Evolutionary Gaming Approach for Decision Making of Tier-3 ISP Networks Migration to SoDIP6 Networks

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Abstract

With the increasing Internet of Things (IoT) devices, current world networking infrastructure is becoming complex in management & operation with lack of IPv4 addresses leading to issues like NAT proliferation, security and quality of services. Software Defined Network (SDN) and Internet Protocol version 6 (IPv6) are the new networking paradigms evolved to address related issues of legacy IPv4 networking system. To adapt with global competitive environment and avoid all existing issues in legacy networking system, service providers have to migrate their network into IPv6 and SDN enabled network. 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 with simulations and numerical results. Our empirical analysis shows the evolutionary process of network migration while different internal and external factors in the organization affect the overall migration. Evolutionary gaming in migration planning is supportive in decision making for service providers to develop suitable strategy for their network migration. This approach of migration decision making is mostly applicable to fairly sustained service providers that are mostly affected due to lack of economic, policy and resources strength.

KEYWORDS

IPv6 network, Software Defined Network, SoDIP6, Evolutionary gaming, ISP network migration

1. Introduction

The achievement of robust, secure, scalable, flexible and manageable network is possible with the advancement on internet protocol addressing and software controlled networking via the emergence of Internet Protocol Version 6 (IPv6) addressing and software defined networking. Sufficiency of addresses to identify network devices and things interconnected in the growing number of smart devices in the networking world leads to the speedy deployment of Internet of Things (IoT) and Wireless Sensor Networks (WSN) towards smart of everything. The opportunity towards smart networking world have been exploited but there exists challenges of transforming current network to future networking like Software Defined Network (SDN) and IPv6 as new technologies.

IPv6 addressing mechanisms, SDN and Cloud Computing are major inventions that the network and cloud service providers are emerging to use for robust services with better efficiency. Figure 1 shows the amalgamation of these technologies and how the IPv4 based legacy network can be migrated to future network consisting of SDN and IPv6. With the exponential growth of smart devices, massive use of IoT and WSN to build smart systems and communities in the cyber physical world, there is considerable demand for IP addresses that can be fulfilled by the IPv6 addresses as there starts IPv4 address trading due to its depletion [1]. The management issues of vertically integrated legacy IPv4 networking system can be avoided with the emergence of SDN while issues of IPv4 addressing and routing can be addressed by the deployment of IPv6. Hence, SDN & IPv6 jointly known as SoDIP6 network [2] addresses all the issues of legacy networking system with the establishment of highly robust network in terms of operation, control, security, quality of service manageability and many more. After its popularity in data center networks, research on SDN migration in Telecom (Telcos) and ISP networks currently become the central focus for researchers worldwide. Hence, we consider the joint migration approach of SDN and IPv6 so that service providers will achieve well performed future network with optimized operational and capital expenditure.

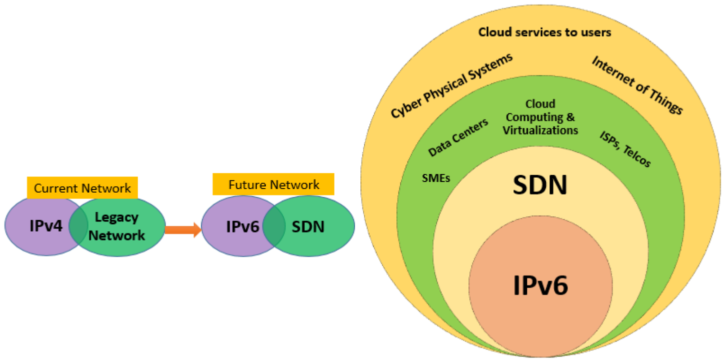

Figure 1. Future networking paradigms

SDN and the IPv6 are interrelated technologies where IPv6 operate on the network layer and SDN controls the network layer devices by detaching control and data plane, making the network more manageable by allowing customized applications at its north bound and open standards at its south bound. IPv6 promises to add scalability and better quality of services while SDN promises to increase the infrastructure flexibility with on-demand provisioning of network resources and integrated into overall cloud orchestration. SDN could help to reduce the organizational capital and operational expenditure (CapEX/OpEX) [3] that encourages the service providers to find better options and attraction towards SDN. Besides the implementation challenges [4], SDN is proven technology towards efficient network management that it solves those existing issues and create highly flexible, programmable, scalable, modular, open interface and abstraction-based networks [5], [6].

Immediate service provisioning of newer technologies according to customer demand could not be viable for service providers. For the fairly sustained network service providers, 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. IPv6 network migration approaches [7] [8] have been developed and its implementation is in action. But SDN deployments at ISP and Telcos networks are still in the beginning stage. In light of this scenario, we present the simulation and analysis on evolutionary process of network migration to newer technologies like SDN and IPv6 jointly for service networks particularly focusing on Tier-3 ISPs. Following are the major contributions of this research.

- We establish mathematical model to take migration decision in the bi-group evolutionary game play and simulate the scenario to measure network utilities. This provides better knowledge for the decision makers of ISPs and Telcos networks to make strategic decision of their network migration.
- With this study, fairly sustained Tier-3 ISPs of developing nations are supposed to be more benefitted for their optimum network transformation planning in terms of time and the cost of migration.
- Changing the strategy for migration by one ISP affects the business of another ISP within the interconnected ISP networks. Hence, we consider the network migration as an evolutionary process and evaluate the strength of migration and its effects on utilities using well known evolutionary gaming approach.

IPv6 and SDN, being an interrelated technologies, we consider joint migration modeling so that overall cost of migration can be optimized. The targeted network is considered to be the quad stack (IPv4, IPv6, Legacy and SDN) SoDIP6 network.

This paper is structured as follows. We identify the common requirements of legacy network migration into SDN and IPv6 network as a common concerns in section 2. Section 3 discusses the evolutionary dynamics of SoDIP6 network migration, while section 4 presents the simulation and analysis of network migration as an evolutionary process. Section 5 presents the related works in SDN enabled IPv6 network migration, while the paper is concluded in section 6.

