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Article

Routing Performance Evaluation of a Multi-Domain Hybrid SDN for its Implementation in Carrier Grade ISP Networks

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Abstract: Legacy IPv4 networks are strenuous to manage and operate. Network operators are in need to minimize the capital and operational expenditure of running network infrastructure. The implementation of Software-defined networking (SDN) addresses those issues by minimizing the expenditure in the long run. Legacy networks need to integrate with the SDN networks for the smooth migration towards the fully functional SDN environment. In this paper, we compare the network performance of the legacy network with the SDN network for IP routing in order to determine the feasibility of the SDN deployment in the Internet Service provider (ISP) network. The simulation of the network is performed in the Mininet test-bed and the network traffic is generated using Distributed Internet Traffic Generator. Open network operating system is used as a controller for the SDN network in which SDN-IP application is used for IP routing. Round trip time, bandwidth, and packet transmission rate from both SDN and legacy networks are first collected and then the comparison is done. We found that SDN-IP provides better bandwidth and latency compared to legacy routing. The experimental analysis of interoperability between SDN and legacy networks shows that SDN implementation in production level carrier-grade ISP network is viable and progressive.

Keywords: ISP; SDN; SDN-IP; legacy network; performance comparison

1. Introduction

Networks are organized groups of devices or nodes with communication links among them. Traditional IP networks are termed as legacy networks. In spite of the Worldwide use, the traditional network is complex and tedious to manage. Adding a new device or changing the network configuration is complex in traditional networking i.e. it should be done using low-level languages and rigid commands thus taking days and months for large networks. Thus, the expansion of the existing legacy network is quite expensive. However, the demand for the network is increasing rapidly. To meet those growing demands, numbers of running hardware should be increased and change should be made in software, which is costly.

Manual configuration, inconsistent policies, and inability to scale are the major problems of the traditional IP networks. Vertical integration has made traditional IP networks more complex in its operation and management. Legacy devices have the control plane and data plane integrated into the same physical device. The data plane, also called the forwarding plane, is hardware unit whose job is to collect the network packets and forward them to the destination based on the routing table. Network policies are enforced in the control plane. The control plane determines how the packets in the data plane should be handled (eg. drop, reject, forward etc.).

In SDN, networks are controlled by SDN controllers and the applications on the top of controllers. The control plane and data plane are separated so that the network switch becomes simply a data plane forwarding device. The control logic is implemented in a logically centralized controller, which runs network operating system (NOS) that runs on commodity server hardware to provide necessary resources to facilitate the proper control and operation of data plane devices based on a logically centralized, abstract network view [1]. The logical centralization of the control logic makes it simply flexible and error-free policy deployment through high-level programming languages as an application programming interfaces (APIs), compared to low-level device-specific configurations frequently done in legacy networks. The controller provides the global view of the overall network that simplifies the development of more robust network functions, services, and applications. The resulting network is also programmable through software applications running on top of the controller OS that interacts with the underlying data plane devices. The APIs at controller can automatically react to spurious changes of the network state and maintain high-level policies intact [1].

Though SDN implementation at datacenter network is popular, its proper implementation with the migration of legacy network at carrier grade ISP (CG-ISP) and telecommunication (Telcos) networks is becoming a central challenge for service providers due to the need of real time migration as well as higher cost of investment [2,3]. Additionally, real time implementation of SDN in production networks is an ongoing research. Hybrid SDN is the only solution for the smooth migration of legacy ISP/Telcos network into SDN [4,5]. In this paper, we consider hybrid SDN implementation and routing performance evaluation by comparing the legacy routing and SDN routing with their interoperability through an experimental analysis using open network operating system (ONOS)/SDN-IP [6] and evaluate the viability of SDN implementation in ISP/Telcos networks.

The rest of this paper is organized as follows. Section 2 presents the background and related work in the field of SDN and legacy network integration. Section 3 presents the problem description of our research and the proposed method. We present the details about experimental setup, analysis, and evaluations in Section 4. Section 5 provides a summative discussion and future work, while the paper is concluded in Section 6.

2. Background and Related Work

Legacy network is less flexible to customized programming and is more vendor specific leading to higher dependency towards support, management, and operation. A better solution would be the implementation of SDN. In SDN, networks are controlled by software applications or SDN controllers. The separation of control and data plane operations in SDN simply transforms the network switches as a forwarding devices.

