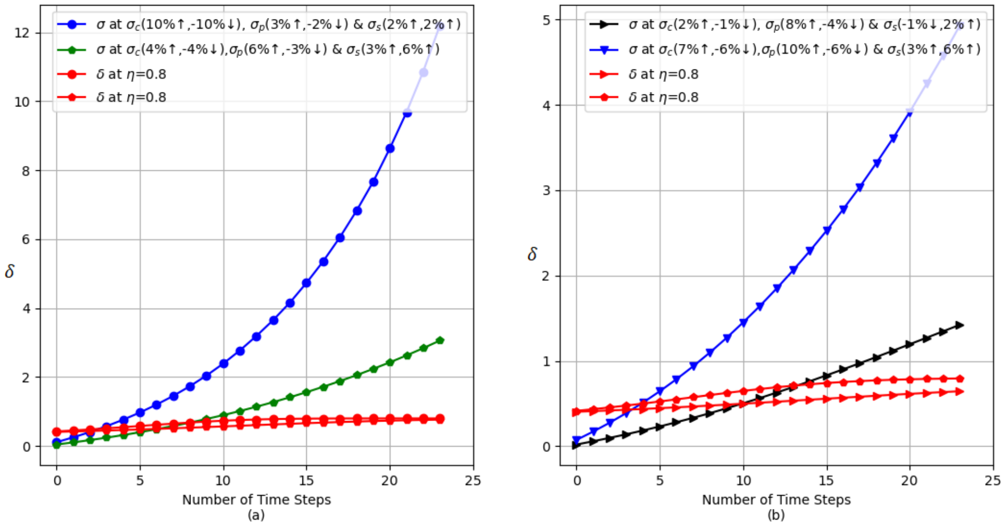


Figure 5.18: Third round plot of $\sigma_{4t}(\sigma)$ at different combinations of σ_c, σ_p, and σ_s

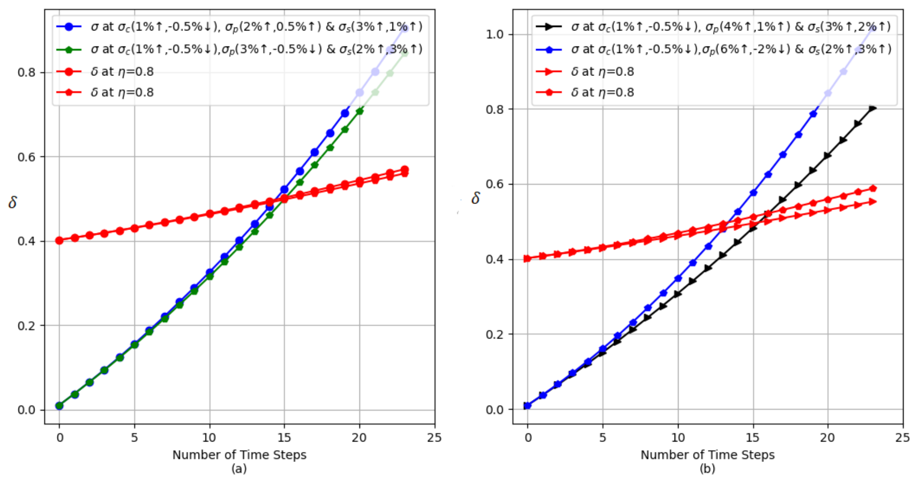


Figure 5.19: Fourth round plot (Sensitivity) of $\sigma_{4t}(\sigma)$ at different combinations of σ_c (rate constant), σ_p, and σ_s

5.5 SoDIP6 Network Migration Implementation with Controller Placement

ONOS/SDN-IP implementation was evaluated by considering a multi-domain SoDIP6 networks and its real life implementation verification for ISP/Telcos networks. At first, routing performance of legacy routing and SDN routing has been evaluated through an experiment by integrating legacy IPv4 network and the SDN. This experimental evaluation established that routing using SDN-IP has better performance than legacy IPv4 routing [200]. Next, the use case scenario to implement multi-domain SoDIP6 network is shown in Figure 5.24. It was assumed that an ISP

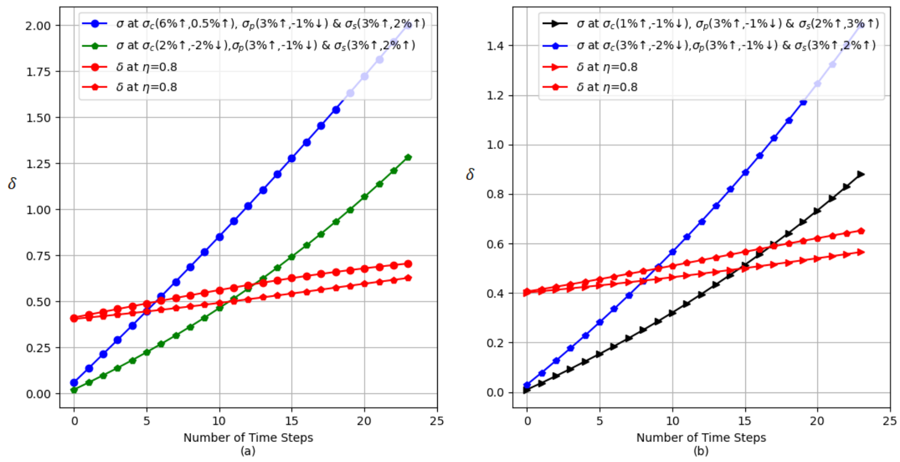


Figure 5.20: Fifth round plot (Sensitivity) of $\sigma_{4t}(\sigma)$ at different combinations of σ_c, σ_p (rate constant), and σ_s

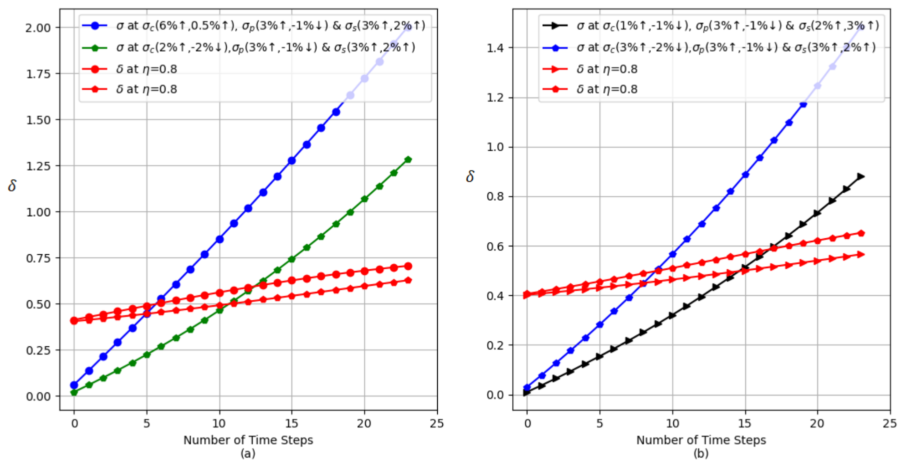


Figure 5.21: Sixth round plot (Sensitivity) of $\sigma_{4t}(\sigma)$ at different combinations of σ_c, σ_p, and σ_s (rate constant)

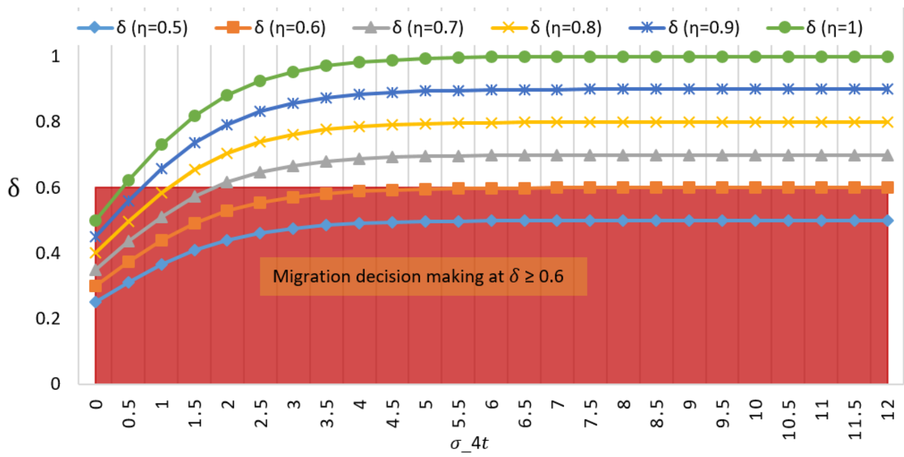


Figure 5.22: Plot of migration strength (δ or δ_{4t}) with increasing adaptation strength (σ_{4t})

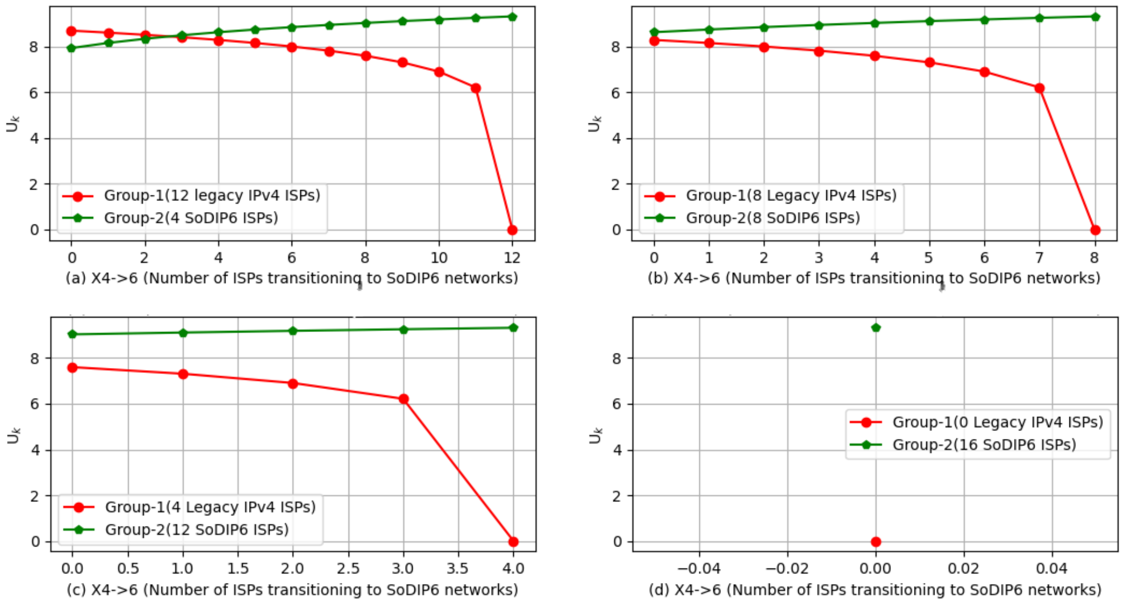


Figure 5.23: Group utility vs. ISPs migrating to SoDIP6 network

consists of multiple ASes running legacy IPv4 and SoDIP6 networks both, while the transit AS (AS0) is to be migrated to SoDIP6 network with proper placement of controller based on OCPL. Switch 'S5' is identified as median router to attach BGP speaker. IPv6 address for a machine was generated using mapping of corresponding IPv4 address. For the six SDN switches in the transit AS, a single instance of SDN-IP in the controller and BGP speaker was implemented. All the gateway routers established iBGP peering session with BGP speaker attached with the controller. The connectivity among the ASes and hosts within the ASes were successfully implemented. Similarly, reactive routing features enabled in the SDN-IP allows for the communication among hosts from transit AS to external AS. The successful implementation of this SoDIP6 network with the legacy network integration shows that bigger enterprise like ISP's and Telcos networks can smoothly be transitioned into operable SoDIP6 networks. The implementation of SoDIP6 network with ONOS/SDN-IP including experimental work snapshots are provided in Appendix C.

The concepts of Section 3.6 and related analysis on Section 5.3 is expanded towards controller placement during migration in addition with migration cost optimization, which is another important problem to be addressed in SDN migration. Algorithm 3.2 presents the joint migration with budget constraints to migrate the routers in the optimal path in a sequential manner from source to destination. This work analyzes the router replacement plan using breadth first traversal approach. BFR optimizes the controller placement with MCPL in the network during migration.

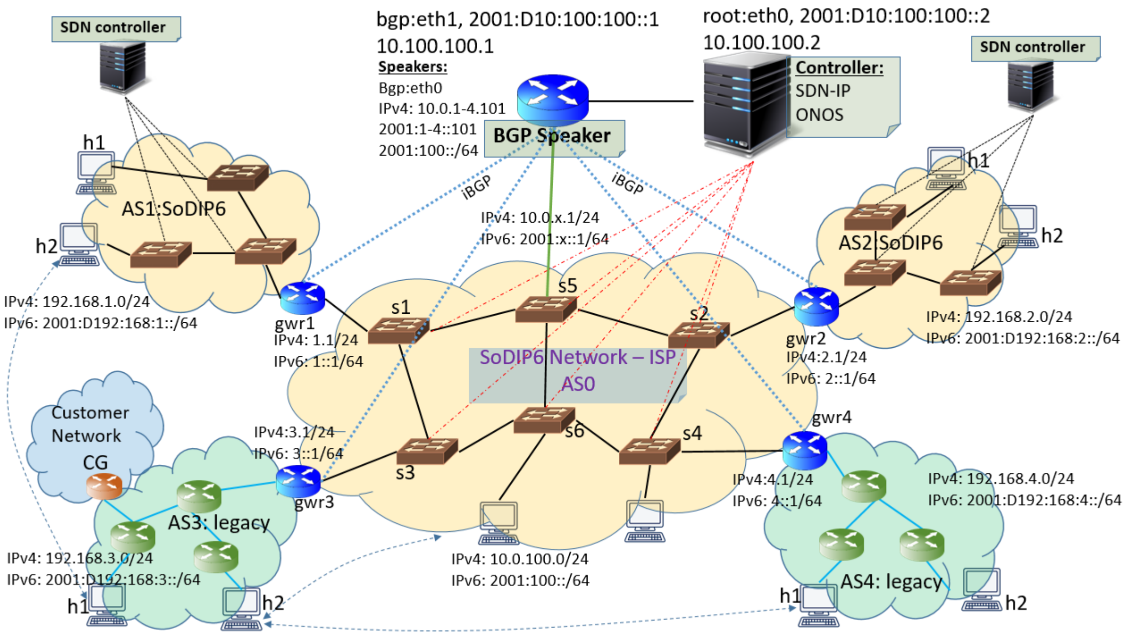


Figure 5.24: Implemented multi-domain SoDIP6 network environment

The proposed approach was implemented with Random and Abilene networks presented in Figure 5.25. For both networks, 'gwr4' was considered as the foreign gateway, while other gateways (gwr1-3) were considered as the AS gateways attached to the customer endpoint router, termed as CG. Simulation was run in two phases, (a) sequential replacement of routers form CG to FG with different RSS set in the LSSP, and (b) BFT to replace routers called BFR with different RSS set in the LSSP. CG and FG routers were added after importing the network for simulations. Controller placement is defined based on the control path traffic latency by the switches and the BGP-peers formed during migration. The green nodes in the figures were already migrated, while red nodes are the gateway routers acted as iBGP peers with ONOS-BGP speaker after migration. In Figure 5.25a, the routers in the LSSP is identified as [S1, S5, S6, S4]. Similarly, in Figure 5.25b, the LSSP routers are Chicago, Indianapolis, Kansas City, Denver, and Seattle. Hence, the network was simulated by setting those shortest path routers as RSS and evaluated the switch/gateway latency to properly locate the controller.

The latency graphs depicted in Figure 5.26a,b show the latency status of the switches and the iBGP-peers in random network without applying BFR technique. Routers were migrated in a sequence ordering the shortest paths from highest to lowest number of routers. Both graphs of Figure 5.26 show that the controller connected to either S5 or S6 gives the MCPL. During the switch migration, iBGP-peers would automatically appears and disappears. After the complete migration of transit routers,

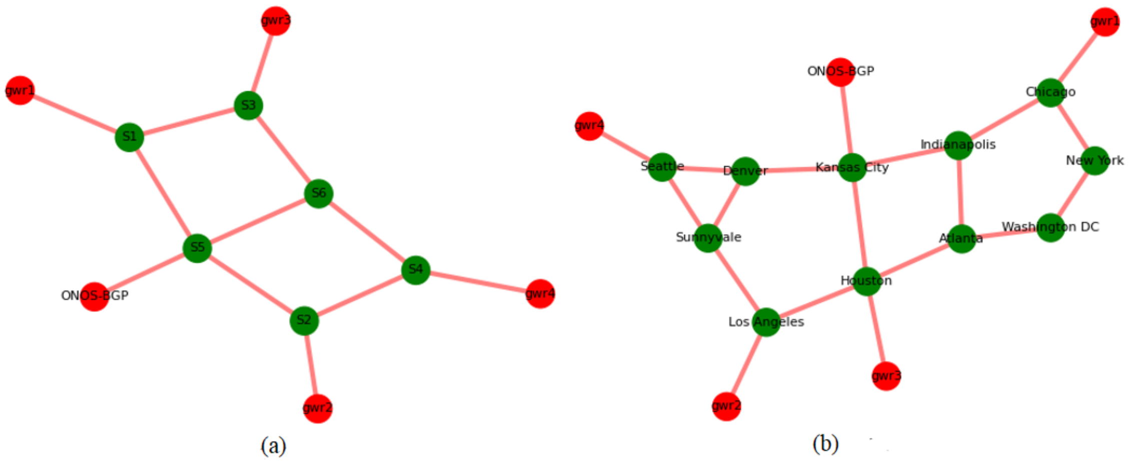


Figure 5.25: Network graphs generated after migration, (a) Random network, and (b) Abilene Network

only AS gateways acted as iBGP-peers. This can be seen from the control path latencies by gateway routers, in which latencies were increasing, reached to a peak value at a moment, and down to zero after complete migration. The control traffic due to AS gateways during migration is avoided. It is supposed that AS gateways are fixed and they generate regular iBGP peering traffic after complete migration of all routers in the transit AS.

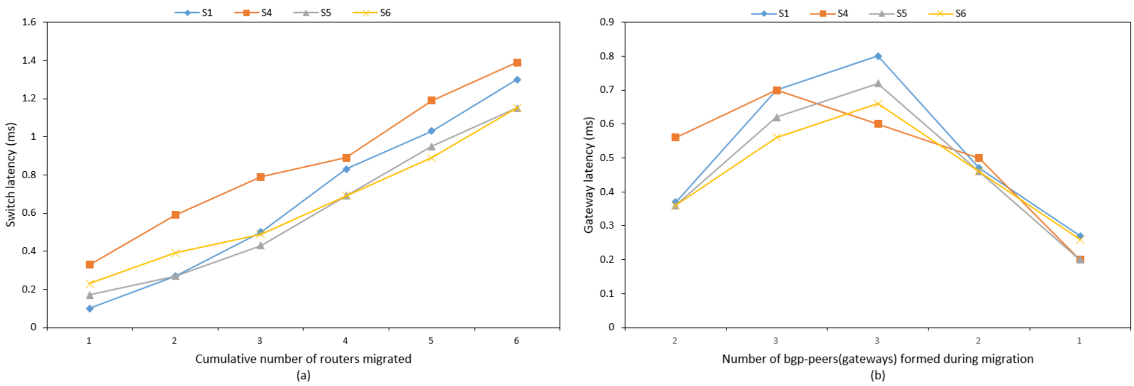


Figure 5.26: Control path latency without BFR in Random network, while setting S1, S4, S5, and S6 as RSS. Control path latency by (a) switch, (b) iBGP-peers formed during migration

The latencies by the switches and the gateways after applying BFR approach is shown in Figure 5.27. From Figure 5.27a, based on switch latency traffic, attaching controller with 'S6' gives minimum latency, while gateway latency shows that setting 'S5' as RSS gives slightly better result. Number of iBGP peers changes dynamically during the routers migration. Hence, minimum latency generated is considered by the switches to take decision for controller placement.