2. Common concerns of SoDIP6 network migration

Software Defined IPv6 (i.e. SoDIP6) Network is introduced at [2] while it is defined as *"The next generation networking infrastructure, standards and applications fully capable to operate with newer networking paradigms like SDN and IPv6 network and their applications".*

There exist several challenges for the service providers [9], [10] mainly in terms of technical, financial and business domains. These are like network operations, skilled human resource development, cost of investment & operation/maintenance, security, quality of service, reliability of service, applications readiness, proper planning, business strategy development and coordination with national or international transit connections to make the network operable with newer technologies. The common concerns for the SoDIP6 network migration are depicted in Figure 2. These are in fact a common challenge for IPv6 and SDN migration both

[2]. Such emerging new paradigms create both the opportunities and challenges to ISPs and Telcos to migrate their networks. It has already been two decades that IPv6 is introduced but complete migration to IPv6 only network could not be achieved yet. Similar scenario could happen with SDN because of transformation complexity. The major challenges in network migration are summarized below for the internet and telecom service providers. These are:

- Lack of confidence to provide uninterrupted service to the customers during migration
- Higher cost of network device migration/replacement
- Higher cost of training and skilled human resource development
- Lack of immediate availability of stable networking & server applications during transition
- Possible issues of security and quality of service during and after the migration

Hence, need of proper strategy and smooth transition planning for service providers considering above issues for their network migration to new technologies encourages us to address the migration problems via this research. Transformation of legacy IPv4 networks into SoDIP6 network is a phase-wise process with real time migration. ON.LAB [11] mentioned that nature of service provider network is typically different than the data center networks so that it requires a carrier grade SDN that supports commercial service with diversity of devices on the southbound as well as rich and flexible APIs on the northbound and southbound that helps for smooth and cost-effective migration. Carrier Grade Network Address Translation (CGNAT) devices are already available as a solution to handle transition of legacy IPv4 network into IPv6 network with continuity of IPv4 based services [12]–[14]. IPv6 and SDN are the underlying network technologies to be considered for the migration. These are related because IPv6 mainly concerns with the protocol recognition by applications, packet processing and routing while SDN concerns with the networking control and routing/switching management. In this regard, considering migration planning of two technologies as a joint migration would help to reduce the organizational costs.

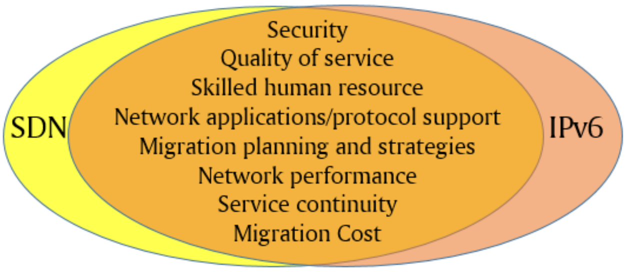

Figure 2. Common concerns of network migration

3. Game theoretic approach on SoDIP6 network migration

Strategic decision making for network migration is the most for service providers. Hence, we consider Tier-3 ISP networks that provide services directly to enterprises and home users to show the evolutionary process of migration. In this section, we first discuss the causes of resistance and attraction for network migration to SoDIP6 network. This gives us better understandings for necessary assumptions in our simulation work. Then we analyze the migration scenario by formulating a game with predefined strategies between two groups of ISPs.

3.1 Resistance to offer SoDIP6 network

The major reasons that any one ISP resists for migration are the huge cost of investment to migrate, lack of full proof applications and protocol support, lack of technical human resources, lack of clear revenue generation strategies and lack of confidence that their investments will be returned after the migration. Legacy IPv4 network is stable, it supports varieties of applications and protocols that service providers are currently providing. Additionally, there are many translation and tunneling approaches developed and applied with least cost to communicate with remote IPv4 ends as well as communication with IPv6 networks. However the IPv4 address is already depleted, the reuse of private addresses and applicable recursive Network Address Translation (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 human resources 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.

3.2 Attraction towards SoDIP6 network

SDN is successfully implemented in the data center networks [5], [11], [15], [16]. Its implementation and migration prospects in the telecom and ISP network is popularly under research, development, implementation and testing. World-wide IPv6 adoption rate is crossing 24% while its growth in the recent years is exponential [17], [18]. In such scenario, being correlated technologies, we modeled the joint migration and its benefits in migration cost optimization for service providers towards incremental deployment to hybrid SDN and dual stack IPv6 network in our previous works [19]. 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, control and operation complexity etc. 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. Jointly looking into the features of SDN and IPv6 network that encourages for network migration are summarized below.

- **Sufficient address space:** the 128 bits length IPv6 addressing structure provides higher than the astronomical value to uniquely identify networking devices in this universe. This creates scalable network while the implementation of IoT and expansion of WSN will be more convenient to create smart world.
- **Efficient & hierarchical addressing and routing infrastructure:** 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. This creates an efficient, hierarchical, and summarized routing infrastructure.
- **Stateless and stateful address configuration:** this 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 configure its link local and global IPv6 address via random assignment by using specific algorithm or by using EUI-64/SEUI-64 address format [20] 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.
- **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 chained fashion after IPv6 header.
- **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 devices simply act as a packet forwarding elements 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.
- **Flow based:** Flow based instead of destination based [21] forwarding decisions are made by the 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.
- **Programmable network:** programmability features 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.
- **Open interface:** standardization of 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.
- **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.
- **Security:** IP Security (IPSEC) is a default security framework defined under IPv6 protocol suite requirement. IPSEC provides set of standards for authentication and encapsulation with key management framework for network security needs and promotes interoperability between different IPv6 implementations. Similarly, network programmability and centralization of control plane in the network adds more flexibility to apply different security policies to build robust and highly secure network environment.
- **Energy efficiency:** due to the lack of smart controlling features with the legacy IPv4 networking equipment, energy consumption by network equipment is higher and increasing the energy bill with the increase of network size as well. SoDIP6 network is more energy efficient in which energy saving can be achieved algorithmically or through the hardware improvements [22]. Implementing SoDIP6 network has significant CapEX saving with energy optimization and reduction of CO_2 emission making the network more energy aware and promote towards green ICT [22], [23].

Thus, 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, demand of new 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. In the below section, we provide assumptions and scenarios for network migration planning with respect to evolutionary process.

3.3 Migration to SoDIP6 network: an evolutionary gaming approach

3.3.1 ISP network interconnection architecture for migration modeling

ISP networks consist of the worldwide interconnection of networks of networks by means of which an access to internet is provided to home users and enterprises. World-wide ISP networks are categorized into Tier-1, Tier-2 and Tier-3 ISPs based on the infrastructure connectivity and the provision of services to clients [24]. 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 able to exchange traffics 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 traffic flow in the hierarchies, ISPs in the same label can have private, public, transit and donut peering with other ISPs [25] and might have settlement-free interconnection agreement. Peering with multiple ISPs can be Tier-1 ISPs to exchange the high speed peering traffic and might have settlement-free interconnection agreement. Multiple ISPs can have peering through Internet eXchange Point (IXP) [26]–[28]. For example, London Internet Exchange (www/linx.net, accessed on 26 December 2019) and NetIX (www.netix.net, accessed on 26 December 2019) are the largest internet exchange in the world, Toronto internet exchange (www.torix.ca, accessed on 26 December 2019) is the largest internet exchange in North America.

For the migration modeling in this study, we assume 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, which represents a particular scenario as a Tier-3 national ISP network interconnection where 16 ISPs are interconnected out of which 5 ISPs are 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 we can see on the national ISP network interconnection architecture. In the bi-group game play, we suppose 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.