New technology implementation cost is higher in terms of capital and operational expenditure (CapEX and OpEX) investment and the development of technical human resources (HR) to manage and operate those newer technologies for CG-ISPs and Telcos service providers. There are also certain implementation challenges with respect to management, availability of technological standards, and user interface provisioning while providing new technology-based services to customers during and after the network migration [7,8].

Dawadi et al. [3,9–11] presented approaches for legacy network transformation to SDN and IPv6 networking so that service providers can smoothly plan for network transformation with optimised migration cost. Authors implemented IPv4/IPv6 routing in multi-domain SoDIP6 network using ONOS/SDN-IP.

Same like traditional operating system, network operating system (NOS) provides the essential resources and abstractions to facilitate the programming of forwarding devices based on a logically centralized, abstract network view. The resulting network is also programmable through software applications running on top of the NOS that interacts with the underlying data plane devices. ONOS [12] is the robust and distributed controller OS, which provides better solution to build next-generation SDN/NFV solutions. The need of Internet and Telcos service providers can simply be fulfilled by the introduction of ONOS to carrier-grade solutions that leverage the economics of white box merchant silicon hardware while offering the flexibility to create and deploy new dynamic network services with simplified programmatic interfaces [12]. ONOS is developed with set of other several applications that makes it flexible, modular, scalable in terms of both the architecture and the cluster, and distributed SDN controller. SDN-IP is one of the ONOS application developed to implement routing with external legacy networks using standard border gateway protocol (BGP) to enable interoperability with legacy routing. in ONOS/SDN-IP, the SDN can be treated as a single autonomous system (AS) and communicate simply with external AS as a traditional routing. SDN-IP integrated BGP and ONOS enables communication with external AS in the hybrid SDN so that SDN-IP behaves as a regular BGP speaker and uses its services to install and update the appropriate forwarding state in the SDN data plane devices.

Friyanto [13] presented the use of multiple ONOS controllers in a cluster for high available services using ONOS/SDN-IP reactive routing. Efficient routing implementations in the different aspects of wired and wireless SDN [14–17] are the primary concerns. But their implementations in production level have to be evaluated considering the smooth transition from legacy to hybrid SDN to pure SDN.

There are many researches looking after the hybrid SDN implementations. For example, HARMLESS [18], Panopticon [19], RouteFlow [20], Fibbing [21], OSHI [22] are some of the attempts, but most of the researches are not in production level. Similarly, few researches dealt with the implementation of SDN in CG-ISP networks using ONOS/SDN-IP [6,23–25]. Our approach in this study is not scoped towards migration techniques, but we focused on the production level implementation of routing in hybrid SDN and its performance comparison with legacy network to measure the viability of transition towards pure SDN by implementing ONOS/SDN-IP.

3. Problem Description and Proposed Method

The overall structure of our experimental evaluation is based on the conceptual implementation architecture of ONOS/SDN-IP as depicted in Figure 1. All the external networks i.e. external autonomous system (AS) are supposed to be the legacy networks, directly connected with backbone transit AS, which is SDN based.

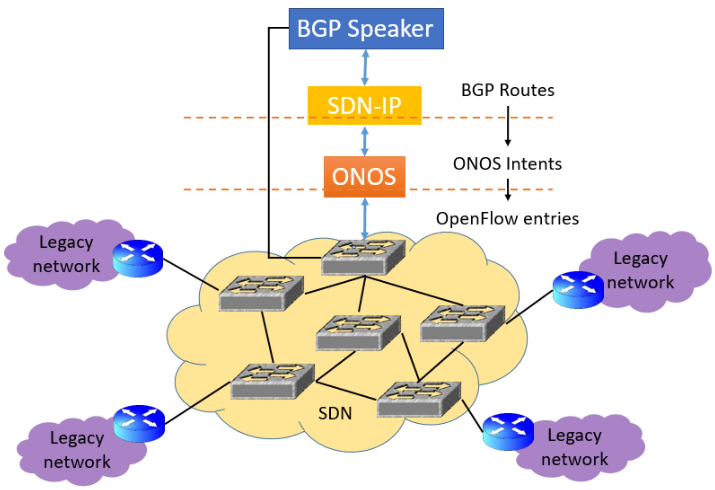

Figure 1. Use case network of SDN integration with legacy networks [26]

A use case topology network as shown in Figure 2 is created in Mininet for experimental analysis in this study. For routing purpose, Quagga routing suite [27] is used at which BGP is implemented. For SDN integration with legacy network, ONOS controller is configured to implement BGP and SDN-IP with reactive routing enabled.