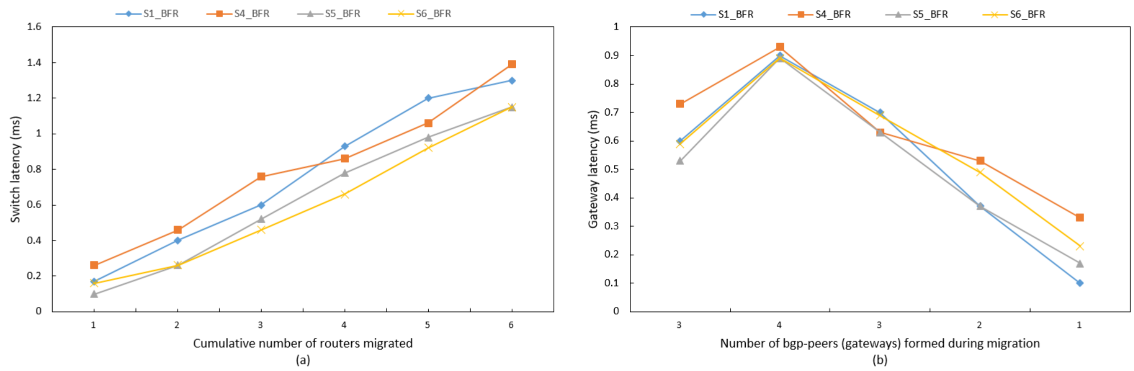


Figure 5.27: Control path latency with BFR in Random network, while setting S1, S4, S5, and S6 as RSS. Control path latency by (a) switch, (b) iBGP-peers formed during migration

The plot of Figure 5.28 shows that applying BFR technique gives better result than sequential replacement to attach the controller with 'S6'.

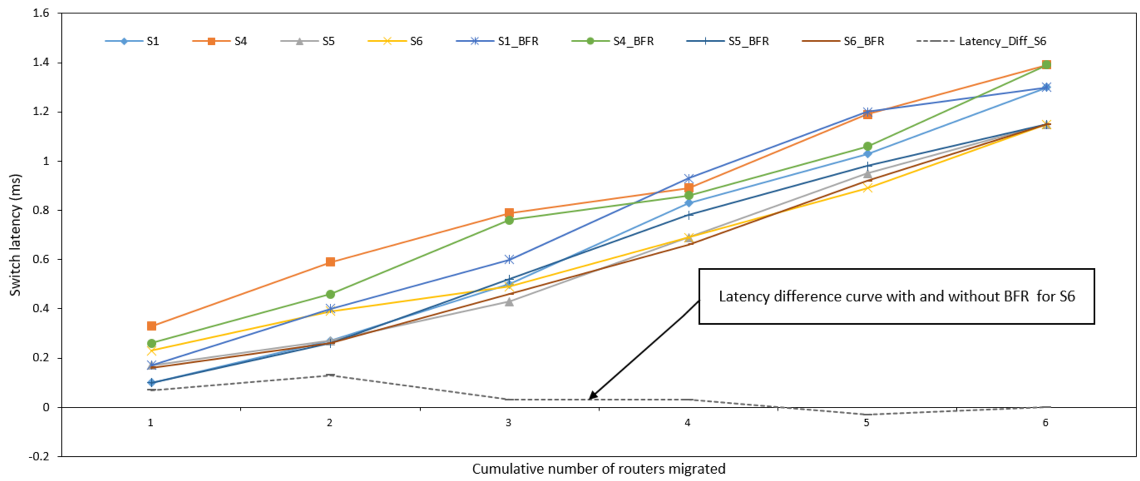


Figure 5.28: Switch latency with and without applying BFR in Random network during migration for controller placement

Another simulation was run with standard Abilene network depicted in Figure 5.29. 'gwr4' is considered as the foreign gateway connected via 'Seattle'. The LSSP is found from gwr1 to gwr4 via [Chicago, Indianapolis, Kansas City, Denver, and Seattle]. Figure 5.29a,b show the graphs of control path latencies by SDN switches and the gateways without using BFR, while Figure 5.30a,b show the same after using BFR. The latency plots in both figures indicate that attaching controller with median router 'Kansas City' gives the best result.

Choosing optimal path for routers replacement sometimes left the stub or backup link routers unmigrated. Those routers left unmigrated are set into migration in the final stage. For example, in Figure 5.31, there were 7 routers identified in

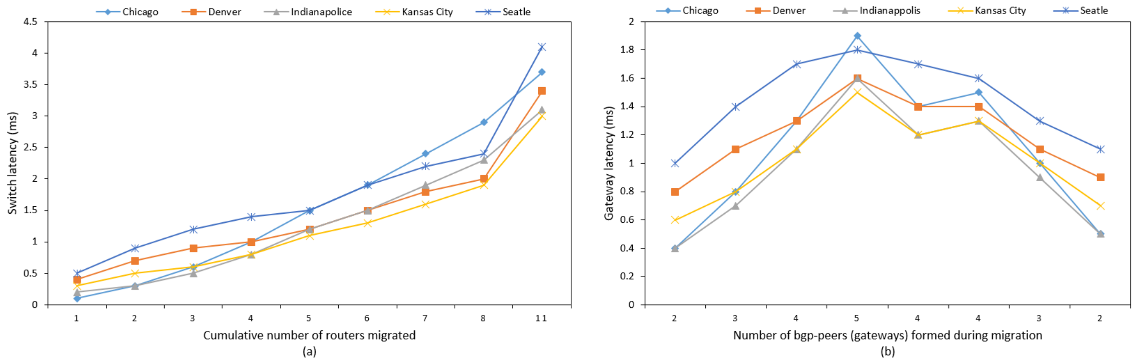


Figure 5.29: Control path latency without BFR in Abilene network, while setting Chicago, Denver, Indianapolis, Kansas City, and Seattle as RSS. Control path latency by (a) switch, (b) iBGP-peers formed during migration

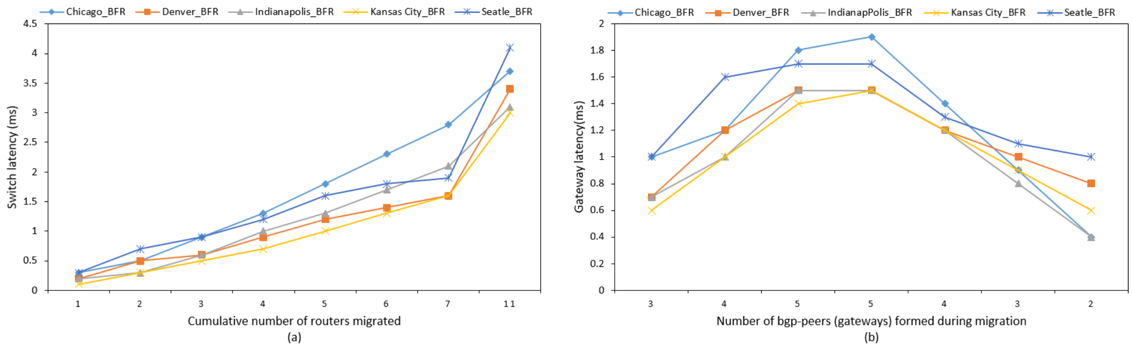


Figure 5.30: Control path latency with BFR in Abilene Network, while setting Chicago, Denver, Indianapolis, Kansas City, and Seattle as RSS. Control path latency by (a) switch, (b) iBGP-peers formed during migration

the shortest path and 4 routers left unmigrated. Hence, these four routers were migrated in the final stage getting the cumulative routers migrated were 11. Figure 5.31 presents the comparative chart of latency plot with and without using BFR in routers migration of Abilene network. The positive value of latency difference curve shows that implementation of BFR approach gives the better result to attach controller with 'Kansas City'.

Once the location of master controller is identified, while in the network migration, overloading of master controller due to increase of SDN switches in the network can be continuously monitored. Figure 5.32 presents the traffic load on master controllers. Taking the reference from Das et al. (2018) [95], The number of OpenFlow requests (γ) was assumed in the range of 0.05-0.105 millions per second by an SDN switch, number of requests handling capacity of controller (σ) as 1.1 millions requests per second, and 0.01 - 0.02 millions iBGP peering session requests per second by iBGP (gateway) routers formed during migration. Figure 5.32a,b,c,d show the number of requests made by the switches and the iBGP-peers (gateways) formed

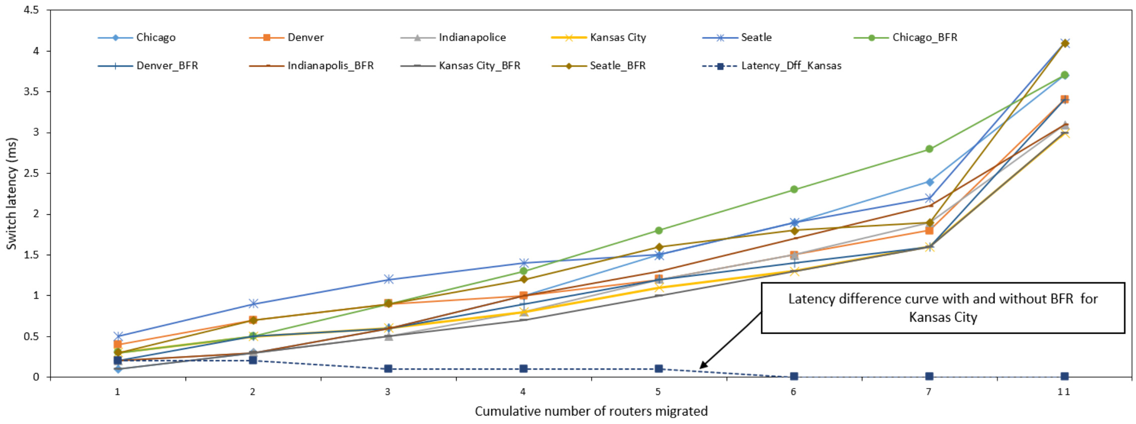


Figure 5.31: Switch latency with and without applying BFR in Abilene network during migration for controller placement

during migration in Random, Abilene, XeeX, and GEANT2009 networks respectively. Horizontal axis of Figure 5.32 shows the sum of number of switches migrated and iBGP gateways formed during migration.

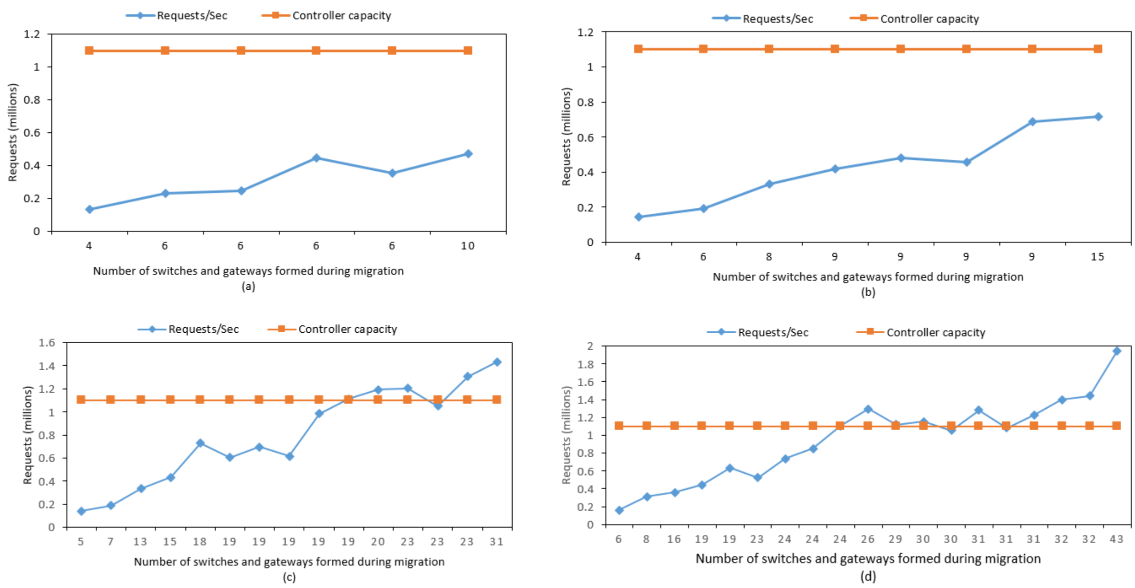


Figure 5.32: Number of requests to controller by switches and gateways made during migration with BFR in (a) Random, (b) Abilene, (c) Xeex, and (d) GEANT2009 networks

Switches were set for incremental migration by one, while number of gateways formed during migration were increased or decreased based on the switch migration. Hence, in some steps of migration, it is seen the same number of nodes migrated due to dynamically changing iBPG peers. The simulations were run with other two networks viz. Xeex and GEANT2009 to measure the controller overloading situation during migration. The Random network has 6 switches and 4 gateways. After migration, in total, 10 nodes generate control/iBGP traffic to the controller. Similarly, Abilene network has 11 nodes and 4 gateways and hence, in total, 15 nodes generate control/iBGP traffic to controller at the end of migration. Similarly, the same applies to Xeex and GEANT2009 networks. Decision for addition of new controller was taken only if, the number of requests made by the switches and the gateways exceeds the controller capacity. For example, in Figure 5.32c,d, the number of requests made by the switches and the gateways to controller exceeds the controller capacity after certain number of routers were migrated.

5.6 Energy Efficiency Evaluation of SoDIP6 Network

The different analysis in previous sections evaluated the deployment of SoDIP6 networks in the Telcos/ISPs with smooth transition and proposed approach for cost reduction during migration as a part of organizational OpEX/CapEX optimization. With the increasing size of ICT network, the increasing energy consumption and the associated bill amount is a major concern for service providers. Major expectation of technology migration is its attraction due to energy optimization to optimize organizational OpEX. Considering the service provider's sustainability, certain experimental analysis were performed to evaluate the energy efficiency of SoDIP6 networks and compared it with legacy networks. It was started with a simple network topology by creating SDN enabled IPv6 network environment modeled as shown in Figure 5.33 using Mininet, OpenDaylight controller, NEC's OpenFlow PF5240-ProgrammableFlow Switches, and Kill-a-Watt for this experiment.

IPv6 address prefix of 2001:DB8:1212::/64 was used for this experimental test. SDN has a smart sleeping [193] feature with dynamic adaption, which the legacy network features doesn't have. A linear profile [172] was followed for energy consumption by network equipment according to traffic load applicable to switches and their links. The measurement of energy consumption was carried out by varying number of switches, and the links. Using smart sleeping, the switches were set to sleep mode during the period from 8PM to 6AM, during when all the switches were supposed to be ideal. In the existing legacy IPv4 network, the network switches and the links were active 24hrs with peak energy consumption. Taking the references from CISCO SG-300 series switch, its power consumption ranges from 50Watt to 120Watt. In an average, 80Watt for the switch and 59Watt power consumption by the link were assumed for the experimental analysis. Old systems means the legacy IPv4 network and the proposed system is the SoDIP6 network. Assuming 14hrs (58%) of time the proposed network system is active, for a network, for example, having 700 switches

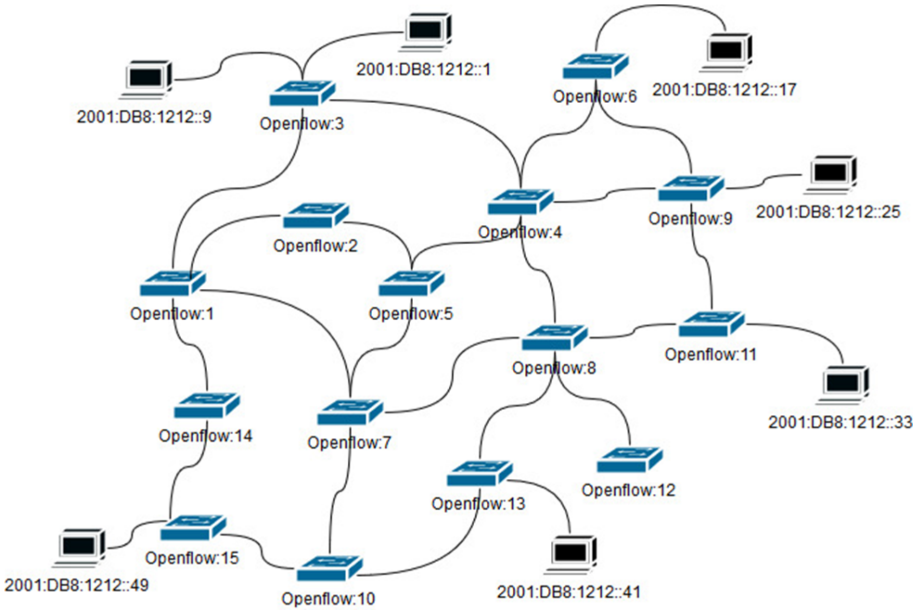


Figure 5.33: Network created in Mininet for energy evaluation.

and 26000 links, the total annual energy saving in SoDIP6 network as compared to legacy IPv4 network is 473.256MWh. It is equivalent to annual OpEx saving of NRs 5,205,816 /- (assuming Rs 11 ≈ 1cent per unit charge of electricity,). This numerical analysis shows that there is significant energy saving with SoDIP6 networks.

5.6.1 End-access SoDIP6 network

Considering the broadband network expansion opportunities of Nepal, an additional experiment was run by referring the end-access ISP network presented as an use-case in Figure 3.12 to recommend SoDIP6 network deployment and its energy efficiency evaluation referring equation 3.32 for the sustainable rural network establishment.

An end-access ISP network is considered consisting of wired and wireless CPEs, switches and their associated links by developing a custom topology using a Mininet-WiFi emulator with an Open Daylight SDN controller over an Ubuntu virtual machine. The SoDIP6 enabled end-access network topology consisted of 14 switches (SDN switch: S0–S5, edge switch: E1–E5 and wireless access points (AP): A1–A3) and 8 CPEs (cpe1–cpe5 and sta1–sta3) including wireless stations. The end-access gateway router is supposed to be a translator router that performed the translation of SoDIP6 traffic to legacy IPv4 and vice-versa. It is also assumed that the ISP backbone network is not SoDIP6 capable. This means it has only legacy IPv4 supports. Hence, end-access gateway can be treated as a customer side translator and the external gateway as a provider side translator. These are translator routers, which perform IPv4 to IPv6 header translations and vice-versa.