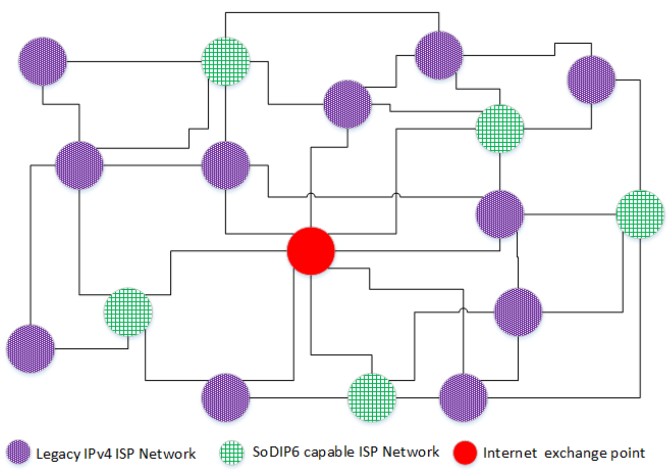

Figure. 3. Tier-3 ISP network interconnections architecture

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, 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-3 or Tier-2 ISPs and hence the cost of transit service use is an expenditure.

Table 1 Symbols and their usual meaning for migration modelling

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

3.3.2 Mathematical modeling for migration cost optimization

We assume 'K' number of ISPs have already migrated to SoDIP6 networks from among 'N' number of ISPs in total and 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. We expect that all ISPs participating in the evolutionary game play will migrate to SoDIP6 network with probability that suitable time for migration decision making can be determined by the migration strength presented as adaptation variable in equation (3) and the fitness value provided by equation (5). 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) and the fitness value provided by equation (4). 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:

$$\mu_k^4 = p_k^4 - c_k^4 \tag{1}$$

The symbols with their usual meaning as depicted in Table 1, initial parameter value assumptions in Table 2 and the mathematical interpretations were adapted from our previous work presented as a preliminary analysis [25]. If anyone ISP at a moment decided to migrate to SoDIP6 network, then the utility for an ISP migrated to SoDIP6 network can be expressed as:

$$\mu_k^{s6} = p_k^{s6} - c_k^{s6} \tag{2}$$

We suppose, SoDIP6 network is backward compatible and hence the utility due to its legacy networking capability will be an added benefits. The literature review shows that the operational cost of SDN and IPv6 network is comparatively lesser than the existing legacy networking system [3], [19], [29], [30] . It means SDN enabled IPv6 network will have higher payoffs as well as less operation cost. Equation (3) 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 $\sigma_c = \frac{n_{kt}}{n_t}.e^{\frac{(n_{t-1}-n_t)}{n_t}}$, $\sigma_p = \frac{(n_p - n_{p4}).ipv6_{in}}{n_p.(ipv4_{in}+ipv6_{in})}$ and $\sigma_s = \frac{HR_{s6t}.B_t}{HR_{all}.C_m}$. Finally, summing all three sub adaptation parameters to calculate overall adaptation strength (σ_{4t}) as follows:

$$\sigma_{4t} = \left|\{\sigma_c\} + \{\sigma_p\} + \{\sigma_s\}\right| = \left|\{\frac{n_{kt}}{n_t}.e^{\frac{(n_{t-1}-n_t)}{n_t}}\} + \{\frac{(n_p - n_{p4}).ipv6_{in}}{n_p.(ipv4_{in}+ipv6_{in})}\} + \{\frac{HR_{s6t}.B_t}{HR_{all}.C_m}\}\right| \tag{3}$$

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 and σ_s measures the strength in terms of organizational budget available and technical human resources available for migration. The absolute sum of three sub adaptation parameter values is considered as the overall strength for migration. Those mathematical parameters are derived based on the Tier-3 network interconnection architecture presented in Figure 3 and the economic models referred from [31]–[33] while changing different parameter values and their effect on overall adaptation strength are presented in section 4.

For this particular simulation, we consider that N (=16) ISPs operating in legacy IPv4 network will migrate in six years for which timestamp for migration decision making is divided into 24. Each timestamp consists of 3 months. i.e. on every three months period, legacy IPv4 ISPs (Group-1 ISP) 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 ISPs regarding their maintenance plan, 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 for 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 human resources 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 of SoDIP6 network operation 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.

Now N (=16) number of ISPs transitioning to SoDIP6 network based ISPs is 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). We consider the Moran process [34] where there is fixed number of populations (i.e. N number of ISPs) remains same and relative fitness to be calculated with fitness function measures in terms of strength of adaptation and the utilities given by equation (4) in which 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 & Group-2 ISPs both have expected payoffs calculated as below.

$$\gamma_1 = \frac{\sum_{k=1}^{N1-X^S_{4\to6}} \mu_k^4}{N1-X^S_{4\to6}},\ \gamma_2 = \left\{\frac{\sum_{k=1}^{N2} \mu_k^{s6}}{N2} + \frac{\sum_{k=1}^{X^S_{4\to6}} \mu_k^{4s6}}{X^S_{4\to6}}\right\}$$

Based on the expected payoffs, the Group-1 and Group-2 will have fitness values [35] calculated as:

$$f_{4t} = 1 - \delta + \delta.\gamma_1 \text{ and } f_{s6t} = 1 - \delta + \delta.\gamma_2 \tag{4}$$

Where $\delta\left[= \left(\frac{1}{1+e^{-\sigma_{4t}}}\right).\eta\right]$ measures the migration strength modeled in terms of migration constant 'η' as a coupling coefficient between two networking paradigms (SDN, IPv6) [19] and the logistic regression with σ_{4t} in the range from 0 to 1 and hence 0 <= δ < 1 is true. When δ = 0, the fitness does not depend with payoffs and the migration strength. This discourages the decision making for migration. Similarly, at $\delta \cong 1$, 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 same. From the principle of evolutionary dynamics [34] [36], 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 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:

$$p_{K,K+1} = \frac{K.f_{s6t}}{K.f_{s6t}+(N-K)f_{4t}}\,\frac{N-K}{N} \text{ and } p_{K,K} = 1 - p_{K,K+1} \tag{5}$$

In absorption states, i. e. at $p_{0,0} = p_{N,N} = 1$, all ISPs apply same strategy. The fixation probability (P_{s6t}) [35], [37] determines the scenario that migration to SoDIP6 favors only if $P_{s6t} > \frac{1}{N}$, where $P_{s6t} = \frac{1}{1+\sum_{k=1}^{N-1}\prod_{j=1}^{k}\frac{f_{4t}(i)}{f_{s6t}(i)}}$

At the end of game play, when all ISPs are SoDIP6 network capable, then equation (1) gives zero payoff. Hence, in an initial random setting, the game is formulated for 'N' ISPs with two groups one with N_1 legacy IPv4 networks (Group-1) and another with N_2 SoDIP6 networks with backward compatibility (Group-2). The size and number of customers for each ISP may vary, Hence, Group-1 and Group-2 utilities are calculated as:

$$\gamma_1 = \sum_{k=1}^{(\mathrm{N1}-X_{4\to6}^{s})} \mu_k^4,\ \gamma_2 = \sum_{k=1}^{(\mathrm{N2}+X_{4\to6}^{s})} \mu_k^{4s6}$$