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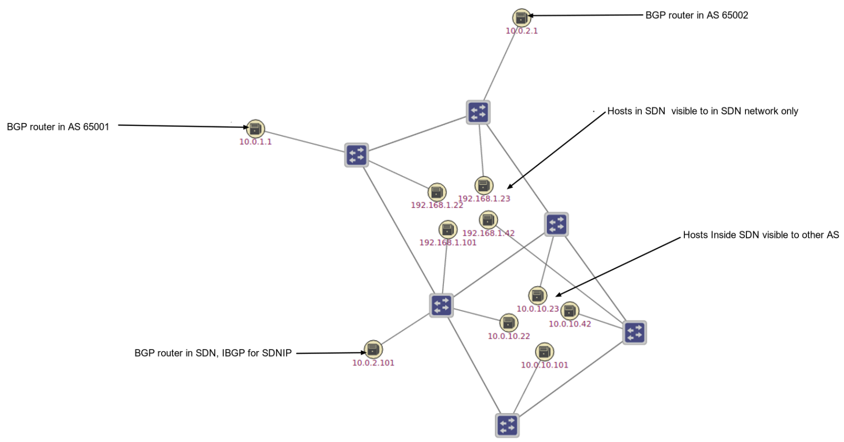

Figure 2. Experimental topology of SDN integrated with Legacy networks

A complete legacy network mimicking Figure 1 is created as shown in Figure 3, where BGP and OSPF are used for routing purpose. Each router is a virtual machine loaded with BGP and OSPF configuration. In the Figure 3, r5 is route reflector router [28] and r4, r3, r6, r7, and r8 are its client, whereas r4-r2 and r3-r1 are BGP peers.

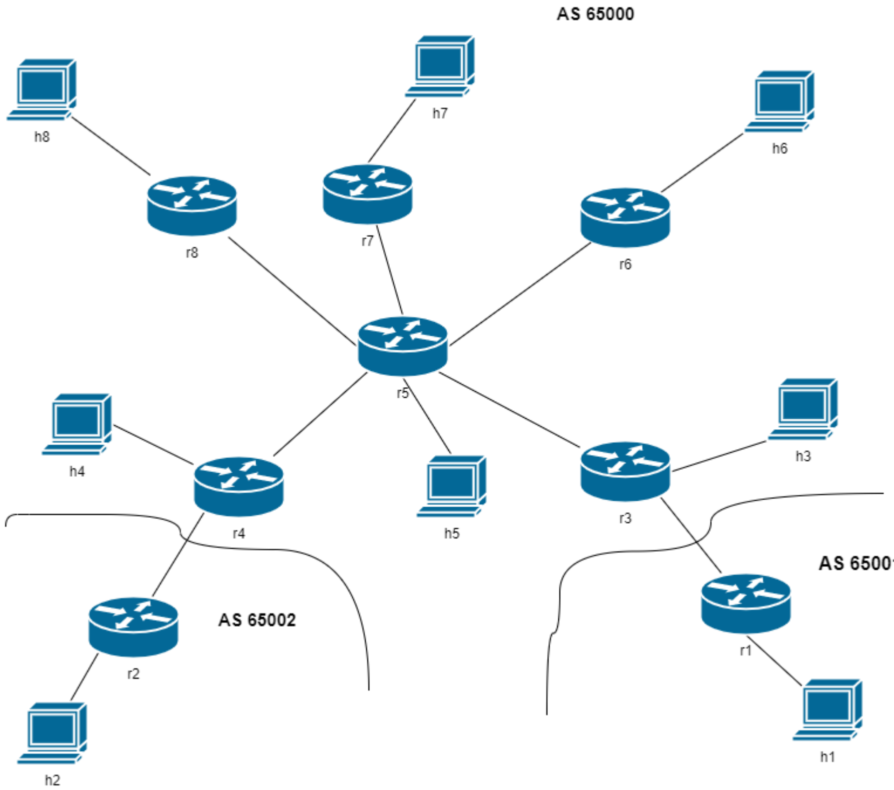

Figure 3. Use-case of legacy routing network

The SDN integrated legacy network and pure legacy network are chosen in the present study to analyze network performance. For comparison between them (hybrid SDN and legacy network), distributed internet traffic generator (D-ITG) [29], Packet InterNet Groper (*PING*), Iperf, and statistical rules are applied. Varying number and size of packets are created and transmitted from one host to another in each network