The simulation was carried out with assumptions that a switch has 110 Watt power consumption in normal conditions [201] and full load links consumes 40 Watt [175], per port power consumption by switch ports per Mbps is 0.01 Watt [192, 202], and active CPE consumes 7 Watt, while considering the 7hrs (10 pm to 5 am) sleeping habit of rural people, the data plane devices can be entered into sleep mode during idle situations and the corresponding links can be shutdown. Traffic was monitored for 24 hrs and monitored the energy consumption by all switches, while the energy consumption pattern by end-access SoDIP6 network is shown in Figure 5.34.

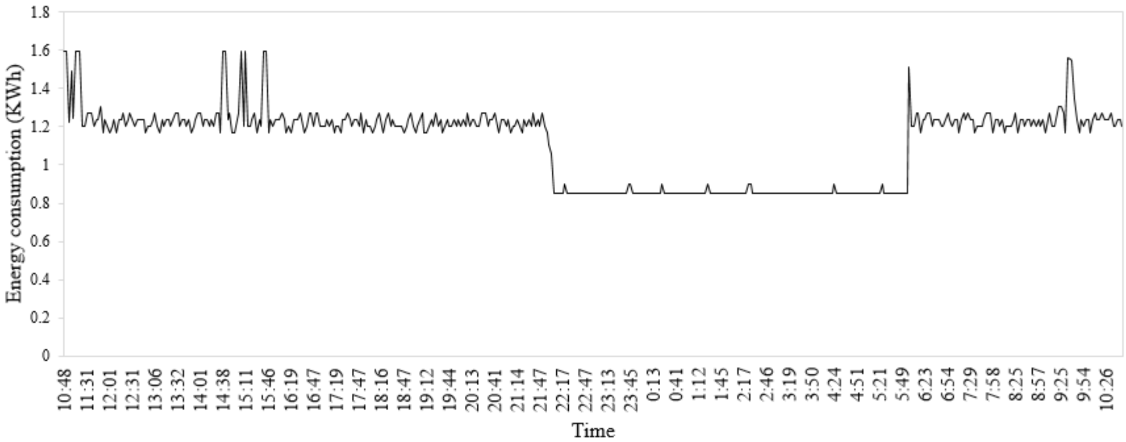


Figure 5.34: Pattern of total energy consumption by SoDIP6 capable switches and CPEs

A comparison of energy consumption by SoDIP6 capable network and legacy network is carried out. Figures 5.35 and 5.36 show the pattern of power consumption by all switches and the links over the period of 24hrs. The outcome of this empirical analysis indicates that switches and access points (APs) frequently entered into sleep mode whenever there is no traffic entering into the device and the links. This lead to the total energy consumption rarely reaching peak value except in some moments that look like spikes in the graphs.

The result is simplified to total annual energy consumption based on the 24 hrs of power utilization pattern by the network nodes and links. An annual energy saving of 31.50% on nodes and 55.44% on links with SoDIP6 network is achieved. Per unit charge of electricity in Nepal is almost equal to one cent. An annual energy bill to be paid by ISPs that have a different number of switches and links in their end-access networks with respect to the legacy IPv4 networks and the SoDIP6 network as per assumptions provided in this experiment was estimated. The comparative chart is shown in Figure 5.37a for the switch and Figure 5.37b for the links. Hence, an ISP having 400 switches and 18000 links at its access network can have annual cost savings of up to three million USD. Most of the ISPs and Telcos of Nepal

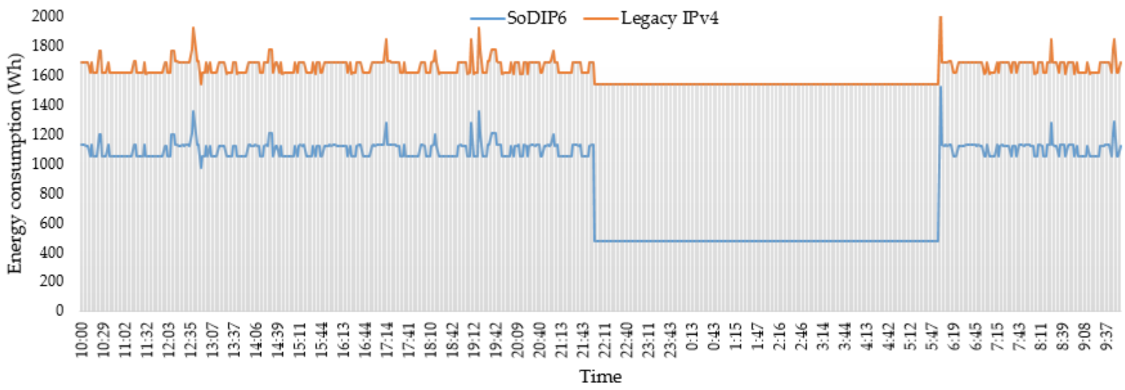


Figure 5.35: Pattern of total energy consumption by switches and CPEs in the legacy IPv4 and the SoDIP6 network

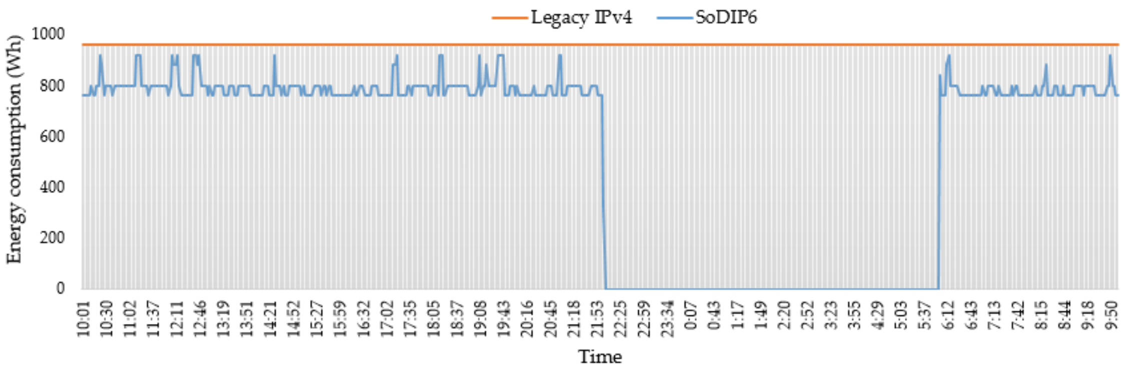
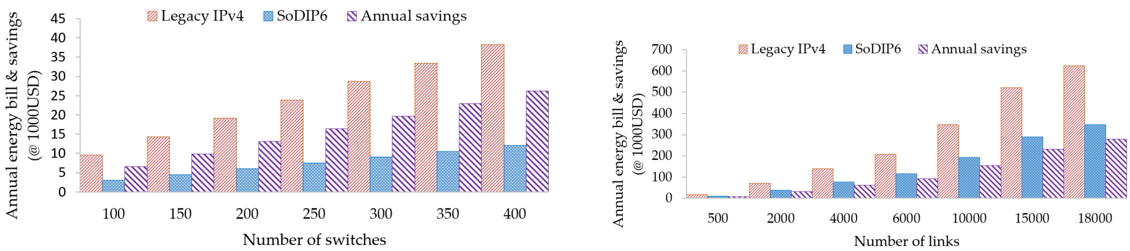


Figure 5.36: Pattern of total energy consumption by links in the legacy IPv4 and the SoDIP6 network

use Cisco, ZTE, and Huawei routers in their networks. For Nepal Telecom, with tentatively 230 Huawei-NE40E-X3A routers (has a full mode power consumption of 600 Watts) and 1150 links, an estimated annual OpEX savings of 143.95K USD could be achieved. Hence, SoDIP6 network is more energy efficient, leading to a reduction in organizational OpEX. This contributes to community and service provider sustainability.



(a) (b)

Figure 5.37: Comparative charts showing the estimated annual energy bill amount by both networks and OpEX savings in SoDIP6 network by (a) switches, and (b) links

5.6.2 Energy saving practices with SoDIP6 network

Three major energy saving approaches [171] in ICT network are: re-engineering, smart sleeping, and dynamic adaption. In this study, only the concept of smart sleeping and load proportional traffic demand of switch were considered as a part of dynamic adaptation in the SoDIP6 network. Re-engineering focused to the design of ICT equipment with complementary metal oxide semiconductor (CMOS) technology for energy saving [187, 203] as well as the refinement on the memory technology like ternary content addressable memory (TCAM) compression for packet processing that optimizes the internal organization of devices [204, 205]. Dynamic scaling can be achieved by means of performance scaling i.e. reducing the CMOS applied voltage by changing clock frequency and turning off the sub components of equipment during the idle condition. In dynamic adaptation, devices are designed to modulate the packet processing capabilities and network interface with respect to actual traffic load and requirements [171].

Adaptive-link-rate (ALR) and low-power-idle (LPI) are the two techniques under dynamic adaptation, in which ALR allows for dynamic modulation of link capacity or processing engine to meet traffic loads and service requirements, while LPI technique forces device or link to enter into low power states during idle time, at which devices are not processing the packets. During the off-peak hours, when traffic flow is low, reducing the operating frequency of network devices can have significant energy saving. For example, saving of energy can be achieved in SDN by lowering the speed of link basically applicable during the SDN policy updates, because SDN policies can be updated with 10Mbps links that consumes 4 watts lower than 1Gbps link [184]. Similarly, dynamic changes to routing in the legacy IPv4 routing engine is nearly impossible, while dynamic optimization in SDN is fairly simple. For example, as a part of dynamic adaptation, energy aware routing in SDN is an established approach, in which traffic can be rerouted through alternate paths at low or no active traffic is identified on the link or interface, so that these devices or links can be shutdown for energy saving [175]. Smart sleeping is an approach, in which the ICT equipment turned into sleep mode, if there is no traffic or low traffic passing through it. Similarly, the idle links, from where no traffic is passing, can be turned-off.

Deployment of additional communication infrastructures for Smart Grids (SGs) should therefore carefully consider the trade-off between the gain in terms of energy saving and the cost of the operating devices, while avoiding the posing an unnecessary energy burden to end-customers. The broad choice among the technologies and networks available will enable the most efficient and economically viable implementation of SGs. Through the government funding under RTDF, Nepalese ISPs and Telcos are expanding their infrastructure towards rural Nepal. Taking this as the best opportunity, SoDIP6 network deployment would help to gain all the benefits associated with it.

In addition with above three energy saving approaches as they are more technical in nature and so can be categorized into 'optimization' for energy saving, in the context of rural ICT network, greening of network is considered from the techno-economic and managerial perspectives. Hence, additional practices for energy saving and carbon emission reduction with SoDIP6 network are recommended in three main categories depicted in Figure 5.38, these are:

- Optimization and placement,
- Policy and deployment, and
- Monitoring and management

A brief discussion on sub-topics identified on each category are provided in the below sections.

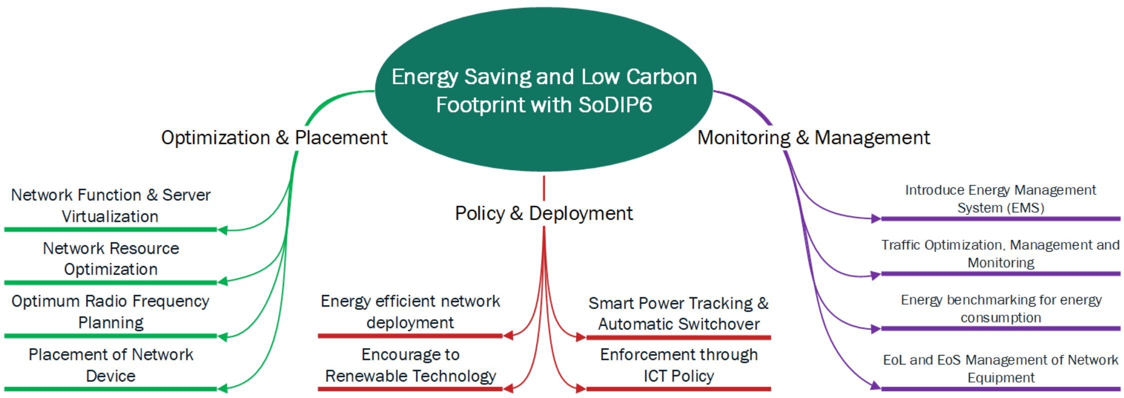


Figure 5.38: Energy saving practices with SoDIP6 network.

1. **Network function and server virtualization**

   Network function virtualization (NFV) and server virtualization help to reduce the energy consumption in a network [206]. The software and network operations previously run in the separate commodity hardware are moved and re-located to a single hardware with virtualization technologies. It means number of computers are integrated or re-located into a single computer leading to energy optimization [207]. We can have a single platform and multiple applications that improves scalability with reduction in energy consumption [208].

2. **Network resource optimization**

   Resource monitoring and its optimum utilization according to traffic condition has leading role in the reduction of energy usage and carbon footprint. SDN enabled IP6 network is flexible and programmable, so that intelligent traffic analysis and bandwidth monitoring would help to maintain the quality of service and proper resource utilization. SDN controller can make decisions based on the traffic volume in system promoting green network and efficient network utilization by rerouting the traffic of node, which has low traffic; then put the device into sleep mode [175, 209, 181]. Similarly, the unused links in the network can intelligently set into sleep mode to save the energy. Boiardi et al [210] introduced elastic tree as an approach in SDN and claimed that 50% power saving can be achieved, in which optimizer module allocates suitable link to efficiently handle the traffic load while meeting Quality of Service (QoS) requirement. Energy efficient routing protocols [211] can be applied in the network for proper saving of energy and routing management according to energy status.

3. **Optimum radio frequency planning**

   Wireless base stations are the most energy hungry network components [212]. Radio access network consumes almost 80% of total power in cellular network [213]. Focusing to sparsely disperse rural population, virtual coverage implementation, like use of openBTS and openCellular technologies would be more energy efficient and cost effective for the telecom operators so that cellular network can be controlled via the program, in which idle base transceiver station (BTS) will enter into low power mode and wake-up only when requested [214, 215, 216, 217, 218].

4. **Placement of network devices**

   Suitable placement of SDN devices in a network could help to save significant amount of energy consumption by the network [184]. Implementation of SDN enables only passive devices (data plane) resides in rural areas, while these data plane devices can be controlled remotely via the controller. This helps to avoid the need of bigger number of skilled HRs to reside in the rural zone for the network operations and management. A more secure infrastructure can be established by placing the controllers in the managed network center, which can easily be accessible and it controls the data plane devices located in rural zone from the remote. For example, every district headquarter of Nepal is reachable by fiber networks. While, in the early stage of network expansion, data plane only devices can be deployed beyond the district headquarter. The controllers that are managed and operated form headquarter creates more secure and managed network environment.

The requirement of number of controllers in the network depends on the network load and the traffic pattern. The proper placement of controller [219] with proper design of network having number of switches and connection can improve the overall efficiency of network with reduction in organization CaPEX and OpEX [220]. It is believed that SDN creates greater opportunities to rural network operators by providing simpler and more efficient network operations by decoupling construction of physical infrastructure from the configuration of network resulting to reduced cost with minimizing gap of technical and business barriers.

5. **Energy efficient network deployment**

   In the context of Nepal, ICT network is expanding and the number of ICT users are increasing [221]. Service providers expand their network considering their business opportunities. The increase in OpEX in terms of increased annual energy bills can be reduced if focusing on to green networking [222]. It means, while deploying the new networking infrastructure, SDN enabled IPv6 network is to be considered for overall efficiency and better future sustainability.

6. **Encourage to renewable energy technology**

   Wind, water, solar, and the warmth in the earth are the major renewable resources that can supply our needs in a sustainable way. Regarding the rural Nepal situation of power provisioning, installation and operation of micro-hydro power plants are increasing. The excess power from micro-hydro is planned to supply to national grid, but this can be achieved only after 2022 according to report of NPC [223]. The current electricity crisis at rural Nepal can be somehow minimized by using alternative energy considered as green energy to power supply the network equipment.

7. **Smart power tracking and automatic switch-over**

   Flexibility in network operation and programmability adds significant contributions to implement smart grid and automatic switch-over of the system according to traffic load condition. SoDIP6 network enables for efficient monitoring of energy usage by the ICT equipment and automatic switch-over of the system according to energy status. This is more applicable in electrical grid network system, because it helps to manage power outage in the electrical network.

8. **Enforcement through ICT policy**

   To the best of author's knowledge, currently Nepal government do not have focus on green ICT and so, have no any energy saving and CO2 emission reduction plan. Strategies have not yet been incorporated on all the ICT policies promulgated till date. Nepal lies between two big industrialized countries: China and India, where the Himalayan belt of Nepal acts like green house gas (GHG) sinking zone impacting more on the climate change. Considering the climate change effect and increasing demands of energy with rapid increase of internet users, green ICT with carbon trading strategies shall be the government focus so that ICT could be the tool for energy optimization and reduction of GHGs. While expanding ICT infrastructure to rural Nepal, piloting the network expansion with SoDIP6 network and eco-friendly equipment installation would help towards Green ICT.

   Regulators can apply ITU standards (ITU-T L.1310) [224] for energy efficiency metrics and measurement methods for telecommunication equipment. Similarly, regulator can introduce incentives to energy-efficient operators as a reward; like several European countries offering incentives to operators on replacement of older technologies/equipment with newer one focusing on green technologies [225].

9. **Energy management system**

   Energy management system (EMS) is a system of computer added tools used by service providers to monitor, control, and optimize the performance of electrical generation system. ISP/Telcos operators could apply centralized energy and carbon emission monitoring system under the framework of EMS. Regulator is to be allowed to access the energy system of operators via power tracking tool, so that regulator can monitor the electrical generation system and the ICT equipment, for example, BTS tower, edge switches, and backbone switches can be accessed to produce different kinds of reports regarding energy consumption and CO2 emissions. Detail about the energy audit and management system with different case studies are discussed at [226].

10. **Traffic optimization, management, and monitoring**

    Monitoring of energy consumption by network equipment helps for better understanding to manage and find the best strategy to adopt in order to maximize reduction of unnecessary usage of electricity. Similarly, BTS energy management is becoming the fundamental needs for sustainable development in the ICT sector [227].

11. **Energy benchmarking for energy consumption**

    Energy audit is the part of energy management system. Benchmarking or auditing of network operations and services help in identifying and quantifying cost effective energy saving opportunities and reporting opportunities for the service providers. In the context of Nepal, regulators can apply energy audit policy at least once in a year for the ICT industries and identify the environmental impact of ICT via energy use and CO2 emissions.

12. **EoL and EoS management of network equipment**

    EoL, EoS, and the last day of support of network equipment are the important parameters required to be maintained by every organization, while running network services. Due to lack of sufficient fund, fairly sustained service providers of developing countries do not plan for the device replacement according to EoL and EoS of network equipment. Due to rapid innovation in hardware as well as software system, ICT equipment's product life cycle is comparatively shortening. New equipment produced are more energy efficient. Hence, it is the role of ISP/Telcos operator to keep records of their network equipment and act accordingly with the product life cycle.