Subject to $0 \le X_{4\to6}^{s} \le N1$ & N1+N2 = N (6)

ISPs of Group-1 are supposed to be migrating to SoDIP6 networks i.e. to Group-2, then for group k (capable of SoDIP6 network) has the utility $U_k = log(\sigma_k + \gamma_k)\,, k = [1,2]$ 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 utility of two groups are:

$U_1 = \log(1 + (\mathrm{N1} - X_{4\to6}^{s}).\mu_k^4)$ and $U_2 = \log(1 + (\mathrm{N2} + X_{4\to6}^{s}).\mu_k^{4s6})$

Subject to $0 \le X_{4\to6}^{s} \le N1$ & N1+N2 = N (7)

The numerical results and their analysis based on equation (7) are presented in figure 11. In the summary, the overall steps of migration modeling are (i) define number of ISPs as finite populations and also define migration constant, (ii) randomly select 'K' number of ISPs in the set of finite ISPs (N) at the beginning for migration, (iii) calculate the adaptation strength of Group-1 ISPs (N1) and expected payoffs of all ISPs in both groups, (iv) calculate the migration strength of each ISP in Group-1 with the fitness value, (v) migrate ISPs having migration strength >= 0.6, and (vi) on every 3 months, repeat from step (iii) until all ISPs are migrated to SoDIP6 Networks.

4. Simulations and Analysis

We perform three rounds of simulations randomly setting different parameter values defined in Table 1 and initial assumptions provided in Table 2 in this simulations. For a total of N (=16) ISPs taken in this simulation, we consider that some ISPs are already migrated so that interconnecting ISPs receives IPv4 and IPv6 traffic both. We consider that all ISPs would migrate to SoDIP6 network within a period of 6 years during when Group-1 ISPs evaluate the adaptation parameter and strength of migration on every three months period. Then candidate ISP makes a decision based on the increasing value of adaptation strength (σ_{4t}) in the consequent previous time steps and migration strength (δ) almost greater than 0.6.

At the beginning, Legacy IPv4 (i.e. Group-1) ISP(s) will be randomly selected for migration. However in the subsequent next timestamp of the game play, ISP(s) with higher σ_{4t} will be selected for migration. We consider that an ISP migrated to Group-2 will never migrate back to Group-1. Hence at every timestamp, only Group-1 ISP will be chosen and evaluate the strength of migration. Equation (3) provides the total strength for ISPs to take the preliminary knowledge on migration decision making while equation (4) measures the fitness for migration. The sub-adaptation parameters and their effects in migration decision making are individually visualized in Figure 4, 5 & 6 respectively. Figure 4(a) shows the plot of adaptation strengths based on customer demands, Figure 4(b) presents the strength based on IPv4/IPv6 traffic entering the network and Figure 4(c) presents the strength with respect to available human resources, migration cost & the organization budget. We provide detail explanation with interpretation below for 1st round of simulations. The visualizations of 2nd and 3rd round of simulations simply depict the measures of sub-adaptation parameters with different random value setting according to interpretations.

Following provides the interpretation of simulation parameter setting and its results in the visualization. For example σ_c at (2%↑, -4%↓) means the customer demand of SoDIP6 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 4(a) 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 and so this increase the cost of ISP to install translator device in the boarder. The ultimate choice for an ISP is either migrate to SoDIP6 network or use extra cost of IPv4 to IPv6 traffic translation and vice versa. This affects the internal operation of ISP and services to be provided to its customers. We consider a scenario of Figure 3 such that each ISP has mesh interconnection with other 15 ISPs. The strength of that migration is plotted over 24 time steps as shown in Figure 4(b), 5(b) & 6(b) respectively. For an ISP migration ratio of 2/3 (i.e. =16/24, 16 Group-1 ISPs 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 4(c), 5(c) & 6(c) present the plots on changing budget and also changing migration cost while we consider SoDIP6 network operation capable human resources are increased by 4.16% (1/24) of the existing capable human resources. 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 will be higher than the income. This also creates alarming situation to ISPs to take early decision for migration. The 2nd and 3rd round simulation presents more analytical results with random values. Plots (a) & (b) of Figure 7, 8 & 9 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 4, 5 & 6 respectively.

Table 2. Assumptions for simulations with expected rate of change of sub-adaptation parameters

- Total customers of an ISP= 1200
- Total migration period=6 years
- Time steps to evaluate adaptation value & migration strength = every 3 months
- Expected utility of group-1 ISP = 500
- Expected utility of group-2 ISP =700
- Incoming IPv4 traffic on a 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 steps) = 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 of SoDIP6 Services	Total customers	Incoming IPv6 traffic	Incoming IPv4 traffic	Organizational budget	Migration cost
1st Round	0%↑	-1%↓	3%↑	1%↑	3%↑	3%↑
	2%↑	-4%↓	4%↑	-1%↓	2%↑	4%↑
	3%↑	-1%↓	5%↑	2%↑	3%↑	1%↑
	1%↑	1.5%↑	4%↑	-3%↓	2%↑	5%↑
2nd Round	2%↑	-0.5%↓	2%↑	1%↑	3%↑	2%↑
	0%↑	-2%↓	1%↑	-3%↓	2%↑	3%↑
	6%↑	-4%↓	8%↑	0.5%↑	3%↑	4%↑
	10%↑	0.2%↑	8%↑	-4%↓	4%↑	5%↑
3rd Round	2%↑	-1%↓	3%↑	-0.5%↓	2%↑	2%↑
	4%↑	-3%↓	4%↑	-2%↓	-1%↓	4%↑
	7%↑	-6%↓	8%↑	-4%↓	1.5%↑	5%↑
	12%↑	-8%↓	10%↑	-6%↓	3%↑	7%↑

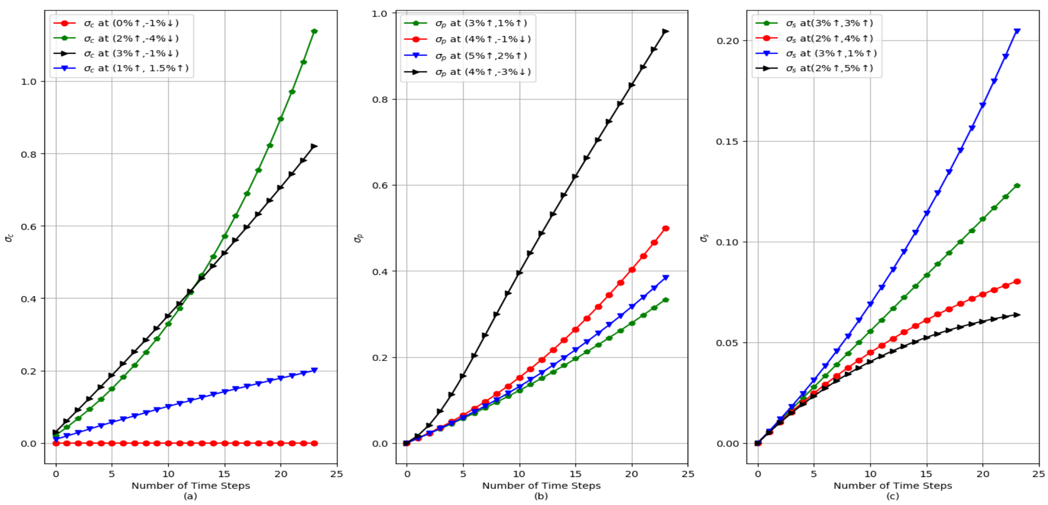

Figure. 4. Plots of 1st round simulation of sub-adaptation parameters σ_c, σ_p & σ_s