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and corresponding delay, latency, and total packet transmission are observed. *PING* utility is used to check the network connectivity between host and server/host. In both networks, first, *ping* is used to ensure total communication in the network, then it is used for finding out RTT. We have used *Iperf* to determine the maximum bandwidths offered by the network. The compatibility and performance of SDN integration with the legacy network for multi-domain routing purpose is clearly depicted by statistical values and comparison techniques required for SDN and legacy network.

Mininet emulated the hosts as a Linux machine. ONOS running on the same machine is used as an SDN controller. In order to run the SDN-IP application, following dependent application were activated.

- OpenFlow [Southbound API]
- Config [Network configuration]
- ProxyARP [ARP like functionality with no flooding]
- SDN-IP [BGP peering]

After running those APIs, we can see the routes learned by ONOS, which can be seen using *routes* command on the ONOS console. In the legacy ASes, an eBGP router is connected with a single host. The SDN network in our proposed use case consists of a BGP border router, which acts as iBGP to SDN-IP and eBGP speaker to the external legacy networks. The BGP policies advertised by external network border routers will be received by the ONOS/BGP speakers in the transit SDN and re-advertised to other external legacy networks by SDN-IP as an iBGP peer. SDN-IP translates the best route policies into ONOS application intent request (AIR) and deployed into data plane devices as forwarding rules to route transit traffic into appropriate external networks. Internal BGP speakers were configured to use TCP port at 179 to communicate with other BGP speakers and TCP port at 2000 to send the route information to ONOS/SDN-IP instances and the external BGP speakers are connected to OpenFlow enabled switches.

The BGP routers are emulated using Linux hosts in which Quagga routing suite is running. The BGP daemon of the Quagga routing suite is used for the BGP routers. Figure 2 shows SDN-IP implementation for an ISP network, where BGP speakers 10.0.1.1, 10.0.2.1, and 10.0.2.101 are connected to OpenFlow switches. BGP speaker 10.0.1.101 is connected to ONOS. i.e SDN-IP. It advertises route information to SDN-IP using which the SDN network acts as a transit AS. BGP speakers 10.0.1.1 and 10.0.2.1 are connected to external AS. These speakers advertise routes to the AS to other BGP speakers. iBGP speaker 10.0.1.101 listens to these routes and sends it to SDN-IP. SDN-IP changes the known BGP routes to intents and ONOS turns the intents to OpenFlow entries. The OpenFlow entries are then deployed into the OpenFlow switches using OpenFlow protocol.

Using D-ITG, UDP flows were generated with varying packet size and packet rate for 15 seconds. Two log files were generated for both the sender and receiver side. The log file generated at the receiver side contained values for different performance indicators such as delay, jitter, bit-rate, bytes received, packets dropped, and average loss-burst size. On decoding the log file, we get a stream of data containing these performance indicators. The values of these parameters are taken from the log file on receiver's side.

Multiple unidirectional flows were sent for fifteen seconds between pairs of hosts in turns by varying transmission rate and packet size to study the performance of the network under low and high load. The packet size were 512 and 1024 bytes and the packet transmission rates were varied to 100, 1000, and 3000 packets per second. These flows were sent in the traffic via UDP where each host acted both as a client and a server.

Ultimately, log files of flows generated between 10 hosts in the SDN network were further processed to a CSV file using a python script. The D-ITG data samples generation snapshot is as shown in Figure 4.

```
----------------------------------------------------------
Flow number: 1
From 10.0.0.4:34771
To    10.0.0.3:9501
----------------------------------------------------------
Total time               =      9.999002 s
Total packets            =         10000
Minimum delay            =      0.000000 s
Maximum delay            =      0.000000 s
Average delay            =      0.000000 s
Average jitter           =      0.000000 s
Delay standard deviation =      0.000000 s
Bytes received           =       7498028
Average bitrate          =   5999.021102 Kbit/s
Average packet rate      =   1000.099810 pkt/s
Packets dropped          =             0 (0.00 %)
----------------------------------------------------------
****************  TOTAL RESULTS   ******************
Number of flows          =             1
Total time               =      9.999002 s
Total packets            =         10000
Minimum delay            =      0.000000 s
Maximum delay            =      0.000000 s
Average delay            =      0.000000 s
Average jitter           =      0.000000 s
Delay standard deviation =      0.000000 s
Bytes received           =       7498028
Average bitrate          =   5999.021102 Kbit/s
Average packet rate      =   1000.099810 pkt/s
Packets dropped          =             0 (0.00 %)
Error lines              =             0
----------------------------------------------------------
```