13. **Government plan and policies**

    Most of the opinions of service providers reflect to the lack of government's proper policy, guidelines, and subsidy plan to promote ICT and green networking at Nepal. State should timely address the pace of global technological change via policy initiatives and create suitable environment to adapt new technologies. Recent initiatives of utilizing RTDF to provide subsidy to expand ICT infrastructure is expected to be contributory towards building smart societies and economic growth of Nepal. The recent political transformations towards stability and government subsidy plan to develop nationwide ICT infrastructure as well as increasing pattern of automation in government offices and companies create good opportunities for service providers to expand infrastructure and services with latest technologies, so that all the stakeholders would be benefitted. Upgrading existing service system's hardware devices and software system to make them compatible with newer technologies is fairly complicated than to establish new system with latest technologies. Hence, in the situation of backbone network IPv6 ready, it would be an opportunity for service providers to establish access network with energy efficient SoDIP6 network and ensure latest service technologies for the long run future sustainability. Implementing edge network with SoDIP6 in the broadband expansion initiatives would encourage for phase-wise backbone network migration with optimized OpEX.

14. **Challenges and opportunities for Nepalese service providers**

This section presents the challenges that stakeholders are facing and opportunities regarding the latest network deployment in lights of the domain knowledge obtained during ISP survey. The major challenges of network migration and way forward for service providers of developing nations like Nepal are as follows.

- **Skilled human resources:** for the existing legacy system operation and management, there is no scarce of skilled HRs as well as the system is well stable. There is always a scarce of skilled HRs to operate new system and technologies as the service providers have to expand their infrastructure with newer technologies as well as migrate their existing infrastructure in a phase. Existing legacy network transitioning to SoDIP6 network is a long term plan, in which the organizational budget, human resources, and system/application readiness play a major role for transition planning. However, migration to SoDIP6 network is technically viable, the scarce of skilled HRs to migrate existing network and establish SoDIP6 network is another major challenge for service providers. Regulator has to conduct research and training to develop skilled HRs in addition with service provider's in-house research and training. As far as it is realized, Industry-University tie up is not strong enough in Nepal. Better collaboration of industries with universities to produce resources as per market demand is the current need to address resource shortage issues.

- **Applications/protocol supports and security:** during the phase of transition i.e. in the early stage of new system implementations, the available applications and protocols may not be compatible and stable. The World-wide status of network migration [228] shows that IPv6 implementations are widely supported and nearly matured with availability of different migration approaches. Similarly, SDN implementations in the ISPs and Telcos networks are under research and development, tests, and implementations [61, 67, 68]. Service providers of developing nations are not in the stage of well secure applications and protocol development. Hence, there is always a fear of system/application security and service interruption, while implementing newer technologies.

- **Demography and geography of Nepal:** the major cause of detraction to enhance ICT in rural Nepal is of diverse demography and difficult geographic distributions, where there is always fear of business continuity issues for service providers due to low purchasing power of rural communities. According to MoPE (2017) [229], projected population of Nepal in 2016 was 28.4 million, in which urban population was almost 20 million and rural population was 8.4 million. By geography, Nepal's land is divided into three regions, these are: Mountain (altitude between 4877 and 8848 meters), Hills (altitude between 610 to 4876 meters) and Terai (regions below elevation 610 meters). Mountains and Hills cover almost 77% of total land but population account 49.7%, while 23% land coverage of Terai region has population ratio of 51.3%. Most of the urban cities are located in the Terai zone. Population growth rate of Terai is higher than other two regions and peoples are migrating to Terai form the Hill and Mountain. This is because of difficult terrain of Hill and Mountain, lack of basic facilities and infrastructure for living, favorable environment for the rebellion, and other political movements against government, for example, 10 years Maoist insurgency [230] caused many people displaced from the Hilly region. 2015's devastating earthquake highly affected the Hilly zones of middle and western part of Nepal. This caused positive vibes to the peoples for urbanization with building earthquake proof houses at rural areas. Similarly, Nepal government has lunched the national reconstruction project and is subsidizing the rural people to build their houses under government's regulatory framework. This helps to minimize the migration issues.

Infrastructure and service expansion in rural Nepal is costly due to lack of proper transportation and absence of proper infrastructure security facilities. The destruction of infrastructure like telecom towers and equipment during the 10 years Maoist movements (period from 1996 to 2006AD) [230] was one of the obstacles of network expansion for private operators. Although the major insurgency was settled, still few known/unknown political movements exit and create less secure environment to the investors to expand services to rural and far rural areas of Nepal.

5.7 Chapter Summary

All the concepts and algorithms developed with mathematical formulations presented in Chapter 3 were implemented through programming and simulations. Then, the outcomes of experimental works were elaborated as a part of research analysis work and properly visualized into tables, graphs, and charts. Suitable migration plan and strategies were presented considering the existing infrastructure status, joint migration modeling, and adaptation to newer technologies through evolutionary aspects of migration for ISPs. Similarly, significant amount of migration cost savings has been achieved, while implementing joint migration and energy saving in SoDIP6 network.

Chapter 6

Discussion and Recommendation

This chapter will provide a brief discussion on this research studies on a task specific basis. The scope and limitations with possible future works will be discussed based on the limitations identified. Finally, some recommendations will be provided in the context of Nepal to establish energy efficient SoDIP6 network focusing on green ICT to develop sustainable future societies.

6.1 Discussion

Present research is focused on the objectives to develop joint network migration analysis and implementation planning for internet service provider's networks. A detailed steps on how ISPs/Telcos proceed for joint migration is presented. Assessment of available resources is required at the beginning of the migration planning. For example, readiness of HR availability to handle latest network infrastructure and services, benchmarking of existing infrastructure to measure the viability of network upgrades or replacement, evaluation of cost estimation and optimization approaches for the migration, measuring the financial strength of migration, recording the status of other interconnected and transit networks to forecast business impact on their network migration, development of sustainability plan during and after the network migration etc. are the major concerns that every service provider should take care during technology migration.

The early stage of SDN migration in service provider networks and low adaptation status of IPv6 addressing World-wide guided to have such joint network migration study, so that service providers basically of developing nations, who are in the early stage of their network migration, can have joint migration planning to optimize the migration cost for their future sustainability. At first, the common concerns between

SDN and IPv6 were identified. Then, a new term 'Software-defined IPv6' network abbreviated as 'SoDIP6' network was introduced.

6.1.1 Device status identification

First step for each ISP/Telcos operator, who is planning to migrate their legacy network into SDN enabled IPv6 network is to identify the operational status of their currently running network devices and identify whether the current networking devices can be upgradeable or requires replacement with latest devices that support targeted newer networking paradigms (SDN and IPv6). Set of measuring parameters were identified for a network router to measure its strength for upgrades or replacement. These are: EoL, EoS, memory usage, throughput, and CPU utilization. Considering the scope, the experiment was particularly confined to certain series of CISCO IP routers. The model was implemented in the standard IP network topology, although there are many network vendors World-wide, who supply network equipment in the market. This is due to lack of sufficient dataset available by other vendors for analysis.

Due to heterogeneous device characteristics, the trained model can't be generalized, while it is implementation specific to CISCO products. For other vendor products, it has to be separately trained, which may need different assumptions in data preprocessing. Proposed model is particularly applicable to SoDIP6 network migration, because the DFS module is conceptualized based on the device support in SDN and IPv6. However, the proposed approach is not computation/resource intensive. Since, technical administrator monitors the system and device operation continuously using different professional monitoring software (e.g. CACTI, PRTG, and Nagios etc.). For the large number of devices in a large network, assessment is required to take further decision for suitable migration planning. It is expected that this approach can easily be integrated into the existing monitoring system and evaluate the device performance for its migration assessment. For the enterprise and data center networking, where large number of switches are in use and they require migration, it is encouraging to implement such approach in the switch migration planning.

6.1.2 Joint migration analysis and modeling

Once the status of all the running routers in the network are identified, it is required to measure the financial strength that how much cost and time is required to transform the current network into operable SoDIP6 network. Since, the cost is related with the standard application and protocols, vendor support, skilled HR development, configuration, and maintenance/support. Set of cost metrics were identified for joint network migration and introduced two variables viz. shared cost coefficient (μ) and strength of correlation (ϵ) between SDN and IPv6. Then, heuristic algorithm (Algorithm 3.2) is developed to implement migration considering customer priority towards the demand of SoDIP6 based services and optimal path routers to be migrated in a phase.

Some literature are found for the migration based on time and budget constraints [231], link utilization minimization and upgrade cost as resource constraints [148], hybrid SDN migration consideration and energy optimization using genetic algorithm [232], and incremental deployment based on least cost path and budget constraints [102]. In the above studies, basically budget constraints and traffic engineering considerations like link utilization and least cost path were considered to replace legacy router to migrate to SDN. None has provided actionable approaches and steps for migration implementation with estimated cost required for transitions. Additionally, all are limited to single technology migration. Following the joint technology migration, not only the replacement of routers, but also focus on possible hardware/firmware upgrades for migration cost optimization has been carried out in this research. Priority of customers was considered with their service demands as a base line strategy for migration planning with least cost path considering traffic engineering and budget constraints. Further, this approach is not limited to time constraints as the service providers can plan the migration setting time constraints on which link to migrate first and when, based on customer demand. Thus, links related to highly prioritized customers can be chosen for migration in the first year and consequently to other secondary priority customers in the following years. After the migration steps were defined, cost estimation and optimization model with result and analysis were presented for the joint migration. The steps in migration are listed below.

1. ISP Maintains the network inventory system that contains specification details of the network device in operation.

2. Prioritize the customers to whom the SoDIP6 network based services are to be provided.

3. Identify the optimal path and set of nodes in the optimal path from customer endpoint router to ISP gateway router.

4. Find the status of every unmigrated node in the optimal path, whether it is upgradeable or replaceable.

5. Calculate the optimum upgrade cost or replacement cost based on the device status and associated cost metrics.

6. Migrate routers in the optimal path based on available budget constraints.

7. Repeat the migration procedure with next priority customer until all the nodes in the network are migrated.

8. Evaluate the functional operation of network with new technologies implemented.

9. Fix the issues if any and continue expanding the network as regular maintenance and business expansion plan.

The recent progress status of IPv6 network migration in ISP and Telcos networks World-wide shows that the application and protocol supports for IPv6 network operations are maturing, while adopting SDN in service provider network is gaining momentum [67, 233, 234]. It is believed that, this work as an addition of a brick with the ongoing research, experimentation, testing, and implementation practices [67, 234, 156, 86, 87] of SDN would enable towards incremental deployment of SoDIP6 network in the service provider networks. Starting from the legacy networks, optimal steps and strategies for migration to SoDIP6 networks have been defined, and performed joint migration modeling and analysis for migration cost optimization.

6.1.3 Evolutionary approach to SoDIP6 network migration

An economic model of an ISP network having interconnection with other ISPs in a tiered internet architecture is presented. The concept is applied to Tier-3 ISP network architecture and analyzed the migration from the game theoretic perspective.

It is important for every ISP to know about *"what other ISPs are doing on the internet?"* from the traffic engineering and business continuity perspectives, because the interconnecting ISPs are exchanging varieties of internet traffic. The two questions, first: *"when to migrate?"* and second: *"how to migrate?"* always create challenges for service providers to decide and plan for their networks migration to newer technologies. This research task is mostly dealt with the first question "when to migrate?"

and also presented the benefits of migration in terms of achieving higher utilities via simulation and analysis. An ISP can only decide for migration once it evaluates its strength considering customer needs, availability of technical human resources, sufficient budget to invest in migration implementation, and technology readiness to make sure that the services are not interrupting after migration. The second question creates spaces for detail migration scheduling and migration cost optimization of individual ISP. The discussion on these were covered in section 6.1.1 and 6.1.2. This part of research was limited only to modeling of nation-wide interconnected Tier-3 ISPs in the evolutionary game play, while it can also be applicable to Tier-2 ISPs, only if they have individual home internet users and enterprises as their customers.

In summary, the overall steps of migration decision making from game theoretic perspective are as follows.

1. Define number of ISPs as finite populations and also define migration constant.
2. Randomly select 'K' number of ISPs in the set of finite ISPs (N) at the beginning for migration.
3. Calculate the adaptation strength of Group-1 ISPs (N1) and expected payoffs of all ISPs in both groups.
4. Calculate the migration strength of each ISP in Group-1 with the fitness value.
5. Take decision to migrate ISPs having migration strength $(\delta) \geq 0.6$.
6. On every three months, repeat from step-(3) until all ISPs are migrated to SoDIP6 Networks.

6.1.4 Energy efficiency evaluation of SoDIP6 network

The increasing rate of energy consumption and CO2 emission in ICT sector is the major factor that affects in global climate change. Legacy networks lack smart electricity use by ICT equipment leading to peak energy consumption by every devices even in the ideal time having no any active communications. One of the promising feature of SDN is the smart electricity consumption management that the network can be controlled based on energy use. Smart sleeping feature in SDN helps to control the network such that the data plane device can easily be entered into sleep mode via a single policy to be issued by an SDN controller. Similarly, energy aware routing in SDN is an ongoing research to have energy efficiency in network communications. Legacy IPv4 networking devices like switches and links run 24 hours with peak energy consumption and so resulted in a higher energy bill annually. The beauty of an SoDIP6 network is that energy consumption can be optimized using dynamic scaling, adaptive link rate, and smart sleeping [171].

The energy efficiency of SoDIP6 network was evaluated by considering end-access ISP network having number of wired and wireless routers using the concept of smart sleeping and traffic load-based energy variance in the experimental analysis. An annual energy saving of 31.50% on nodes and 55.44% on links were achieved with SoDIP6 network deployment. An annual energy bill to be paid by ISPs that have a different number of switches and links in their end-access networks with respect to the legacy IPv4 network and the SoDIP6 network as per assumptions provided in the experiment was estimated.

With different discussion on energy saving and CO2 emission reduction practices with SoDIP6 network implementation, some recommendations are provided in the context of Nepal by reviewing its current electricity availability and distribution plan to focus on green networking with ICT expansion to develop sustainable societies.

6.2 Broadband Network Deployment: Context of Nepal

There are some factors that issue the affordability and sustainability of rural communities in the deployment of rural broadband infrastructure and services [235, 236]. These are (i) low household income, (ii) lower literacy rate, (iii) sparse population, (iv) difficult terrain, (v) higher rate of population migration, (vi) energy, (vii) accessibility, (viii) policy and regulatory environment, (viii) broadband price, (ix) technology deployment cost, (x) technical HRs, (xi) local barriers, and (xii) content and language barriers. Briefly summarizing the above points, it is realized that rural people have low purchasing power, lack opportunities like to get efficient government services, transportation, education, healthcare etc. [237]. Since, the last two decades in Nepal, people from the Hilly areas are migrating to Terai zones due to the cause of limited resources as well as other seen/unseen political movements.

Energy is the major pillar of economic development of the country, but lack of electricity supply system in rural Nepal, lack of connectivity like road network to make the rural area accessible, higher network deployment cost, absence of governance and citizen services for the rural communities, and lack of dedicated/visionary policy are the major hindrances to have affordable and sustainable broadband services. Similarly, road network and broadband infrastructure expansion is still difficult due to unnecessary obstructions by local people, direct/indirect political movements with language barrier, in which more than hundred languages are spoken at different parts of the country. In this context, NTA initiations to make the availability of ICT infrastructure only do not guarantee the improvement on living standards of rural communities. However, use of ICT stimulates activities to automate local industries, agriculture, healthcare, and education etc.. Primary concern is the strong presence of government regarding connectivity and coverage, then to ICT and awareness in the unserved and underserved areas of rural Nepal. The existing national ICT and broadband policies [238, 239] seem to be amended for dedication, suitable vision, and strategies to attract service providers to offer high-speed network connections and services for rural communities.

Based on the literature, to have affordable broadband services to rural communities, some focus areas are depicted in Figure 6.1. These are basically categorized into i) policy, ii) infrastructure, and iii) innovation, research and development. The subtopics listed under these focus areas are briefly discussed below.

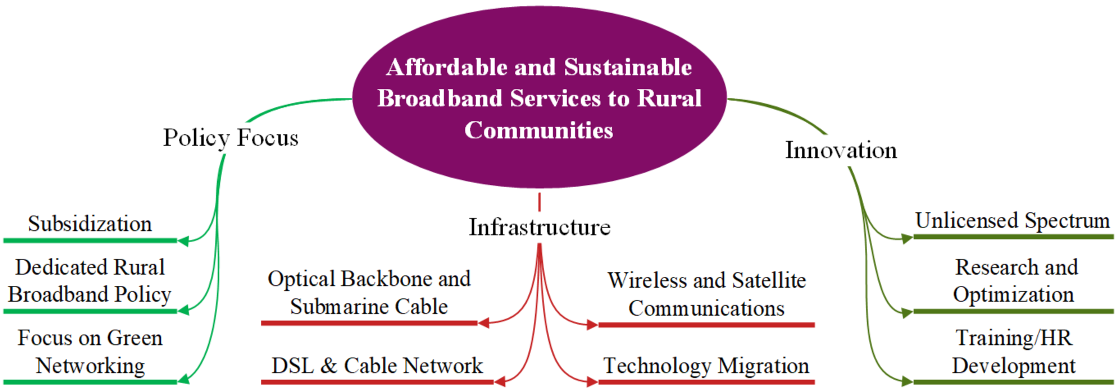


Figure 6.1: Focus areas for affordable and sustainable broadband services

1. **Subsidization**

   Even if the network infrastructure is ready for rural communities, service providers won't be attracted to provide services to rural areas due to lack of guarantee of return on investment. Hence, government grants and loan in the form of subsidization is to be provided to maintain their digital infrastructure under the community network including subsidies to the operation of health centers, hospitals, schools, community farms etc. so that they will be encouraged for rural utilities and other broadband services [240]. Access to government information to be delivered to citizens like '.np' domain contents, educational materials, health, and agricultural farming related information should be available free of cost to rural communities in the beginning, so that rural people will be attracted to ICT based services. For example, fully subsidized IT lab setup at government schools throughout Nepal is a good initiation by NTA that helps to establish IT based education centers at rural areas of Nepal [197]. Free access to contents can also be ensured via geographical limit in which marginalized citizens of those areas can be set into priority to provide free access to internet and services. Digital content production in the language and sharing among in the rural communities can stimulate societal development from within the societies [235].

Developed countries like America and South Korea had put direct investment as well as guarantee loans to the rural communities to reduce digital divide via reliable broadband infrastructure and services [241]. Discounts or direct funding to end users as an incentive based subsidies may be more effective via provisioning of broadband vouchers to economically marginalized people of rural areas [242].

Service providers will be encouraged to expand their infrastructure and services to rural areas, only if they are guaranteed some subsidies, for example, tax exemptions on the network equipment that are imported for rural broadband expansion. Hence, exemption on local taxes and or taxes while importing equipment as well as direct subsidies through public private partnership (PPP) can be considered as an important avenue for social development and reduce the digital divide by means of reliable and sustainable broadband services [243]. By priority, subsidies need to be guaranteed first to build new network rather than upgrading existing network [244].

2. **Dedicated rural broadband policy**

   Particularly, considering the rural areas of Nepal, adequate policy intervention is required to develop sustainable rural society. A dedicated and community focused policy helps to address the subsidization schemes mentioned in the above section. The recent broadband policy [239] requires additional amendment for the effective mobilization of RTDF to provide subsidies to communities and service providers to run the broadband infrastructure and services in a PPP model. Clear policy vision is to be derived to address the sustainability issues of disadvantaged school, public libraries, community health centers, and many more [198]. For example, low income households with their children joined to community schools can be provided broadband internet as much as in low price or no price [199]. Broadband services have significant impact in the economic growth of rural communities on their organizations and small businesses [245]. Over the favorable environment that government, if guarantee via policy means, affordable services and operational sustainability can be achieved with broadband network at rural and remote areas [246].