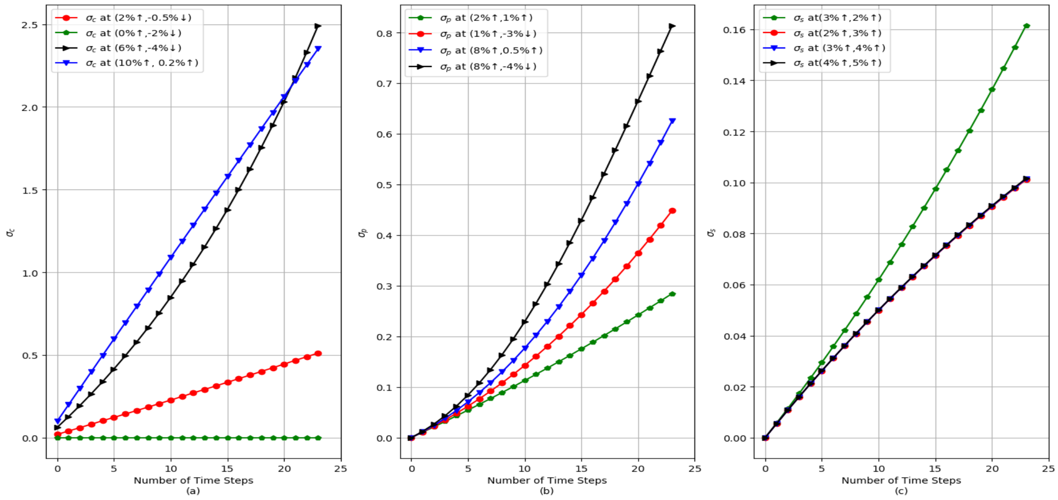

Figure. 5. Plots of 2nd round simulation of sub-adaptation parameters σ_c, σ_p & σ_s

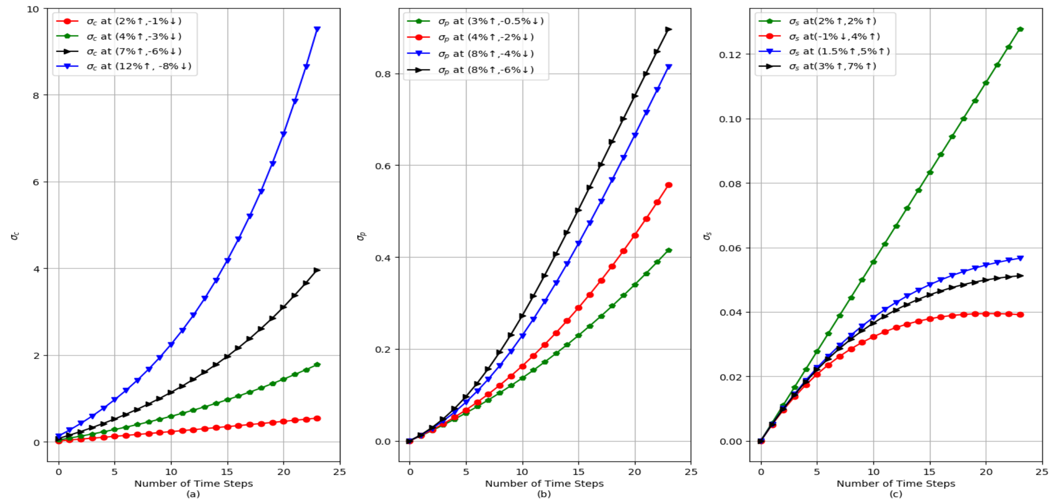

Figure. 6. Plots of 3rd round simulation of sub-adaptation parameters σ_c, σ_p & σ_s

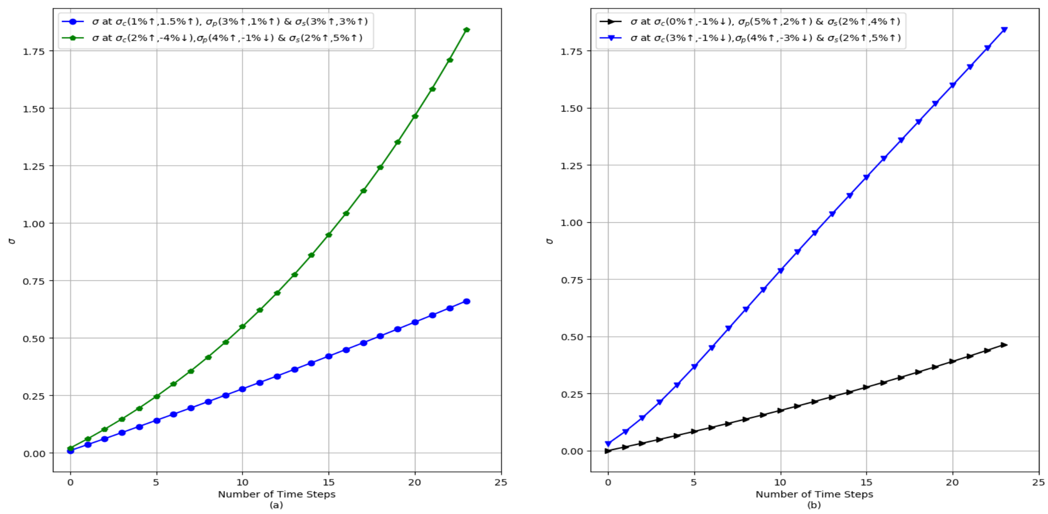

Figure. 7. 1st round plots of $\sigma_{4t}(\sigma)$ at different combinations of σ_c, σ_p & σ_s