Figure 4. Snapshot of a D-ITG output

Moreover, 468 data samples were generated. The bi-variate distribution of numerical attributes can be observed in the pair plot shown in Figure 5. The pair-plot allows us to look at the diagonal distribution of the attributes, and on the non-diagonal linear relationship between the attributes, i.e. it is possible to identify, in which space the classes will be well separated from each other. Certain scatter plots that follow a clear linear pattern with an increasing slope can be seen, which shows that some conclusions can be drawn from our dataset. Such linear patterns are representation of dependencies among the attributes.

The correlation of all the numerical attributes as a heat-map using Spear-man correlation coefficient is shown in Figure 6. It can be observed that average delay and average jitter are highly correlated with a Spear-man coefficient of 0.92. Similarly, bytes received, average bit rate, and average packet rate are highly correlated as well. Parameters, e.g. average delay and average packet rate can be observed to be negatively correlated with Spear-man coefficient of -0.75. These observed correlations were obtained as expected, which provide statistical significance to this experiment.

4. Analysis and Evaluations

This section aims to highlight the differences between the integrated SDN network and the legacy network by comparing them in terms of various performance indicators. Additionally, the performance of the integrated SDN network was further observed by taking note of the network quality of service (QOS) parameters defined.

4.1. Comparison between SDN and legacy network

In this section, we provide a comparative analysis of the use case network proposed as hybrid SDN and legacy network in terms of QoS parameters defined. The compar-