3. **Focus to green networking**

   With the exponential growth of internet users World-wide, evolving smart cities with increase of WSN and IoT devices, the energy consumption by ICT equipment are exponentially increasing leading to increased CO2 emission. The volume of CO2 emission produced by ICT sector was estimated to be at least 2% of total World carbon footprint in 2020 [172]. ICT sector was forecasted to contribute 1.3Gt of greenhouse gas emission in 2020 [247]. Global warming and then to climate change effect is more sensitive in the context of Nepal, because of being a mountainous country. The rapidly retreating glaciers (average retreat rate of more than 30M/year), erratic rainfalls, frequent flooding, and drought that leads to alarming situations for developing country, Nepal [248]. With the increasing network connectivity to rural Nepal covering the Hilly areas, the situation of global warming effect will be alarming. With the increasing ICT infrastructure and users, the sector consumes more energy leading to higher volume of CO2 emission. Hence, this scenario is expected to increase rapidly if no mitigation approaches via greening techniques are adopted. Greening of network, for example, use of renewable energy technologies to power the network equipment, use of energy efficient latest networking technologies like SDN and IPv6 network, while deploying the connection would help to create sustainable societies as well as supportive to service provider sustainability. Significant amount of energy savings in ISP network would help to reduce the annual energy bill as a part of organizational OpEX [10] saving. Considering the greening approach by newer networking paradigms like SDN and IPv6, there are several studies that contribute to green ICT with energy aware routing scheme for energy saving and carbon footprint reduction to show that IPv6 and SDN have greater flexibility towards green networking [172, 173, 174, 184, 249].

4. **Optical backbone and submarine cable**

   With the reducing price of optical fiber cable and requirement of high speed broadband network, fiber cable is becoming the default choice to establish nation-wide broadband network. RTDF funded project initiated by NTA will establish fiber backbone connecting every district head quarter by 96-core fiber and every rural municipality, wherever possible by 48-core fiber backbone. Due to powerful wind at high altitude and frequent snow fall with zig-zag locations at rural areas of Nepal, in most of the places where, underground backbone fiber installation is not viable. This issues can be avoided if to deploy optical direct buried cables recognized as fiber packed armored cable (F-PAC) in Nepalese rural areas. As per the proposal of Murata et al. (2011) [250], their practical implementations indicate that F-PAC cabling can have aerial lying and under-ground lying with sufficient counter measures against birds and animals attack. Hence, it is more cost effective with better safety, security, and reliability than deploying more costly wireless and satellite links for broadband communications [251].

5. **xDSL and cable network**

   Fiber to the anywhere (FTTx) has become more popular World-wide to provide broadband communication services [252]. However, in the Nepalese context, FTTx service has just entered into the market as a major competitor, but digital subscriber line (DSL) basically an asymmetric DSL (ADSL) service and cable based services are recognized as still popular connectivity services that are implemented by service providers. In most of the offices, where public switched telephone service is available, Nepal Telecom (NT), the incumbent operator has provided ADSL and FTTH connectivity enabling phone, data, and IPTV services throughout Nepal. ADSL became the proprietary of incumbent operator in Nepal. Internet and cable TV services through coax connection is also a popular services adapted by ISPs and cable service providers, but they are mostly city/urban centric. Wireless internet connectivity services provided by Nepal Wireless project [253] in some of the rural areas of Nepal and NT's ADSL services to every rural municipality including 3G/4G, WiMAX services [254] are the basic connectivity available in rural areas. Based on the viability and possibility of network expansion, local wireless services utilizing TV White Space (TVWS) also enabled for low cost and affordable services to rural communities.

6. **Wireless and satellite communications**

   In the mountainous regions, where wired network is not possible, wireless communication like Wi-MAX, 3G/LTE/4G technologies and use of TV white spaces (TVWS) for long distance wireless coverage have to be established. Additionally, some places require satellite communications. Geostationary earth orbit (GEO) satellites are comparatively simple and cost effective as compared with other constellations [244]. Focusing on the unserved and underserved communities, low earth orbit (LEO) satellites provide low latency and high speed broadband services to rural communities. LEO satellite system is becoming the global communication service providers to counterpart local terrestrial paging, cellular, and the fiber network. Like Telesat, OneWeb, SpaceX [255, 256], and Amazon have initiated for LEO satellites to establish low cost affordable and sustainable global communications.

7. **Technology migration**

   With the rapidly changing global scenarios regarding evolution of latest technologies like advancement on hardware, software, applications, and protocols, service providers have to be well adapted so as to provide the efficient, reliable, and faster services to their customers. The latest technologies developed will be more robust, efficient, cost effective, and more operation friendly. Hence, encouragement to service providers towards timely migration to newer wired and wireless technologies with SDN and IPv6 network, wireless virtualization, use of OpenBTS and OpenCellular technologies are required for sustainable services.

8. **Unlicensed spectrum**

   Government of Nepal has already announced to all the cable television companies to transform their cable service network from analogue to digital television broadcasting. In this context, not all channels of the UHF TV band are occupied at each location. The portion of the spectrum left unused by broadcasting, known as TVWS (interleaved spectrum) that have traditionally been used for TV broadcasting and its opening for cognitive access, has greater opportunity to avoid spectrum scarcity issues [257, 258]. Radio signals with TVWS are suitable for travelling to long distance over hills, mountains, and around/through the buildings. This is more applicable in the context of rural Nepal, where most of the places are not possible to connect via wired network. Most of the countries worldwide are exploring the ways to use TVWS for wireless broadband communications [244, 257, 258]. Hence, low power telecommunication transmissions leading to affordable broadband for rural communities, can also be achieved with the use of TVWS.

9. **Research and optimization**

   Innovations, research, development, and service optimization are the major entities to develop cost effective and provide sustainable services based on end-users or community requirements, demographic and geographic situation, costumes, cultures, and many more for the rural communities. Actual needs of the society are to be considered and suitable technology has to be implemented. The RTDF utilization to develop broadband network as initiated by NTA is expected to uplift economic status of rural people including improvements on several other dimensions of the society. For this, it requires suitable policies, plan, and strategies, so that government services can be effectively provided to the citizens including promotions of local industries and create environment for effective use of technologies to develop sustainable rural societies. Hence, broadband data collections from rural communities to effectively analyze the existing services, customer needs, and requirements will help to get back to actions after research to optimize the service use and cost of operation.

10. **Training and HR development**

    Sustainable issue is raised majorly due to the lack of skilled HRs to maintain and operate network systems to provide broadband services in the rural areas. Similarly, lack of knowledge to consumers about access and use of Internet including other factors like socio-economic and demographic factors are regarded as the challenges of sustainable broadband services for rural communities. Hence, public and private stakeholders in the rural communities are to be trained through consumer education with training initiatives and broadband affordability program including other incentives to attract to use the services [259].

Chapter 7

Conclusions and Future Enhancement

7.1 Conclusions

IPv6 and SDN are the emerging latest generation networking paradigms to be considered for legacy IPv4 network migration. To maximize efficiency, scalability, flexibility, and manageability of the network and full the demand of growing internet users, service providers need to migrate their legacy IPv4 networks to SDN enabled IPv6 networks. Traditional network cannot meet the exponential growth of users, because of its static parameters that cannot be changed on-the-fly. Additionally, SDN provides better visibility, programmability, and scalability of the network and IPv6 supports a large number of devices to identify uniquely in the global scale.

Switches and routers are the major networking components, which are to be kept up to date for efficient and reliable latest services to be provided to customers. Present research considered traditional ISP network transformations to SoDIP6 network to classify the network routing devices in terms of upgrades or replacement by implementing ANFIS. The proposed ANFIS model outperforms well as compared with other classification methods in terms of performance and accuracy.

Present study introduced shared cost coefficient (μ) and strength of correlation (ϵ) between SDN and IPv6, and formulated an ILP problem for joint migration. The simulation results and formal analysis show that joint migration approach is more beneficial than the individual migration. Analyzing the result at $\mu = 2$ for the two technologies (SDN and IPv6) and setting the correlation strength (ϵ) value from 0.4 to 0.7 gives more realistic optimizations in practice so that at $\mu = 2$, and ϵ=[0.4, 0.5, 0.6, 0.7], total joint migration cost optimization of 12.94%, 29.29%, 34.02%, and

38.44% respectively can be achieved.

Migration of one network affects the business strategy of another interconnected network. Hence, evolutionary dynamics of joint network migration based on the adaptation strength and fitness value considering customer demands, interactions with other ISPs, and status of organizational CapEX and OpEX are demonstrated.

Realization of network migration and functional evaluation in production level in the carrier grade ISP/Telcos network is an ongoing research. With the migration planning, present study additionally evaluated the functionality of multi-domain SoDIP6 network and its integration with legacy system using ONOS/SDN-IP. Additionally, suitable placement of controller during the network migration using BFR approach is proposed considering MCPL in a multi-domain SoDIP6 network.

The increasing demand of energy in the field of ICT and its effects should be addressed in a timely manner to avoid increasing annual energy bills due to higher energy consumption by ICT equipment for the service provider sustainability. The evaluation on the energy efficiency of SoDIP6 network provided better result as compared with legacy IPv4 networking systems. Additionally, present study has experimentally evaluated the energy consumption by SoDIP6 network considering the test-bed with ISP end-access network. The results show that SoDIP6 network can achieve 31.50% energy saving in switches and 55.44% saving in the links as compared with legacy IPv4 networking system. A discussion on energy saving approaches in terms of technology, operations, and management with recommendations to concerned stakeholders of Nepal are also presented. A brief discussion on different factors to realize affordable broadband services for rural communities is provided and recommended solutions to make affordable broadband services by considering SoDIP6 networks for rural communities .

7.2 Academic Contributions

Based on the defined scope of works, five conference papers were presented. Similarly, seven journal papers were already published, while one more journal paper is under review for possible publication in the prestigious international journal. The abstract of conference/journal papers with contributions are summarized in this section.

7.2.1 Paper abstracts and contributions

Title: Software Defined IPv6 Network: A New Paradigm for Future Networking (JP1).

Abstract: *Recent advancement in the field of Information and Communication Technology (ICT) has encouraged all stakeholders to move towards the new networking paradigm. Internet Protocol version 6 (IPv6) addressing, Software Defined Network (SDN) and Network Function Virtualization (NFV) are regarded as technologies for enhancing network efficiency and effectiveness. However, the technology migration become one of the central challenges for the stakeholders such as service providers, end users, and regulatory bodies. This is more challenging in case of developing countries due to lack of sufficient cost and skilled human resources. In this paper, we provide an overview and survey of SDN and IPv6 networking technologies, their benefits and future challenges. Then we introduce Software Defined IPv6 (SoDIP6) network as a next generation networking technologies and their unified approach of deployment over the Tier-3 ISPs of the developing nations that could help for speedy and smooth migration with optimized cost. The demonstrated superior features of SDN enabled IPv6 network from different perspectives with its contributions to green ICT are recognized as the networks of the future generation in the networking world.*

Contributions:

- Software defined IPv6 (SoDIP6) network is introduced and defined.
- Challenges of legacy network migrations towards joint transition to SoDIP6 network are discussed.

Title: Intelligent approach to network device migration planning for the incremental deployment of SoDIP6 networks (JP2, extended version of CP2)

Abstract: *Internet and telecom service providers world-wide are facing the financial sustainability issues to migrate their existing legacy IPv4 networking system due to*

backward compatibility issues with next generation networking paradigms viz. Internet protocol version 6 (IPv6) and the Software-Defined Networking (SDN). Benchmarking of existing networking devices is required to identify their status whether they are upgradable or needs replacement to make them operable with SDN and IPv6 networking so that internet and telecom service providers can have proper planning of their network migration to optimize capital and operational expenditures for their future sustainability. In this paper, we implement adaptive neuro fuzzy inference system (ANFIS), a well-known intelligent approach for network device status identification to classify whether a network device is upgradable or requires replacement. Similarly, we establish a knowledge base (KB) system to store the information of device IoS/Firmware version, its SDN and IPv6 support with end-of-life and end-of-support. Device performance parameters, for example average CPU usage, throughput, and memory capacity are being extracted and mapped with information obtained from KB for input dataset to ANFIS. The experimental results show that proposed approach is more accurate and optimal that assists service providers for smooth transitioning to SDN enabled IPv6 networks.

Contributions:

- A classification model is developed using ANFIS to detect network device (IP router) for upgrade or replacement towards transition to SoDIP6 networks.
- The proposed model outperforms well in terms of accuracy as compared with other recent classification methods.
- Proposed approach helps service providers for network migration planning with optimized migration cost.

Title: Migration cost optimization for service provider legacy networks migration to Software-defined IP6 networks (JP3, extended version of CP1.

Abstract: *This paper studies a problem for seamless migration of legacy networks of Internet service providers to a Software-defined networking (SDN) based architecture along with the transition to the full adoption of the Internet protocol version 6 (IPv6) connectivity. Migration of currently running legacy IPv4 networks into such new approaches require either upgrades or replacement of existing networking devices* *and technologies that are actively operating. The joint migration to SDN and IPv6 network is considered to be vital in terms of migration cost optimization, skilled human resource management and other critical factors. In this work, we first present the approaches of SDN and IPv6 migration in service providers' networks. Then, we present the common concerns of IPv6 and SDN migration with joint transition strategies so that the cost associated with joint migration is minimized to lower than that of the individual migration. For the incremental adoption of Software-defined IPv6 (SoDIP6) network with optimum migration cost, a greedy algorithm is proposed based on optimal path and the customer priority. Simulation and empirical analysis show that a unified transition planning to SoDIP6 network results in lower migration cost.*

Contributions:

- Individual migration approaches to IPv6 and SDN are briefly presented. Their interrelationships are identified via joint migration considerations.
- A greedy algorithm is proposed based on customer priority and optimal path for phase-wise service provider network migration with available budget and the customer priority.
- Mathematical modeling and analysis are provided for migration cost estimation and percentage of cost optimization by introducing shared cost coefficient and correlation strength between two paradigms (i.e. SDN and IPv6).
- It is verified that the joint migration to SoDIP6 network optimizes the total migration cost for service providers.

Title: Evolutionary gaming approach for decision making of Tier-3 Internet service provider networks migration to SoDIP6 networks. (associated with JP4, extended version of CP5).

Abstract: *With the increasing number of Internet-of-Things (IoT) devices, current networking world is suffering in terms of management and operations with lack of IPv4 addresses leading to issues like NAT proliferation, security and quality of services. Software Defined Networking (SDN) and Internet Protocol version 6 (IPv6) are the new networking paradigms evolved to address related issues of legacy IPv4*

networking. To adapt with global competitive environment and avoid all existing issues in legacy networking system, network service providers have to migrate their networks into IPv6 and SDN enabled networks. But immediate transformations of existing network is not viable due to several factors like higher cost of migration, lack of technical human resources, lack of standards and protocols during transitions and many more. In this paper, we present the migration analysis for proper decision making of network transition in terms of customer demand, traffic engineering and organizational strength with operation expenditure for network migration using evolutionary gaming approach. Joint migration to SDN enabled IPv6 network from game theoretic perspective is modelled and is validated using numerical results obtained from simulations. Our empirical analysis shows the evolutionary process of network migration while different internal and external factors in the organization affect the overall migration. Evolutionary game in migration planning is supportive in decision making for service providers to develop suitable strategy for their network migration. The proposed approach for migration decision making is mostly applicable to fairly sustained service providers who lack economics, regulation/policy and resources strengths.

Contributions:

- A mathematical model is presented to take migration decision using bi-group evolutionary game play and performed empirical analysis to measure network utilities. This provides better knowledge for the decision makers of ISPs and Telcos to make strategic decision of their network migration.

- Presented approach is contributory to fairly sustained Tier-3 ISPs of developing nations for their optimum network transformation planning in terms of time and the cost of migration.

- Evolutionary dynamics of joint network migration based on the adaptation strength and fitness value considering customer demands, interactions with other ISPs, and status of organizational CapEX and OpEX are being demonstrated.

- Strategic migration decision, when taken in a suitable time based on the adaptation factors and fitness results as presented in this article would help to optimize OpEX to achieve higher utilities.

Title: Legacy network integration with SDN-IP implementation towards multi-domain SoDIP6 network environment. (JP6, extended version of CP4).

Abstract: *The logical separation of data plane and control plane of the network device conceptually defined by Software-defined networking (SDN) creates many opportunities to create smart networking with better efficiency for network management and operation. SDN implementation over telecommunications (Telcos) and internet service providers (ISP) networks is a challenging issue due to the lack of maturity level of SDN based standards and several other critical factors that are to be considered during the real time migration of existing legacy IPv4 networks. Different migration approaches have been studied, however, none of them seem to be closed to the reality of implementation. This paper implements the SDN-IP and open network operating system (ONOS) SDN controller to migrate legacy IPv4 networks into multi-domain Software-defined IPv6 (SoDIP6) networks and experimentally evaluate the viability of network migration to next generation SDN in the ISP networks. We present results using extensive simulations for the optimal placement of master ONOS controller during network migration by considering minimum control path latency using optimal path routing and breath first router replacement (BFR) technique. Our evaluation shows that identification of median router to attach master controller and router migration planning using BFR gives better result for carrier grade legacy networks migration to SoDIP6 networks.*

Contributions:

- Incremental deployment of SDN enabled IPv6 network using ONOS/SDN-IP is implemented.
- Suitable approach for controller placement based on minimum control path latency is presented using breadth first router replacement (BFR) approach for router migration planning during the migration of carrier grade service provider networks.

Title: Towards energy efficiency and green network infrastructure deployment in Nepal using software defined IPv6 network paradigm (JP7, extended version of CP2).

Abstract: *The use of Information and Communication Technology (ICT) has resulted in significant impacts on social welfare, economic growth, transparency and good governance in developing countries like Nepal. Due to the diverse geographic and economic situations, ICT network and service expansions throughout Nepal has been becoming quite challenging. Private network operators mostly have confined their services to urban areas. Nepal Telecommunications Authority (NTA) collects 2% royalty form Internet Service Providers (ISPs) and Telecom Operators as Rural Telecommunications Disbursement Fund (RTDF) to enhance ICT services to rural Nepal. Broadband expansion projects initiated by utilizing RTDF to expand ICT infrastructure throughout Nepal is expected to have considerable societal and economical transformations in the rural communities of Nepal. This paper not only presents the current ICT deployment scenario of Nepal but also studies design, analysis, evaluation of green networking that leverages both Software Defined Networking (SDN) and Internet Protocol version 6 (IPv6) - aka Software Defined IPv6 (SoDIP6) - for energy efficient networking, robust services and sustainable ICT ecosystem for developing nations like Nepal. We evaluate the SoDIP6 network by considering a typical ISP with end access networks and present benefits and recommendations. Experimental results show that the proposed SoDIP6 network help significantly reduce the energy consumption and carbon footprint leading to overall economic benefits to service providers and the society. Furthermore, energy saving practices through SoDIP6 networks and some policy directions to the government to focus on green networking considering sensitivity of climate change and global warming impact in the mountainous and developing countries like Nepal are presented.*

Contributions:

- Contributions of SoDIP6 networks towards green networking have been evaluated.
- Energy saving practices via SoDIP6 network implementation are presented.