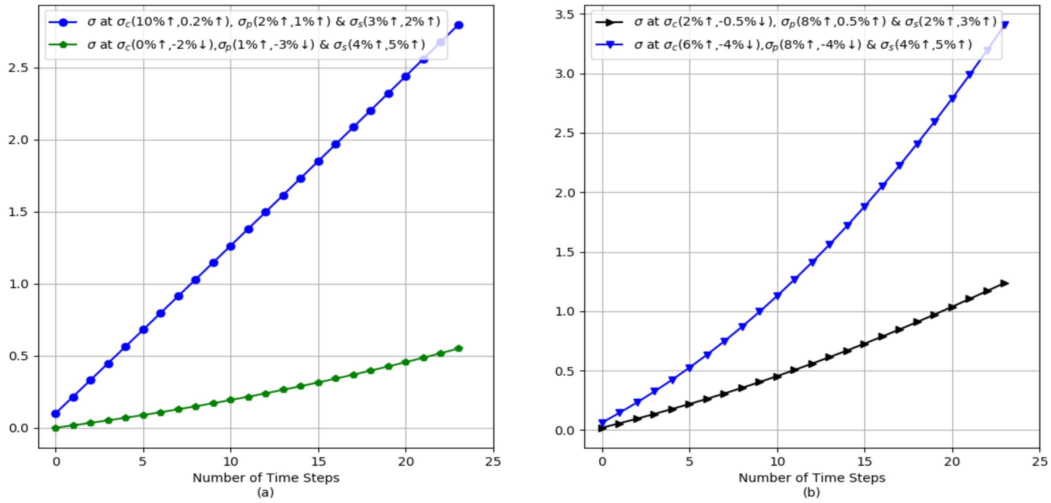

Figure. 8. 2nd round plots of $\sigma_{4t}(\sigma)$ at different combinations of σ_c, σ_p & σ_s

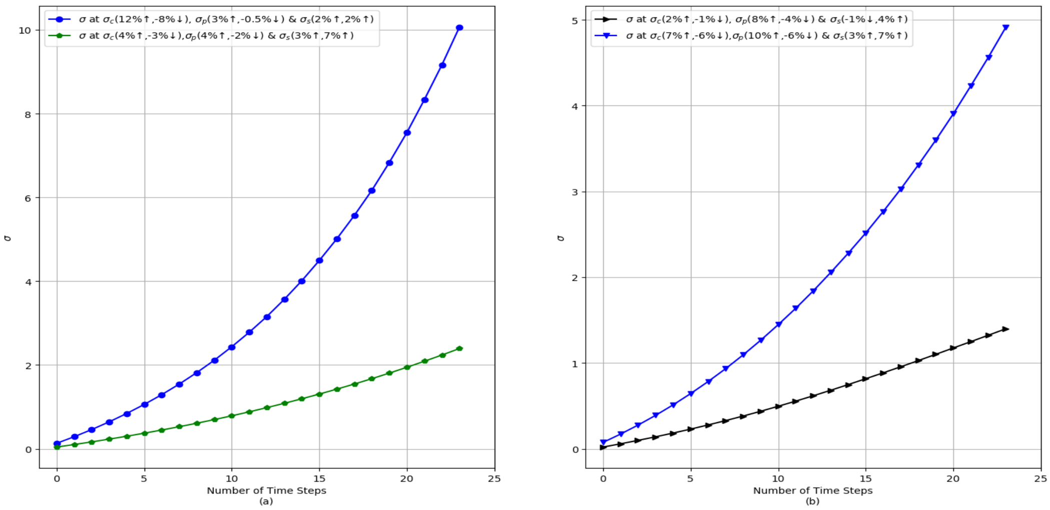

Figure. 9. 3rd round plots of $\sigma_{4t}(\sigma)$ at different combinations of σ_c, σ_p & σ_s

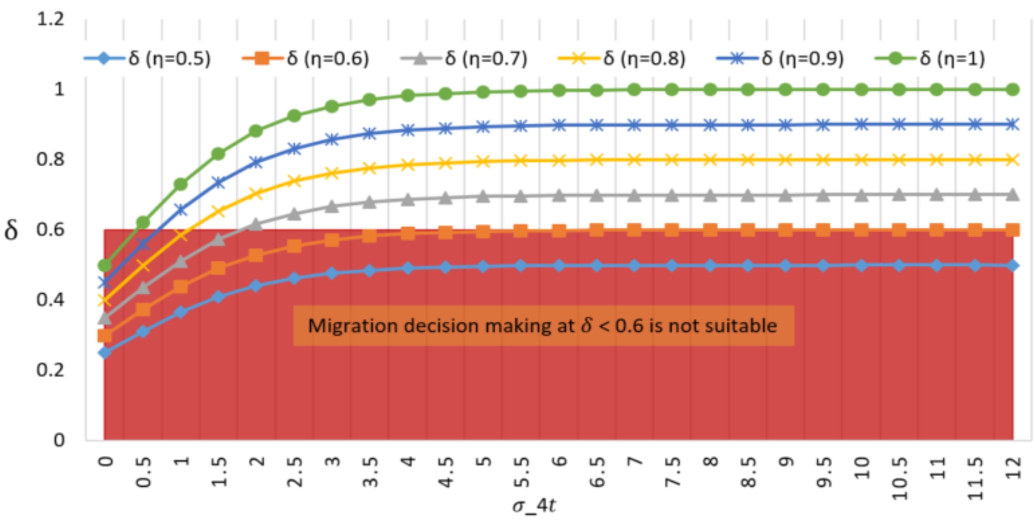

Figure. 10. Plot of migration strength (δ) with increasing adaptation strength (σ_{4t})

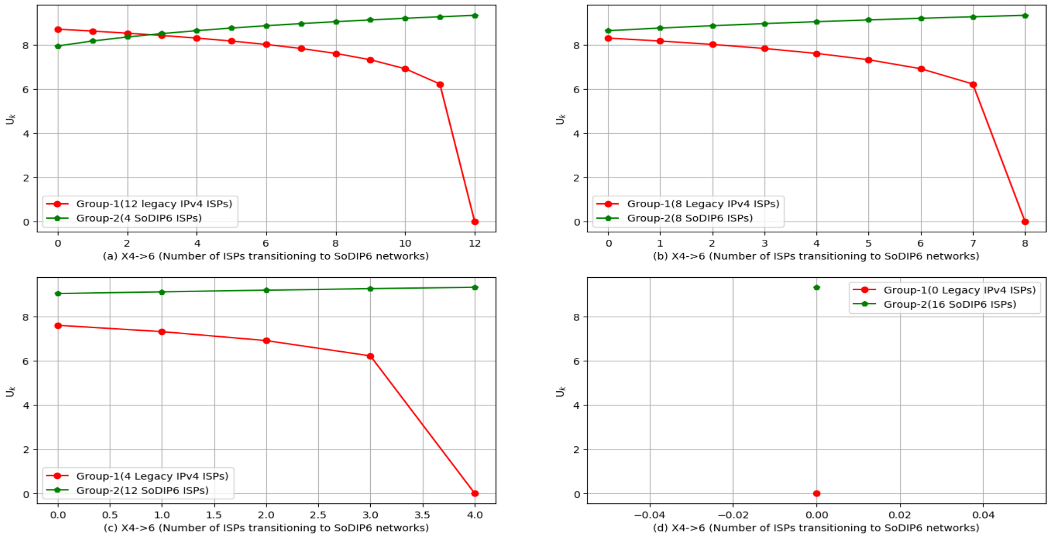

Figure. 11. Group utility vs. ISPs migrating to SoDIP6 network

The plot of adaptation variable (σ_{4t}) at $[\sigma_c\ (2\%\uparrow, -4\%\downarrow), \sigma_p\ (4\%\uparrow, -1\%\downarrow), \sigma_s\ (2\%\uparrow, 5\%\uparrow)]$ presented in Figure 7(a) 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 traffic have been increased by 4% and IPv4 incoming traffic 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 records increasing value leads to migration decision making while the strength of migration (δ) normalizes value of adaptation variable between 0 to 1 and the choice of suitable value for migration constant (η) increase confidence level to the decision maker to take migration decision. Hence, at η & δ both above the value 0.6 gives the better decision for an ISP to make a migration decision.

Figure 11 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 16 ISPs in Group-2 at (d). The simulation is 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 11 (d).

5. Related Works in SoDIP6 Network Migration

We find sufficient researches with different migration approaches presented for IPv6 and SDN migration separately. This is our first attempt to develop game theoretic approach on joint migration of SDN and IPv6 network including migration cost, customer demand and organization strength in terms of budget & skilled human resources for Tier-3 ISPs. Trinh et al. (2010) [33] visualized the game theoretic approach to IPv6 network migration applied over generic tiered ISP network architecture. This approach is focused on an IPv6 only network migration over an Autonomous System (AS) while an ISP might have more than one ASes. Incremental adoption of IPv6 migration from the perspectives of different service providers like ISPs, Content providers & content users have been discussed in [38]. Similarly, migration cost optimization by joint network migration for service providers is presented at [19].

Researchers are carrying out researches for the post migration planning like design and placement of SDN controllers and load balancing [39]–[44] while study of these considering the incremental deployment of SoDIP6 network are an ongoing research. In this paper, we are more focused on evolutionary process of joint migration of SDN and IPv6 network for legacy Tier-3 ISP networks in which we present the migration scenario by measuring the adaptation strength and fitness value that are to be considered by service providers themselves for their migration decision making.

6. Conclusion

Adaptation to new technologies always create risk in decision making in which service providers are always in fear of service interruption & reliable services during the moment they take decision for network migration. Especially, service providers of developing countries require optimum planning for migrating their traditional network to emerging SDN and IPv6 network because they lack sufficient budget for migration. However, it is important to expand the networking infrastructure by the service providers to make their service network adaptable with newer technologies for their future sustainability and compete with global market.

Furthermore, due to the limitation of IPv4 address space, network expansion to support growing number of connected devices which are uniquely identifiable globally can be achieved by using IPv6 addressing. In this paper, we presented the overview of two network layer technologies (SDN & IPv6) and their common concerns on joint migration. Evolutionary dynamics of joint network migration based on the adaptation strength & fitness value considering customer demands, interactions with other ISPs and status of organizational CaPEX & OpEX are being demonstrated. It is also seen that migration to SoDIP6 network is affected by several internal factors while it is greatly affected by the interconnected other ISP networks with availability of stable applications, protocols and standards. But 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 the organizational expenditure and achieve higher utilities.

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References

[1] I. Livadariu, A. Elmokashfi, and A. Dhamdhere, "On IPv4 transfer markets: Analyzing reported transfers and inferring transfers in the wild," *Comput. Commun.*, vol. 111, pp. 105–119, 2017.

[2] B. R. Dawadi, D. B. Rawat, and S. R. Joshi, "Software Defined IPv6 Networks: A New Paradigm for Future Networks," *J. Inst. Eng.*, vol. 15, no. 2, pp. 1–14, 2019.

[3] S. N. Rizvi, D. Raumer, F. Wohlfart, and G. Carle, "Towards carrier grade SDNs," *Comput. Networks*, vol. 92, pp. 218–226, 2015, doi: 10.1016/j.comnet.2015.09.029.

[4] S. Sezer *et al.*, "Are we ready for SDN? Implementation challenges for software-defined networks," *IEEE Commun. Mag.*, vol. 51, no. 7, pp. 36–43, 2013.

[5] O. N. F. S. Brief, "SDN Migration Considerations and Use Cases," 2014.

[6] M. H. Raza, S. C. Sivakumar, A. Nafarieh, and B. Robertson, "A comparison of software defined network (SDN) implementation strategies," *Procedia Comput. Sci.*, vol. 32, pp. 1050–1055, 2014.

[7] B. R. Dawadi, S. R. Joshi, and A. R. Khanal, "Service provider IPv4 to IPv6 network migration strategies," *J. Emerg. Trends Comput. Inf. Sci.*, vol. 6, no. 10, 2015.

[8] P. Wu, Y. Cui, J. Wu, J. Liu, and C. Metz, "Transition from IPv4 to IPv6: A state-of-the-art survey," *IEEE Commun. Surv. Tutorials*, vol. 15, no. 3, pp. 1407–1424, 2012.

[9] L. M. Contreras, P. Doolan, H. Lønsethagen, and D. R. López, "Operational, organizational and business challenges for network operators in the context of SDN and NFV," *Comput. Networks*, vol. 92, pp. 211–217, 2015, doi: 10.1016/j.comnet.2015.07.016.

[10] Y. Sinha, K. Haribabu, and others, "A survey: Hybrid sdn," *J. Netw. Comput. Appl.*, vol. 100, pp. 35–55, 2017.

[11] ON.LAB, "Driving SDN Adoption in Service Provider Networks," 2014.

[12] SANDVINE, "Carrier Grade NAT: Mitigate IPv4 address exhaustion while maintaining network visibility," 2018. [Online]. Available: https://www.sandvine.com/hubfs/Procera_Live_Site_Files/PDF_Live_Site/Solutions_brief/SB_CGNAT.pdf. [Accessed: 20-Sep-2019].

[13] Cisco Systems Inc., "Implementing the Carrier Grade NAT on Cisco IOS XR Software," in *Cisco IOS XR Carrier Grade NAT Configuration Guide for the Cisco CRS Router*, CISCO, Ed. CISCO, 2013, p. 86.

[14] F5, "Carrier-Grade NAT (CGNAT) for Service Providers." [Online]. Available: https://www.f5.com/services/resources/use-cases/carrier-grade-nat-for-service-providers. [Accessed: 20-Sep-2019].

[15] M. Kobayashi *et al.*, "Maturing of OpenFlow and Software-defined Networking through deployments," *Comput. Networks*, vol. 61, pp. 151–175, 2014, doi: 10.1016/j.bjp.2013.10.011.

[16] H. Babiker, I. Nikolova, and K. K. Chittimaneni, "Deploying IPv6 in the Google Enterprise Network. Lessons learned.," in *Proceedings of the 25th international conference on Large Installation System Administration*, 2011, p. 10.

[17] APNIC, "IPv6 capability measurement." [Online]. Available: https://stats.labs.apnic.net/ipv6. [Accessed: 15-Jul-2019].

[18] Google Incl., "IPv6 user access status." [Online]. Available: https://www.google.com/intl/en/ipv6/statistics.html. [Accessed: 16-Jul-2019].