Title: Affordable Broadband with Software Defined IPv6 Network for Developing Rural Communities. (JP8, Extended version of CP5)

Abstract: *The software defined networking (SDN) paradigm with enhanced features of IPv6 offers flexible network management and better network visibility for enhancing overall network performance, network manageability, and security. Thus, along with the IPv6 network deployment worldwide, SDN migration has emerged worldwide, but network service providers suffer from different issues when migrating their existing legacy network into operable SDN and IPv6 enabled networks. In this paper, we investigate the affordability of broadband network services for the rural communities in the context of information and communication technology (ICT) infrastructure deployment throughout Nepal. During the phase of network transformation, it will be more challenging for the service providers of Nepal to have a proper choice of technologies to expand the network while considering the proper policy formulation, affordability, need of skilled human resources, deployment cost, and many other aspects. We also present the service provider affordability via energy optimization in software defined IPv6 network (SoDIP6) implementation that contributes to a reduction in organizational operational expenditure (OpEX). We perform an experimental analysis over an SoDIP6 network test-bed and present a comparison of the annual energy and OpEX savings for network service providers. Our empirical analysis shows that an energy saving of 31.50% on switches and 55.44% on links can be achieved with an SoDIP6 network compared to a network with legacy devices and network management. Optimization on service provider network operational cost leads to sustainability and affordable services to both customers and service providers.*

Contributions:

- Nationwide broadband infrastructure deployment initiatives by Nepal government is discussed.
- Sustainable solutions for service providers and communities with the implementation of SoDIP6 networks are presented.

7.2.2 Summary of Contributions

The major contributions of presented research are:

- A greedy algorithm is presented based on customer priority and optimal path routing for phase-wise network router migration implementation with migration cost optimization of Tier-3 ISPs in which an ANFIS based classification approach is proposed to identify the status of routers for migration planning.
- The suitable placement of controller during network migration using BFR and MCPL approach is proposed, and evaluated the functionality of hybrid SoDIP6 network in the production level.

The minor contributions of presented research are:

- Software-defined IPv6 (SoDIP6) network is introduced.
- Challenges and issues of legacy network migration to SoDIP6 network are discussed.
- Common concerns of SDN and IPv6 with their interrelationships are identified.
- Multi-ISP network migration using evolutionary gaming approach is presented.
- A study on viable implementation of muti-domain SoDIP6 network in the production level is carried out.
- ICT and broadband policies of Nepal are critically reviewed for its implementation possibilities.
- Contributions of SoDIP6 network towards greening of ICT network has been presented.

7.3 Future Enhancement

SoDIP6 network is the new paradigm in the networking domain, which has greater challenges of implementations with issues including security, quality of services, application stability, protocol standards, and its compatibility with other communication standards.

The ongoing research and implementations have been creating a compelling situations for service providers to migrate their existing legacy IPv4 network into SoDIP6 network. However, the migration process has to handle from the multi-dimensional perspectives in terms of CapEX and OpEX optimization with availability of skilled HR. Similarly, migration of ISP/Telcos network considering backbone (MPLS/VPN) network, and metro networks requires separate study based on its technology and standards used.

Present study was particularly confined to the IP routers migration of end-access network in the Tier-3 ISPs. Following are considered as the limitations of this study and recommended as open problems for future enhancement.

1. The proposed approach of IP router status identification to measure its upgradability towards SoDIP6 capability is implemented with CISCO products. The model development with other products and for backbone network devices, for example, MPLS/VPN, and ATM switches etc. is considered as future enhancement.

2. The presented economic model and game theoretic approach of network migration is based on Tier-3 ISP networks. Migration implementation approaches in Tier-2 and Tier-1 ISPs are considered as future enhancement.

3. Finding suitable cost metrics for migration cost estimation and optimization is a major challenge of present study. In the case of availability of real dataset related to different cost metrics of ISP network migration, other machine learning methods like ant-colony optimization, particle swarm optimization, and genetic algorithm etc. shall be applicable for cost optimization.

4. For small enterprise networks, single SDN controller is sufficient, but for large ISP networks having large number of network devices, there are limited studies on controller placement and controller load balancing problems during incremental deployment of SoDIP6 network [95, 220]. These need to be further investigated.

5. The paradigm shifts in mobile communications by the conceptualization and implementation of 5G added strong requirement of SDN and IPv6 in the modern network environment. The wired/wireless network and server virtualization, high speed communications at highly dense smart devices with ultra-low

latency for real time mission critical applications, energy efficient smart network deployment with efficient radio access network (RAN) design and smart spectrum management and implementation are the part of 5G that directly concerns people's modern lives. Hence, from core network to end-access network service provisioning, cloud computing to fog computing to edge computing mostly related with the availability of 5G, SDN, and IPv6. The next generation core transport network is conceptualized by transport-SDN (T-SDN), while the wireless network virtualization is the part of 5G network and services. Hence, migration from TDM to IP networks and 4G to 5G networks, which are also related with the SDN and IPv6 implementation to establish latest generation networking for the Telcos service providers are also considered as future enhancement.

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Appendix A

Dataset for Simulations and Analysis

Table A.1: Customer priority Database - Random

cust_id	cust_name	cust_addr	cust_gateway	cust_priority
#R1	R Customer 1	b	b	1
#R2	R Customer 2	a	a	2
#R3	R Customer 3	b	b	3
#R4	R Customer 4	c	c	3
#R5	R Customer 5	d	d	4
#R6	R Customer 6	a	a	5
#R7	R Customer 7	c	c	4

Table A.2: Customer priority Database - Abilene

cust_id	cust_name	cust_addr	cust_gateway	cust_priority
#AC1	A Customer 1	Sunnyvale	Sunnyvale	1
#AC2	A Customer 2	Washington DC	Washington DC	2
#AC3	A Customer 3	Chicago	Chicago	3
#AC4	A Customer 4	Los Angeles	Los Angeles	3
#AC5	A Customer 5	Houston	Houston	4
#AC6	A Customer 6	Denver	Denver	2
#AC7	A Customer 7	Seattle	Seattle	4

Table A.3: Customer priority Database - XeeX

cust_id	cust_name	cust_addr	cust_gateway	cust_priority
#XC1	X Customer 1	Amsterdam	Amsterdam	1
#XC2	X Customer 2	Atlanta	Atlanta	2
#XC3	X Customer 3	Pittsburgh	Pittsburgh	4
#XC4	X Customer 4	Hong Kong	Hong Kong	3
#XC5	X Customer 5	Tokyo	Tokyo	1
#XC6	X Customer 6	Chennai	Chennai	5
#XC7	X Customer 7	San Francisco	San Francisco	3
#XC8	X Customer 8	San Diego	San Diego	4
#XC9	X Customer 9	Miami	Miami	3
#XC10	X Customer 10	Nashville	Nashville	3
#XC11	X Customer 11	Columbus	Columbus	2
#XC12	X Customer 12	Las Vegas	Las Vegas	6

Table A.4: Customer priority Database - BTAsia

cust_id	cust_name	cust_addr	cust_gateway	cust_priority
#BC1	B Customer 1	Auckland	Auckland	1
#BC2	B Customer 2	New Delhi	New Delhi	2
#BC3	B Customer 3	Manila	Manila	3
#BC4	B Customer 4	Seoul	Seoul	4
#BC5	B Customer 5	Tokyo	Tokyo	4
#BC6	B Customer 6	Jakarta	Jakarta	5
#BC7	B Customer 7	Taipei	Taipei	5
#BC8	B Customer 8	Mumbai	Mumbai	4
#BC9	B Customer 9	Palo Alto	Palo Alto	6
#BC10	B Customer 10	Perth	Perth	6
#BC11	B Customer 11	Chenai	Chenai	7
#BC12	B Customer 12	Bangkok	Bangkok	7
#BC13	B Customer 13	Los Angeles	Los Angeles	8
#BC14	B Customer 14	Kuala Lumpur	Kuala Lumpur	8
#BC15	B Customer 15	San Jose	San Jose	4

Table A.5: Customer gateway attachment on the Random network.

ID	Name	AS Gateway	Gateway Number	Remarks
S1	AS1	gwr1	1	CG
S2	AS2	gwr2	2	CG
S3	AS3	gwr3	3	CG
S4	AS4	gwr4	4	FG

Table A.6: Customer gateway attachment on the Abilene network.

ID	Name	AS Gateway	Gateway Number	Remarks
Chicago	Chicago	gwr1	1	CG
Los Angeles	Los Angeles	gwr2	2	CG
Houston	Houston	gwr3	3	CG
Seattle	Seattle	gwr4	4	FG

Table A.7: Customer gateway attachment on the XeeX network.

ID	Name	AS Gateway	Gateway Number	Remarks
Chennai	Chennai	gwr1	1	CG
San Diego	San Diego	gwr2	2	CG
San Francisco	San Francisco	gwr3	3	CG
London	London	gwr4	4	FG
Denver	Denver	gwr5	5	CG
Miami	Miami	gwr6	6	CG
Amsterdam	Amsterdam	gwr7	7	CG

Table A.8: Customer gateway attachment on the GEANT2009 network.

ID	Name	AS Gateway	Gateway Number	Remarks
IE	IE	gwr1	1	CG
PT	PT	gwr2	2	CG
TR	TR	gwr3	3	CG
HR	HR	gwr4	4	FG
NO	NO	gwr5	5	CG
FI	FI	gwr6	6	CG
IL	IL	gwr7	7	CG
MT	MT	gwr8	8	CG
RU	RU	gwr9	9	CG

Appendix B

Experimental Platform and Work Snapshots

In this appendix section, some snapshots of our experimental works are included. We developed a complete software package in python throughout the study including all the simulations, analysis and visualizations. Some experimental works were carried out in Mininet virtual machine for real time traffic analysis, energy evaluation of SoDIP6 network, and controller placement.

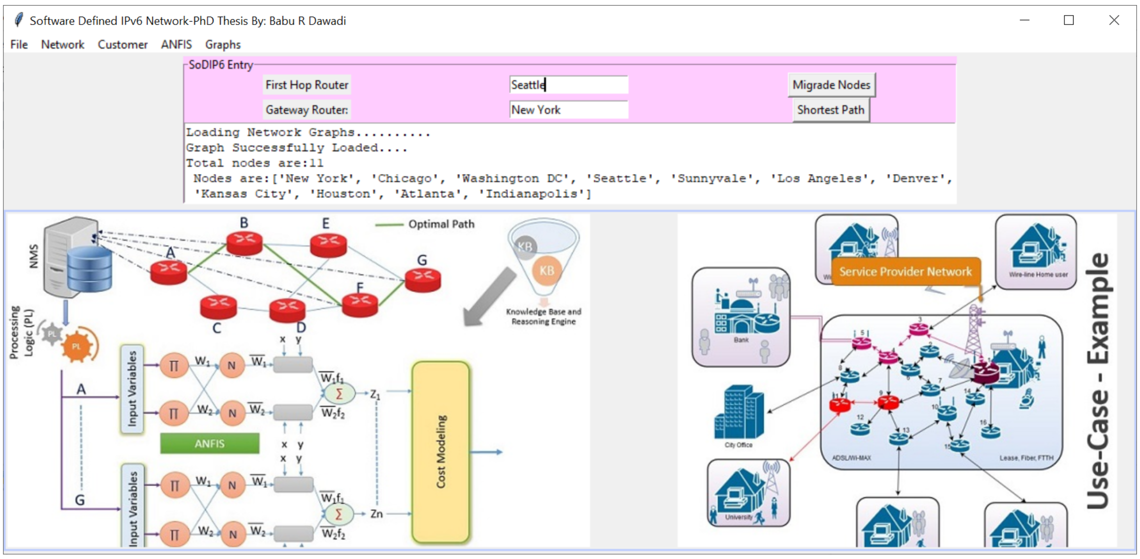

Figure B.1: Main interface window

Network menu is used to perform graph visualization, shortest path calculation, and ONOS-BGP master controller placement

Through the customer menu, we can explicitly add new prioritized customer or add set of customers from the file and view the customer details.

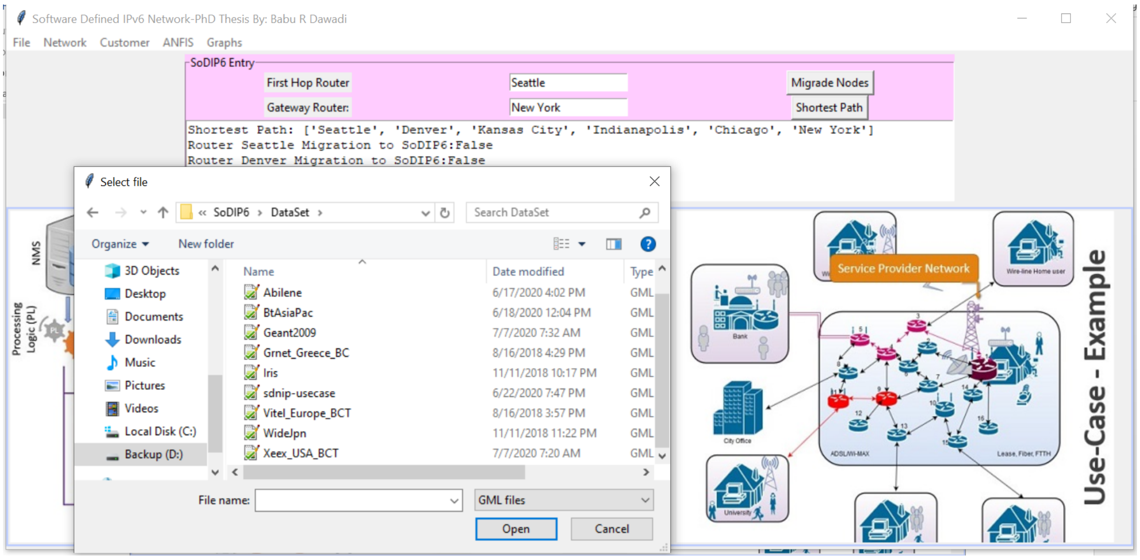

Figure B.2: Dataset load interface (File Menu). We can load network topology CSV/GML file, priority customer list, gateway routers can separately be attached on the loaded network topology.

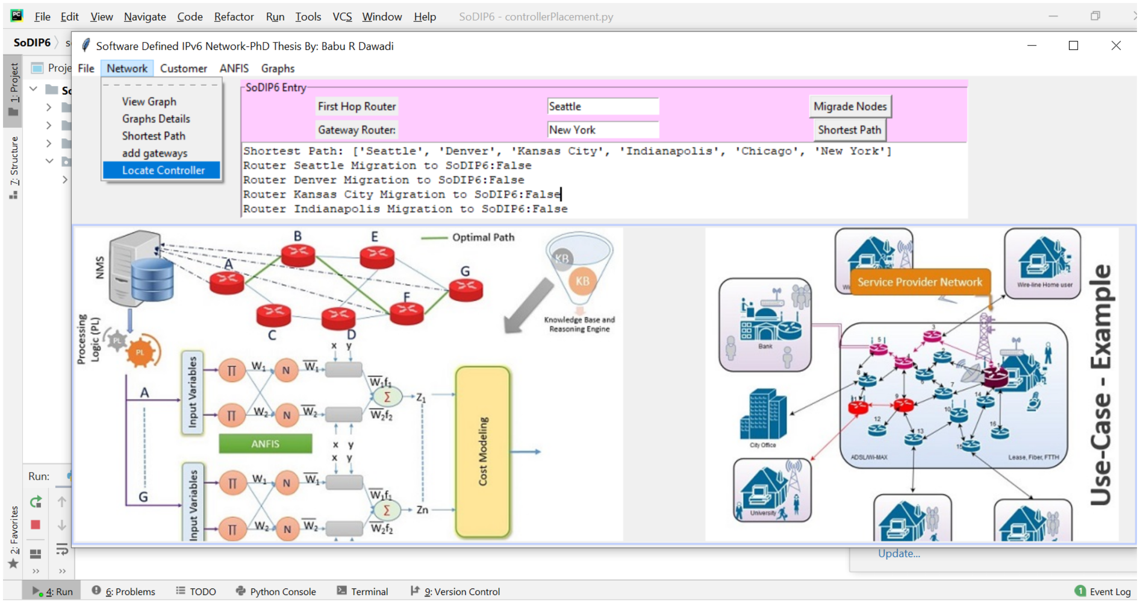

Figure B.3: Network menu

ANFIS menu is used for API call of trained ANFIS menu to predict router status. The model was trained in MATLAB 2020a, we developed a simple API call using MATLAB-engine API that opens the fuzzy logic tool box for visualization. Similarly, our program code simply passes the argument values and the ANFIS model provide the status result, which is then plotted using Python NetworkX module.

Graph menu is used to visualize all analyses and evaluations. This menu consists of the visualization of migration cost optimization, energy efficiency evaluation, game

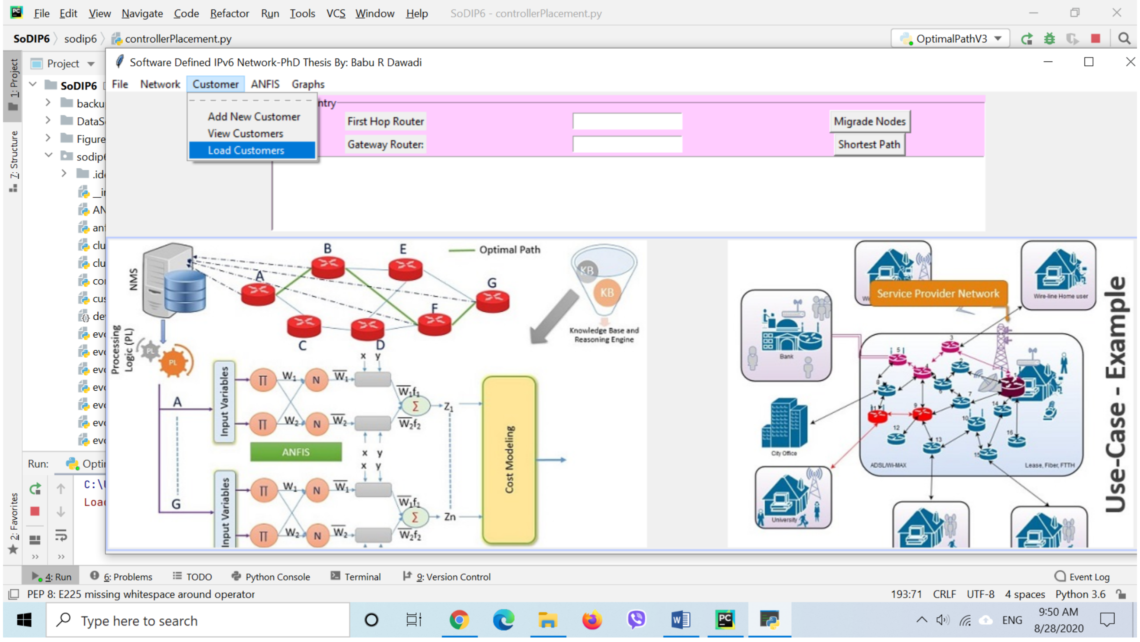

Figure B.4: Customer menu

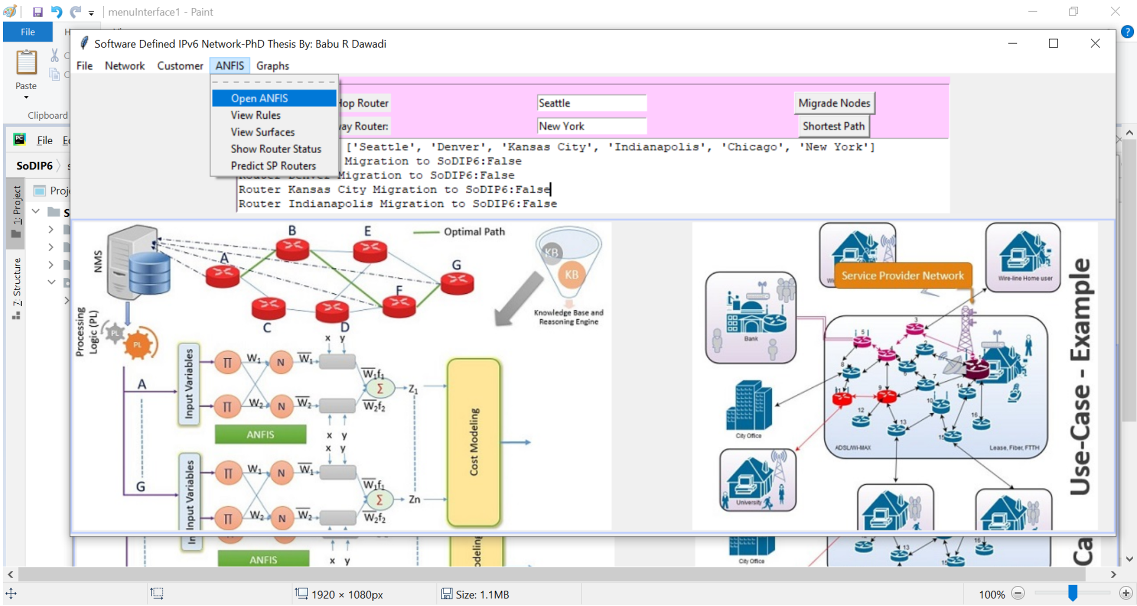

Figure B.5: ANFIS menu

theoretic approach of migration analyses and complete simulation of all routers migration in the network.

Preliminary energy consumption analysis was carried out with network topologies presented in Figure B.8.

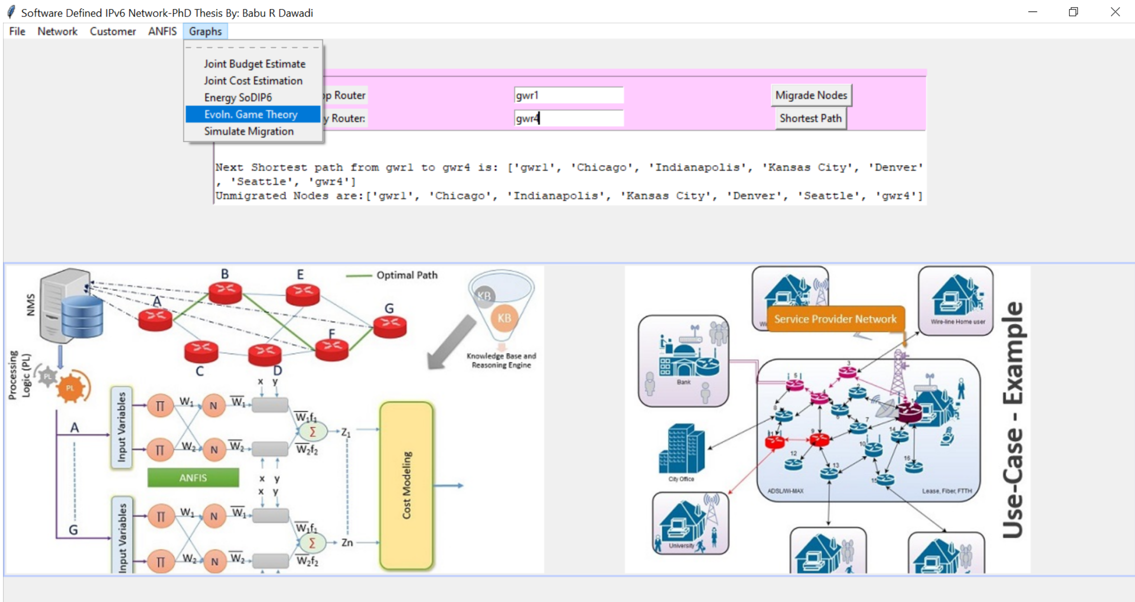

Figure B.6: Graphs menu

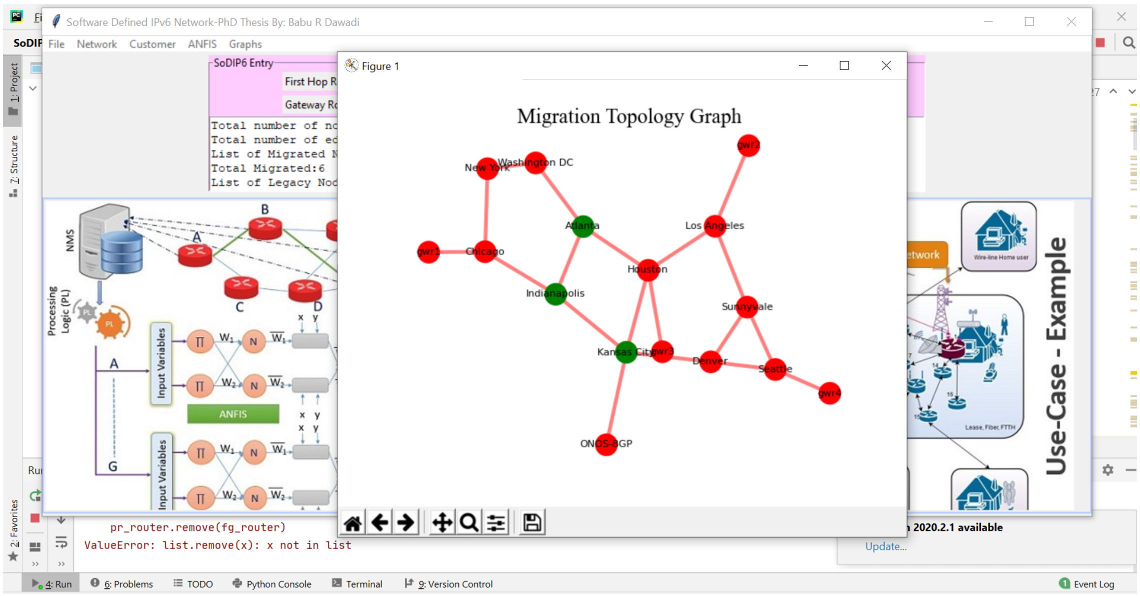

Figure B.7: Graph visualization after controller placement by the program in Abilene network.

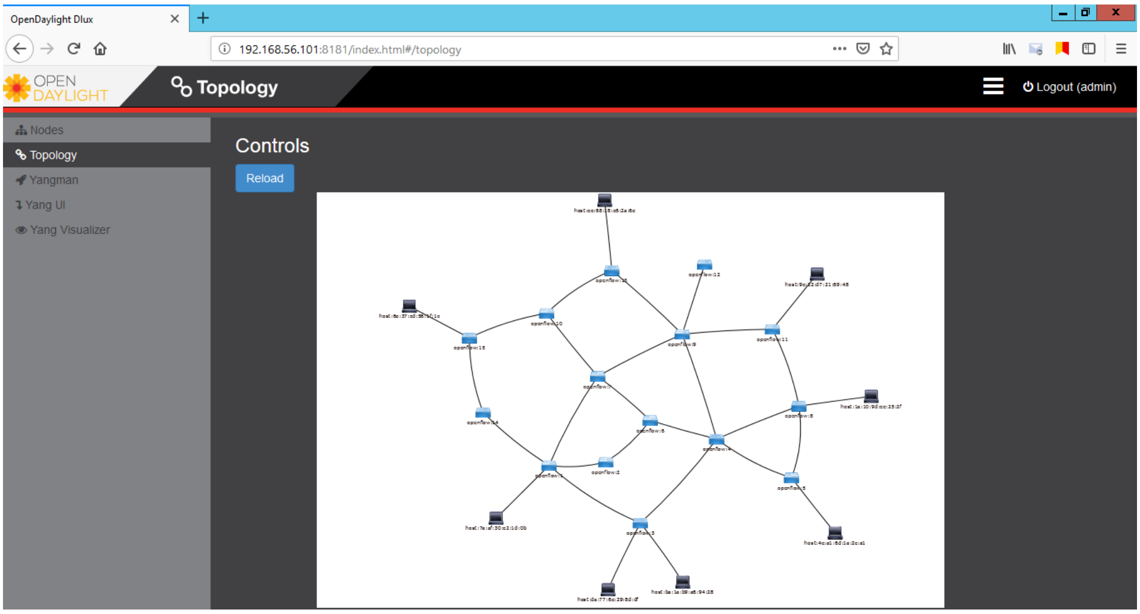

Figure B.8: SoDIP6 network topology created in Mininet with Open Daylight controller

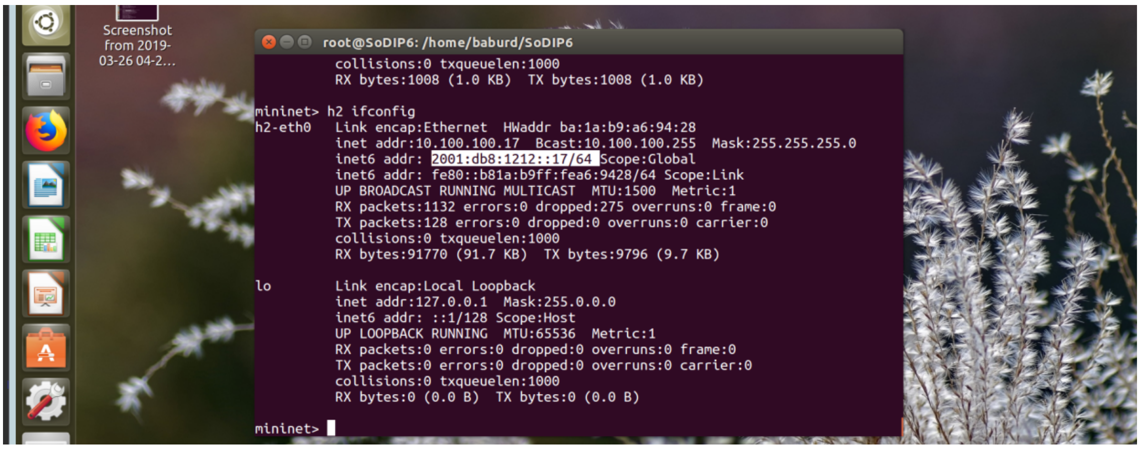

Figure B.9: IPv6 address configuration on virtual host

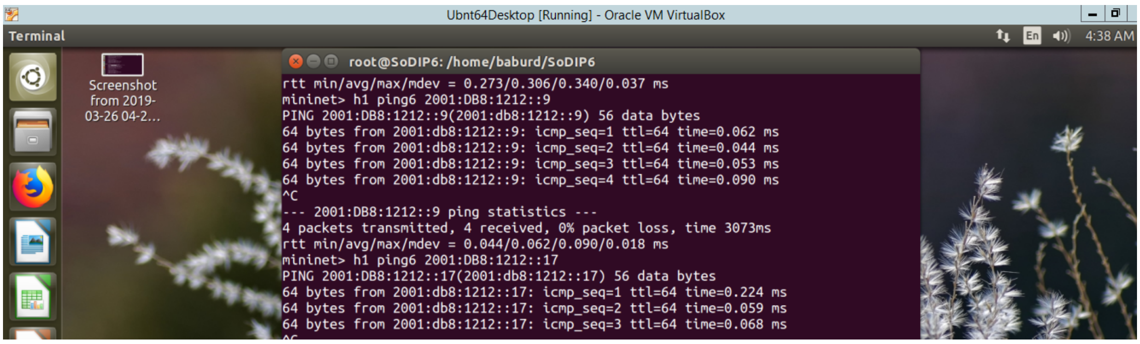

Figure B.10: IPv6 IPv6 connectivity tests among hosts in SoDIP6 network

Figure B.11: IPv6 traffic status monitoring.

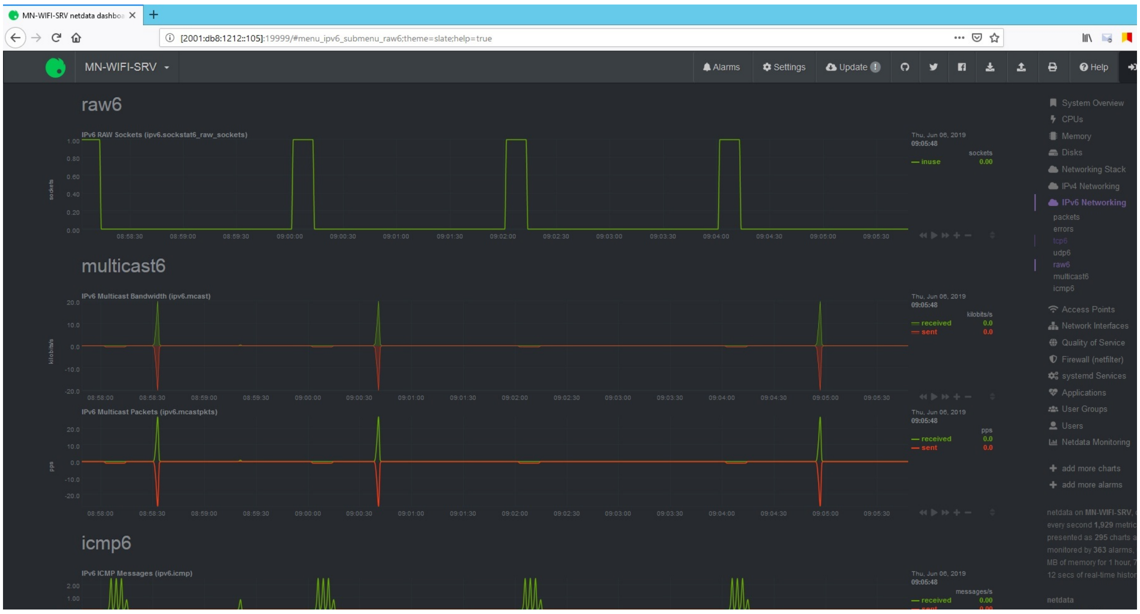

Figure B.12: Other IPv6 packet types traffic status.

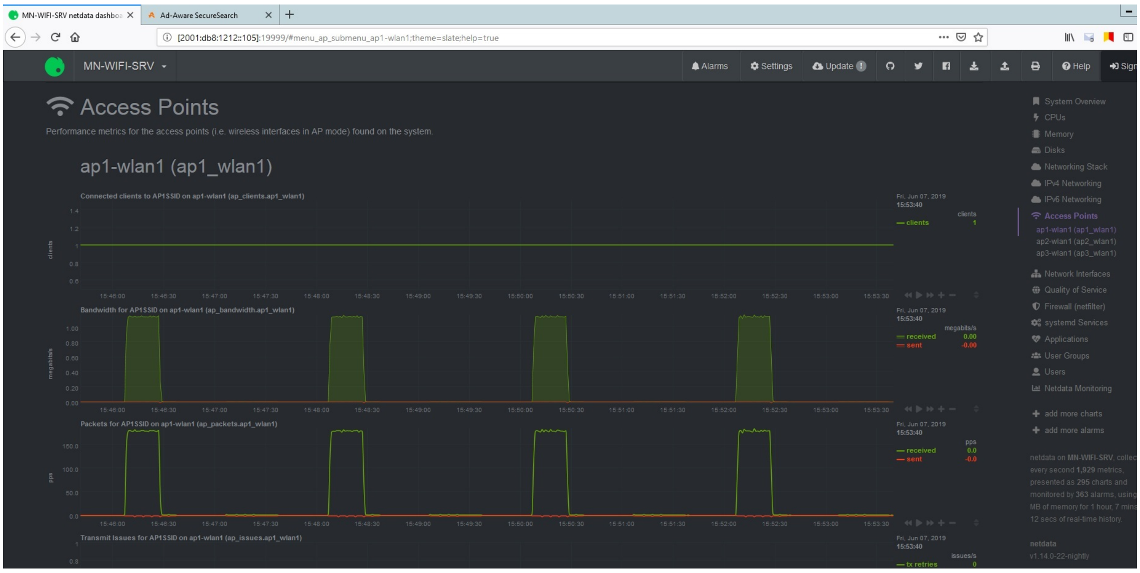

Figure B.13: Network interface (Access Point-WLAN) SoDIP6 traffic status monitoring.

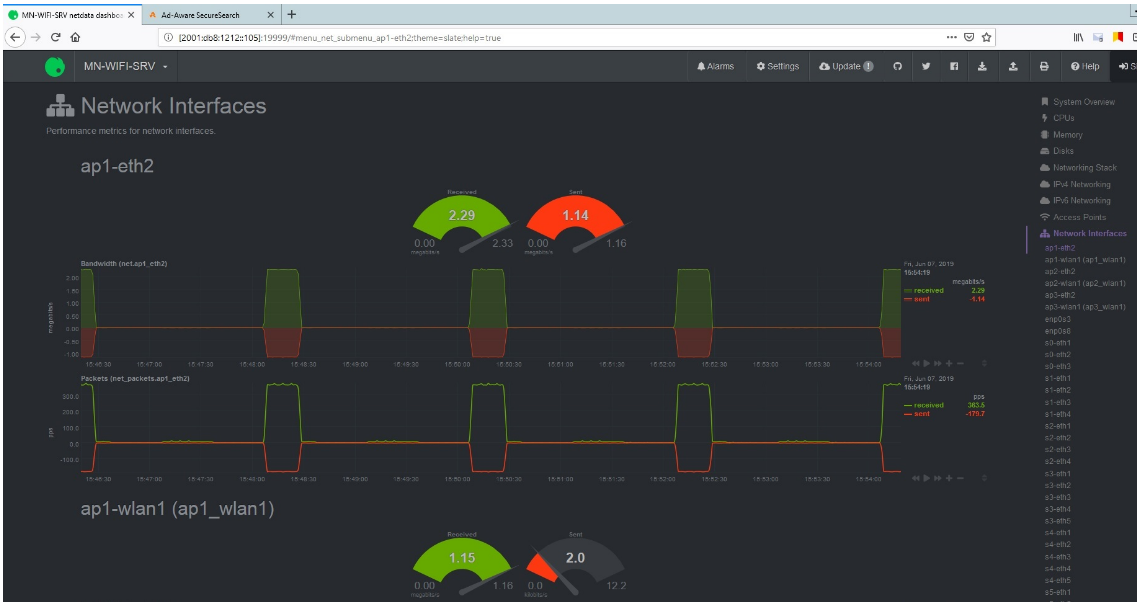

Figure B.14: Network interface (Access Point - ETH2) SoDIP6 traffic status monitoring.