[19] B. R. Dawadi, D. B. Rawat, S. R. Joshi, and M. M. Keitsch, "Joint cost estimation approach for service provider legacy network migration to unified software defined IPv6 network," in *Proceedings - 4th IEEE International Conference on Collaboration and Internet Computing, CIC 2018*, 2018, doi: 10.1109/CIC.2018.00056.

[20] S. A. Abdullah, "SEUI-64, bits an IPv6 addressing strategy to mitigate reconnaissance attacks," *Eng. Sci. Technol. an Int. J.*, vol. 22, no. 2, pp. 667–672, 2019, doi: 10.1016/j.jestch.2018.11.012.

[21] D. Kreutz, F. Ramos, P. Verissimo, C. E. Rothenberg, S. Azodolmolky, and S. Uhlig, "Software-defined networking: A comprehensive survey," *arXiv Prepr. arXiv1406.0440*, 2014.

[22] B. R. Dawadi, D. B. Rawat, S. R. Joshi, and M. M. Keitsch, "Towards energy efficiency and green network infrastructure deployment in Nepal using software defined IPv6 network paradigm," *Electron. J. Inf. Syst. Dev. Ctries.*, 2019, doi: 10.1002/isd2.12114.

[23] B. R. Dawadi, D. B. Rawat, S. R. Joshi, and M. M. Keitsch, "Recommendations for Energy Efficient SoDIP6 Network Deployment at the Early Stage Rural ICT Expansion of Nepal," in *2019 International Conference on Computing, Networking and Communications, ICNC 2019*, 2019, doi: 10.1109/ICCNC.2019.8685567.

[24] M. Winther, "Tier 1 isps: What they are and why they are important," *IDC White Pap.*, pp. 1–13, 2006.

[25] B. R. Dawadi, D. B. Rawat, and S. R. Joshi, "Evolutionary Dynamics of Service Provider Legacy Network Migration to Software Defined IPv6 Network," in *International Conference on Computing and Information Technology*, 2019, pp. 245–257.

[26] D. Ó. Briain, D. Denieffe, Y. Kavanagh, and D. Okello, "A Proposed Architecture for Distributed Internet eXchange Points in Developing Countries," in *2018 IST-Africa Week Conference (IST-Africa)*, 2018, p. Page--1.

[27] N. Chatzis, G. Smaragdakis, and A. Feldmann, "On the importance of Internet eXchange Points for today's Internet ecosystem," *arXiv Prepr. arXiv1307.5264*, 2013.

[28] P. S. Ryan and J. Gerson, "A primer on Internet exchange points for policymakers and non-engineers," *Available SSRN 2128103*, 2012.

[29] K. Bogineni and others, "Introducing ONOS: A SDN network operating system for service providers," *White Pap.*, 2014.

[30] M. Karakus and A. Durresi, "Economic Viability of Software Defined Networking (SDN)," *Comput. Networks*, vol. 135, pp. 81–95, 2018, doi: 10.1016/j.comnet.2018.02.015.

[31] S. Shakkottai and R. Srikant, "Economics of Network Pricing With Multiple ISPs," *IEEE/ACM Trans. Netw.*, vol. 14, no. 6, pp. 1233–1245, Dec. 2006, doi: 10.1109/TNET.2006.886393.

[32] M. B. Weiss and S. Shin, "Internet Interconnection Economic Model and its Analysis: Peering and Settlement," in *Communication Systems: The State of the Art IFIP 17th World Computer Congress --- TC6 Stream on Communication Systems: The State of the Art August 25--30, 2002, Montréal, Québec, Canada*, L. Chapin, Ed. Boston, MA: Springer US, 2002, pp. 215–231.

[33] T. A. Trinh, L. Gyarmati, and G. Sallai, "Migrating to IPv6: A game-theoretic perspective," in *IEEE Local Computer Network Conference*, 2010, pp. 344–347.

[34] B. Voelkl, "Simulation of Evolutionary Dynamics in Finite Populations," *Math. J.*, vol. 13, pp. 1–16, 2011, doi: 10.3888/tmj.13-8.

[35] E. P. de Souza, E. M. Ferreira, and A. G. M. Neves, "Fixation probabilities for the Moran process in evolutionary games with two strategies: graph shapes and large population asymptotics," *J. Math. Biol.*, vol. 78, no. 4, pp. 1033–1065, Mar. 2019, doi: 10.1007/s00285-018-1300-4.

[36] P. Klimek, S. Thurner, and R. Hanel, "Evolutionary dynamics from a variational principle," *Phys. Rev. E*, vol. 82, no. 1, p. 11901, 2010.

[37] T. A. Trinh, L. Gyarmati, and G. Sallai, "Migrating to IPv6: A game-theoretic perspective," *Proc. - Conf. Local Comput. Networks, LCN*, pp. 344–347, 2010, doi: 10.1109/LCN.2010.5735739.

[38] M. Nikkhah, "Maintaining the progress of IPv6 adoption," *Comput. Networks*, vol. 102, pp. 50–69, 2016, doi: 10.1016/j.comnet.2016.02.027.

[39] T. Hu, P. Yi, J. Zhang, and J. Lan, "A distributed decision mechanism for controller load balancing based on switch migration in SDN," *China Commun.*, vol. 15, no. 10, pp. 129–142, 2018, doi: 10.1109/CC.2018.8485475.

[40] P. Tao, C. Ying, Z. Sun, S. Tan, P. Wang, and Z. Sun, "The Controller Placement of Software-Defined Networks Based on Minimum Delay and Load Balancing," in *2018 IEEE 16th Intl Conf on Dependable, Autonomic and Secure Computing, 16th Intl Conf on Pervasive Intelligence and Computing, 4th Intl Conf on Big Data Intelligence and Computing and Cyber Science and Technology Congress (DASC/PiCom/DataCom/CyberSciTech*, 2018, pp. 310–313.

[41] K.-Y. Wang, S.-J. Kao, and M.-T. Kao, "An efficient load adjustment for balancing multiple controllers in reliable SDN systems," in *2018 IEEE International Conference on Applied System Invention (ICASI)*, 2018, pp. 593–596.

[42] H. Xu, X.-Y. Li, L. Huang, H. Deng, H. Huang, and H. Wang, "Incremental deployment and throughput maximization routing for a hybrid SDN," *IEEE/ACM Trans. Netw.*, vol. 25, no. 3, pp. 1861–1875, 2017.

[43] M. Khorramizadeh and V. Ahmadi, "Capacity and load-aware software-defined network controller placement in heterogeneous environments," *Comput. Commun.*, vol. 129, pp. 226–247, 2018.

[44] W. Lan, F. Li, X. Liu, and Y. Qiu, "A Dynamic Load Balancing Mechanism for Distributed Controllers in Software-Defined Networking," in *2018 10th International Conference on Measuring Technology and Mechatronics Automation (ICMTMA)*, 2018, pp. 259–262.

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