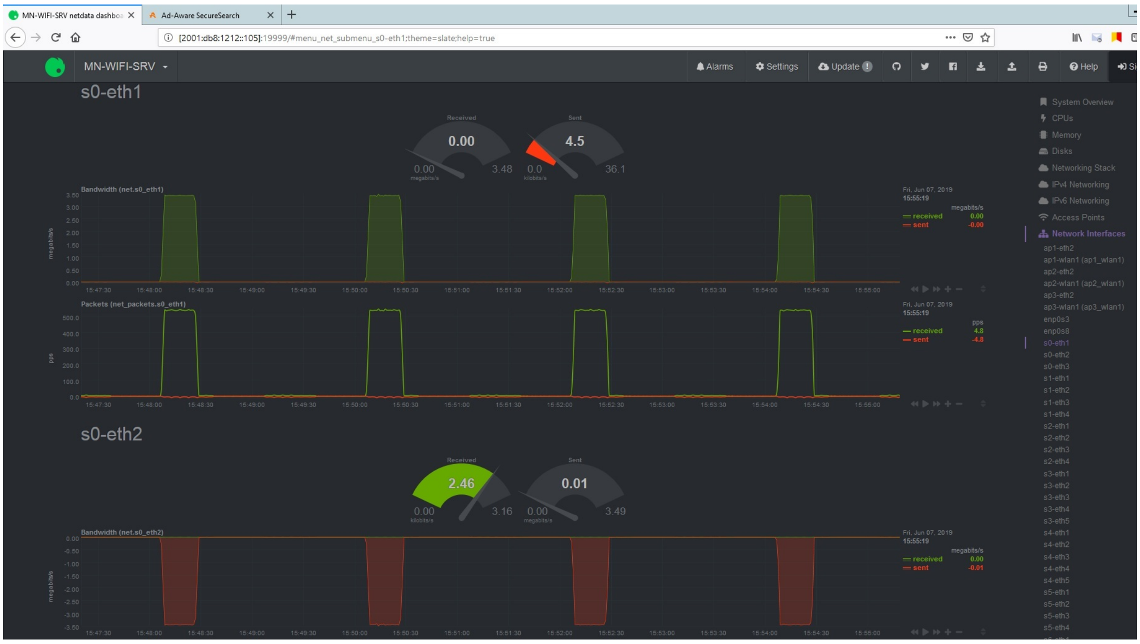

Figure B.15: OpenFlow switch interface traffic status.

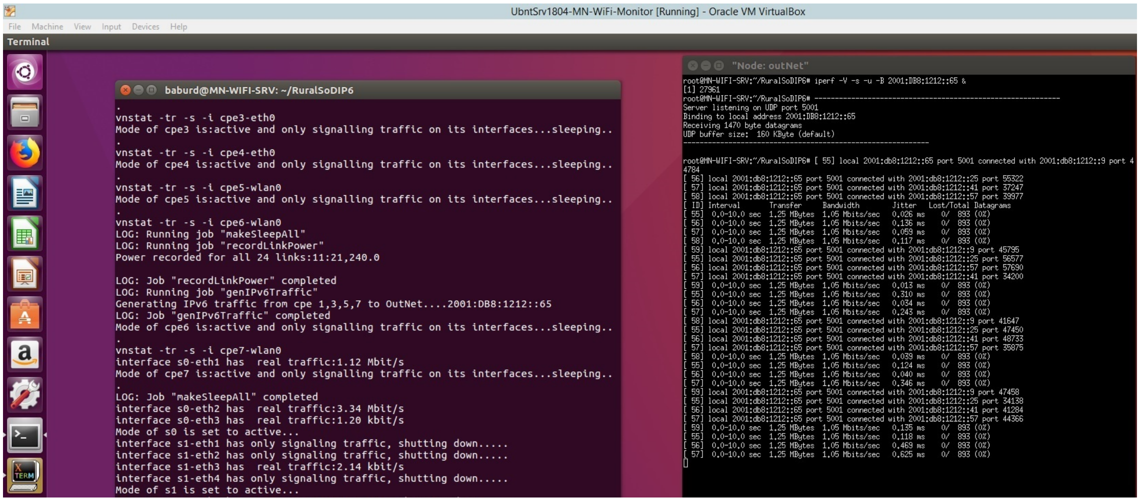

Figure B.16: IPv6 traffic generation and power monitoring daemon window.

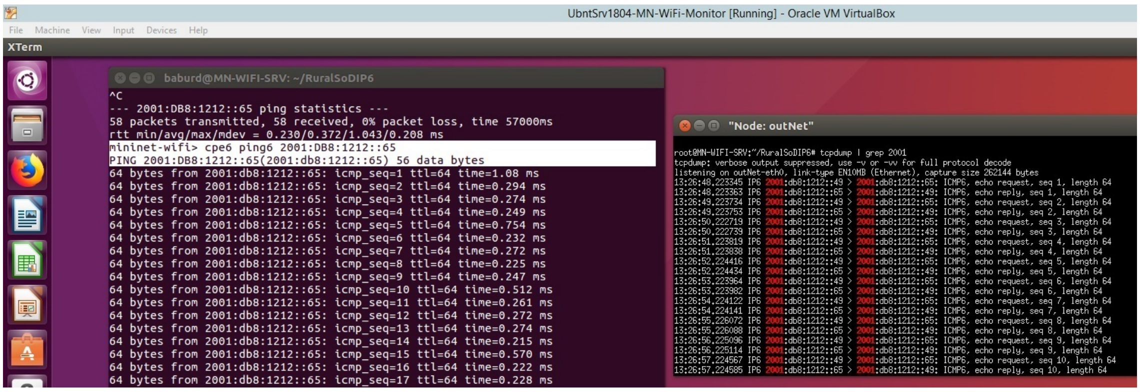

Figure B.17: IPv6 traffic generation and status monitoring - ping6 test.

Appendix C

Program Code and Configuration Details

The complete package program code, simulation configuration details, network/router configuration details with analysis data-sets are publicly available at the following GitHub link.

https://github.com/baburd/SoDIP6

Brief summary of major modules are as follows.

1. SoDIP6-Topo.py » SoDIP6 network topology created and test in Mininet VM.

2. OptimalPathV3.py » Main platform execution file.

3. RuralSoDIP6WiFi.py » Energy efficiency analysis based on end-access ISP network.

4. /sodip6/ controllerPlacement.py » simulation and analysis for the master controller placement using BFR and Non-BFR approaches.

5. /sodip6/implementANFIS.py » ANFIS API call code using MATLAB engine API via python program.

6. /sdnip/ » Router/Host/Network/BGP configuration files for ONOS-SDN-IP implementation in Mininet.

7. /DataSet/ » GML/XML and other data files for network topology, and other necessary analyses.

Appendix D

Questionnaire Survey Form

Questionnaires for ISPs/Telcos (Answer more than one if applies)

1. How big is your existing network? (Number of backbone routers/switches):........

2. Could you please provide the following?
   - Served number of home internet users:.......
   - Served number of enterprises (SMEs):........

3. Do you have your own backbone network? YES NO
   - If YES, mention from where you are leasing the capacity:..........

4. What types of technologies are you using for backbone networks?
   (a) SDH
   (b) Routers
   (c) DWDM
   (d) IP Microwave
   (e) TDM Microwave

5. Which technology are you using for internet service delivery?
   (a) Legacy TDM
   (b) All IP (NGN)
   (c) Hybrid (TDM + IP)

6. What types of equipment/devices you are using to deliver the broadband internet service?
   (a) TDM based SDH
   (b) NG SDH (IP+TDM)
   (c) Routers
   (d) Microwave

7. What types of service are you offering to the customers?
   (a) Telephone service

(b) VoIP

(c) Internet

(d) IPTV

(e) Corporate lease connection

8. What types of media are you using for connection to the customers?

(a) Wireless

(b) Copper network (UTP)

(c) Copper network(Coaxial)

(d) Fiber Network

9. Have you ever performed customer research to identify the customer demand?

(a) Yes, How often (monthly, quarterly, annually)

(b) No, Why? Please mention.......

10. Do you have target to increase the number of internet users within next three years? YES NO
- If Yes, What is your expected internet users in next 3 years?..............

11. What are the main demand factors you are seeing for growing demand of internet service?

(a) Service coverage/availability

(b) Low cost service and connection charge

(c) Educational awareness and government encouragement on e-Learning

12. What is the Average Revenue Per User (ARPU) of internet service you are offering? NRs........

13. What was the rate of increase of your customers per year? Average in last 3 years.

(a) Increased by > 10%

(b) Increased by > 20%

(c) Decreased by (specify):......%

(d) Remains constant

(e) Specify if any:..........

14. What is your annual CAPEX on Network and technology (percentage of total investment)? NRs:......

15. Do you have sufficient public IPv4 address to expand your current network? YES NO
If No, How do you plan to expand your network in the future to increase the internet users?

(a) Use existing network and apply NAT/CGN

(b) Migrate to IPv6 and Apply transition Technique like Dual

Stack Lite, CGNAT

(c) Do nothing

(d) Specify if any:.......

16. What is the mostly purchased company brands of your existing network router/switch?

    (a) CISCO (Model No if any).........

    (b) JUNIPER Versions (Model No if any)......

    (c) HUWAI (Model No if any)........

    (d) Specify any other brand:........

17. What is the original purchase price of your existing router? (just mention the range if any) Maximum price: NRs......Minimum Price NRs........

18. How old the existing router/switches?

    (a) Routers are replaced on expiration of its life (EOL) - e.g. every 5yrs .

    (b) Routers are running not more than 5 years

    (c) Some routers are running more than 5 years.

    (d) Some are running even more than 10 years

19. Are you aware of IPv6 network migration process? YES NO

20. Have you planned for IPv6 network migration? YES NO

21. Have you reserved/obtained IPv6 prefix from APNIC or from other Org.? YES NO

22. Does your backbone network support service with IPv6? YES NO - If NO, what action do you prefer with your existing backbone router to make it IPv6 Operable?

    (a) Upgrade the device hardware/IoS

    (b) Replace the device

    (c) Specify if any:........

23. What are the major causes that led you to replace the router/switch at your backbone network to make it compatible with IPv6?

    (a) However device is upgradable, Maintenance Cost is High

    (b) Existing network devices are not energy efficient

    (c) No more device support available

    (d) Can't upgrade device hardware (does not support additional CPU/Memory)

(e) Can't upgrade device IoS

(f) Specify if any:...........

24. Does your Customer End Network support service with IPv6? YES NO

25. Have you commercialized your service network with IPv6? YES NO

26. If you are planning for your network migration to IPv6. What is your target year to the complete migration to IPv6 only Network?........ How much budget have you allocated this year for device upgrade or replacement?........ How much budget have you allocated this year for training/human resource development?.........

27. Are you aware of SDN migration in the Telecom/ISP domain? YES NO
- If YES, Have you planned for SDN Migration in your network? YES NO

28. Currently, IPv6 and Software Defined Network advances as a new and better technique for network management and operation. Have you planned to upgrade your existing network into SDN? YES NO

29. Does your existing Backbone network equipment (router/switch) support OpenFlow? YES NO

30. What are the major causes that led you to replace the router/switch at your backbone network to make it compatible with SDN framework?

    (a) However device is upgradable, Maintenance Cost is High

    (b) No more device support available

    (c) Can't upgrade device hardware (does not support additional CPU/Memory)

    (d) Can't upgrade device IoS

    (e) Specify if any:...........

31. What are the major causes that delays the migration to IPv6 at your service network?

    (a) No customer demand

    (b) Still have sufficient IPv4 public addresses for network expansion

    (c) Cannot afford the device migration/replacement cost

    (d) Don't have proper government policy that compulsion for migration

    (e) International transit service is not ready with IPv6

(f) Technology limitation: compatible hardware and/or software for IPv6 is not available

(g) Specify if any:........

32. How much cost is incurred to maintain your backbone Netwrok/Router? (Please mention the estimated cost like HR cost, maintenance cost etc... based on your experience).

    (a) Human Resource Training cost per year NRs:....

    (b) Maintenance cost per year per router NRs:....

    (c) Support cost per year per router NRs:.....

    (d) Installation/configuration cost (one time) per router NRs:.....

    (e) Miscellaneous cost per router NRs:.....

33. What is your overall annual maintenance and support cost to maintain your backbone Network? (percentage of total investment) NRS:.......

34. What is your annual customer support cost (percentage of total investment)? NRs:......

35. What is your annual marketing and promotion cost (percentage of total investment)? NRs:......

36. How much power your backbone network device (Router/Intelligent-Switch) consumes in an average per month? (WATT, KWATT):..........

37. How much energy bill in an average have you paid in last three years to power supply your backbone network equipment? NRS:........

38. How do you guarantee the Return on Investment (ROI) against your investment on migration to new technologies like SDN and IPv6?

    (a) Migration is inevitable for the sustainability

    (b) Network will be more secure and manageable. So reduced the operation/management cost

    (c) Expand the network infrastructure and increase the user

    (d) RoI is not guaranteed hence delayed the migration

    (e) Specify if any:.......

Questionnaires for Policy Makers

1. How do you rate Nepal's broadband service development compared to South Asian Countries?
   (a) Good
   (b) Average
   (c) Bad
   (d) Unable to rate
2. Do you think the broadband service expansion initiatives are adequate to increase the coverage of service across the country? YES NO
3. What are the main policy constraints restraining the broadband infrastructure development?
   (a) Policy related to infrastructure sharing
   (b) Policy related to convergence of network, services and contents
   (c) Telecom Acts for licensing
   (d) Unified policy for infrastructure development
   (e) Specify if any:...........
4. What are main points required to change the Act, policy, directives for efficient and effective role out of broadband service?
   (a) Variable licensing policy(multiple service at multiple geographical locations)
   (b) Conditional licensing policy (related to RTDF licensing policy
   (c) Convergence of service, network and contents
   (d) No Change Required
   (e) Specify if any:..........
5. What shall be done to provide affordable broadband service across the country?
   (a) Provide subsidy to develop infrastructure
   (b) Mandate service providers to provide services in remote areas
   (c) Provide tax and customs incentive for equipment and services
   (d) Create local services and content
   (e) Reduce cost of international bandwidth
   (f) Specify if any:...........

How can we reduce the cost for internet service in Nepal?

(a) Increase subscriber base

(b) Encourage local contents

(c) Reduce cost of international bandwidth

(d) Provide attractive service schemes

(e) Require Government subsidies

(f) Specify if any: ....

What major strategies have to be adopted to boost broadband infrastructure development in Nepal?

(a) Government initiatives

(b) Encourage service providers to invest by providing subsidies

(c) Create separate and autonomous infrastructure entities

(d) Specify if any:..........

Do you think the current regulatory and legal framework in Nepal is sufficient for fast roll-out of broadband network? YES NO
- If NOT, what areas of regulatory and legal framework is required and how?...................

Do you have any policy initiatives regarding IPv6 Network migration? YES NO
-If YES, specify:...............

Do you have any policy initiatives regarding Software Defined Network Migration? YES NO
-If YES, specify:............

How do you encourage service provider and Govt. enterprises to migrate their network into new technologies?

(a) Mandate as part of service provider license regime

(b) Provide financial incentive to migrate

(c) Provide policy incentive to migrate

(d) Reward timely and effective migration

(e) Provide tax subsidy on service tax and equipment procurement

(f) Specify if any:........

Questionnaires for Cloud service providers

enumerate

Do you have sufficient public IPv4 address to expand your current DC (Data-center) network? YES NO
-If NO, How do you plan to expand your network in the future to increase services?

(a) Use existing network and apply NAT/CGN

(b) Migrate to IPv6 and Apply transition Technique like Dual Stack Lite, CGNAT

(c) Do nothing

(d) Specify if any:.............

What are the most widely used brands of your existing DC network router/switch?

(a) CISCO (Model No if any)........

(b) JUNIPER (Model No if any).......

(c) HUWAI (Model No if any)........

(d) Specify if any other:............

What is the original purchase price of your existing router? (just mention the range if any) Maximum price: NRs.........Minimum Price NRs ....

How old are the existing router/switches in your DC Network?

(a) Routers are replaced on expiration of its life (EOL).

(b) Routers are running not more than 5 years

(c) Some routers are running more than 7 years

(d) Some are running even more than 10 years

(e) Specify if any:............

Have you planned for IPv6 network migration at your DC? YES NO

Have you reserved/obtained IPv6 prefix from APNIC or from other Org.? YES NO

Does your DC network support service with IPv6? YES NO -If NO, what action do you prefer with your existing backbone router to make it IPv6 Operable?

(a) Upgrade device hardware/firmware

(b) Replace device

(c) Specify if any:.............

What are the major causes that led you to replace the router/switch at your backbone network to make it compatible with IPv6?

(a) Although device is upgradable, Maintenance Cost is High

(b) Existing network devices are not energy efficient

(c) No more device support available

(d) Can't upgrade device hardware (does not support additional CPU/Memory)

(e) Can't upgrade device IoS

(f) Specify if any:.........

Are the DC servers (DNS, Web...)

/routers are migrated to IPv6 operable network? YES NO
- If YES, can you provide the service under IPv6 network on demand? YES NO
- If NO, do you have any plan to migrate the DC into IPv6? YES NO

Have you commercialized your DC service network with IPv6? YES NO

What are the major causes that delays the migration to IPv6 at your service network?

(a) No customer demand

(b) Still have sufficient IPv4 public addresses for network expansion

(c) Cannot afford the device migration/replacement cost

(d) Don't have proper government policy that compulsion for migration

(e) International transit service is not ready with IPv6

(f) Technology limitation: compatible hardware and/or software for IPv6 is not available

(g) Specify if any:..........

If you are planning for your DC network migration to IPv6.
- What is your target year to the complete migration to IPv6 only Network? ....
- How much budget have you allocated this year for device upgrade or replacement?........
- How much budget have you allocated this year for training/human resource development? ....

Are you aware of SDN migration in the DC network? YES NO
- If YES, Have you planned for SDN Migration of your DC network? YES NO

Currently, IPv6 and Software Defined Network advances as a new and better technique for network management and operation. Have you planned to upgrade your existing network into SDN? YES NO

Does your existing DC network equipment (router/switch) support OpenFlow? YES NO

What are the major causes that led you to replace the router/switch at your DC network to make it compatible with SDN framework?

(a) However device is upgradable, Maintenance Cost is High

(b) However device is upgradable, Maintenance Cost is High

(c) Can't upgrade device hardware (does not support additional CPU/Memory)

(d) Can't upgrade device IoS

(e) Specify if any:........

Appendix E

Summary of Research Visits

Babu Ram Dawadi had visited following international universities as a part of this research studies.

1. Visited as PhD research scholar at the Department of Design, Norwegian University of Science and Technology (NTNU), Trondheim, Norway.

   Period : July 13 - Dec. 18, 2018
   Visiting Advisor : Prof. Dr. Martina M. Keitsch
   Funding : NTNU-MSESSD-program in support of EnPe (NORAD)

2. Visited as PhD research scholar at the Department of Computer Engineering, Networking Research Group (GRC), Universitat Politècnica De València (UPV), Spain.

   Period : Feb 10 - July 9, 2020
   Visiting Advisor : Prof. Dr. Pietro Manzoni
   Partial Funding : PhD mobility program, ERASMUS+ KA107 project