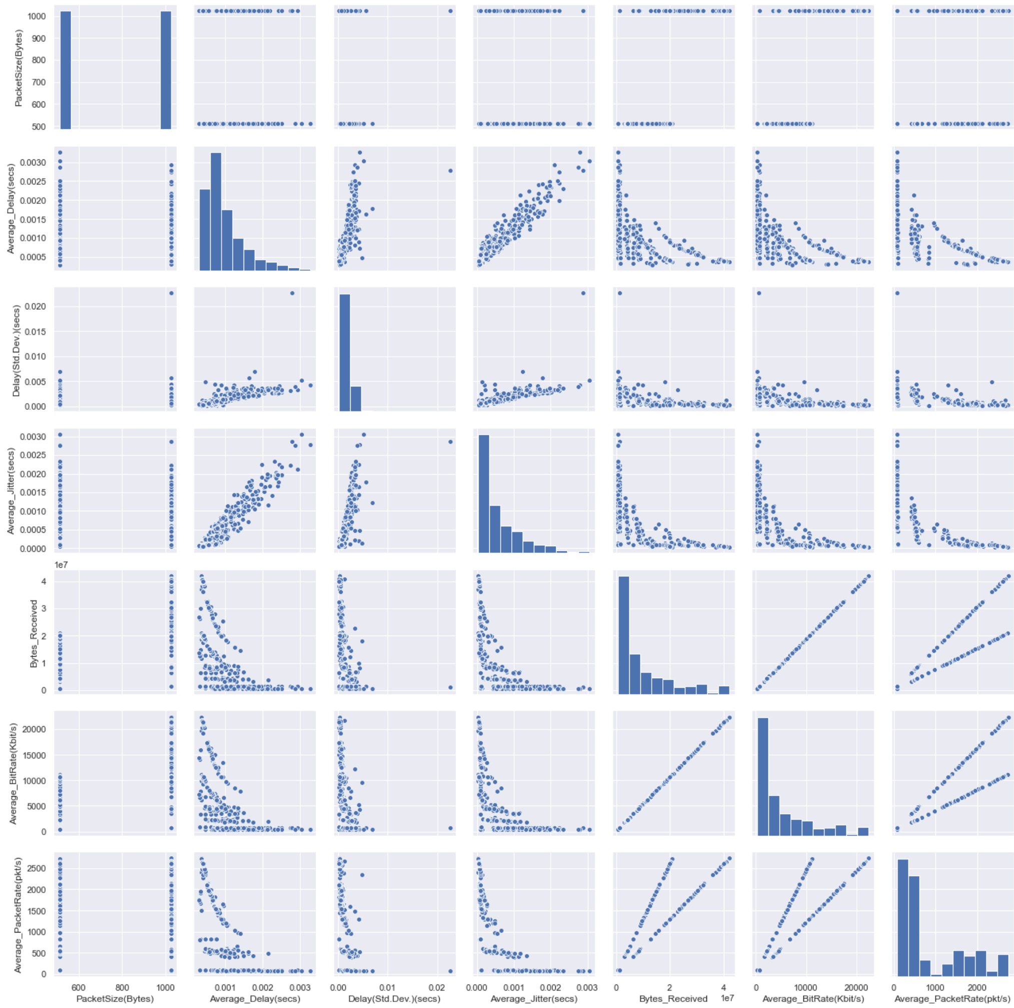

Figure 5. Pair-plot of Data set

ison is done by analysing the performance of both network topologies on the basis of bandwidth capacity, packet transmission rate and time required to transmit packet from source node to the destination node.

4.1.1. Bandwidth

The results of bandwidth capacity in both the SDN and legacy network is obtained by using *'Iperf'* tool in Mininet. Here, we show the maximum bandwidth between hosts in neighbouring AS and within the same AS for both the SDN and the legacy network. In addition to that, maximum bandwidth when the hosts that use AS65000 or SDN as a transit network to connect is also shown. As shown in the Figure 7, the maximum bandwidth seems to be higher in the case of SDN network, which can highlights the ability of SDN to transfer more data per second compared to their legacy counterparts.

It can also be seen that the maximum bandwidth is higher for nodes within AS65000 or within the SDN compared to neighbouring AS or when AS65000 and SDN are used as a transit network.

4.1.2. Packet transmission rate (PTR)

We compared both topologies based on the PTR obtained by executing *'PING'* tool in Mininet. PTR for both topologies is shown in Figure 8 for source and destination hosts that use AS65000 or SDN network as transit network for varying number of packets.

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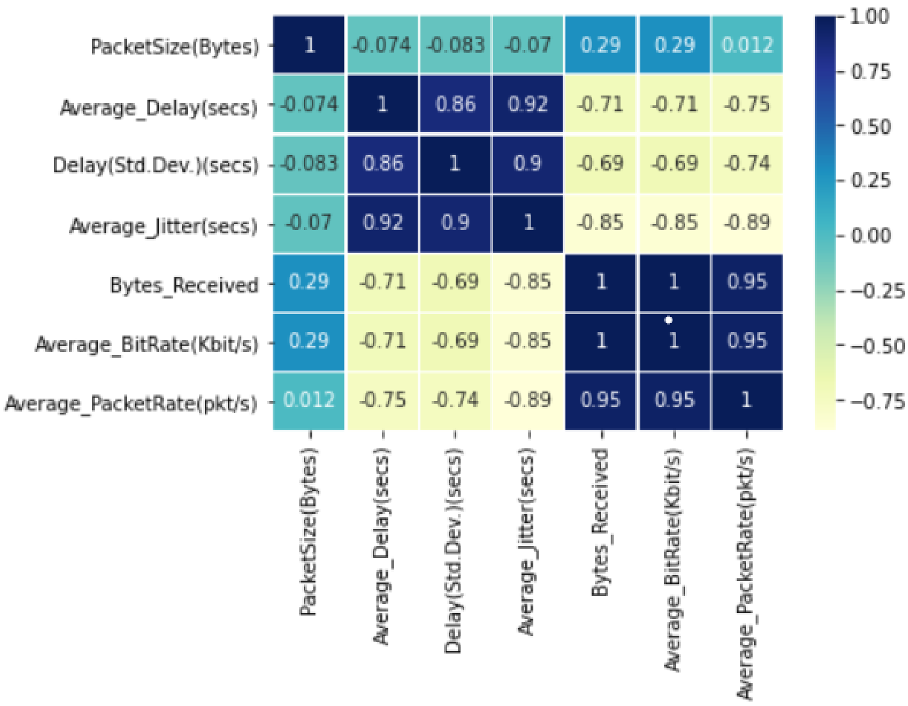

Figure 6. Spear-man correlation heat-map

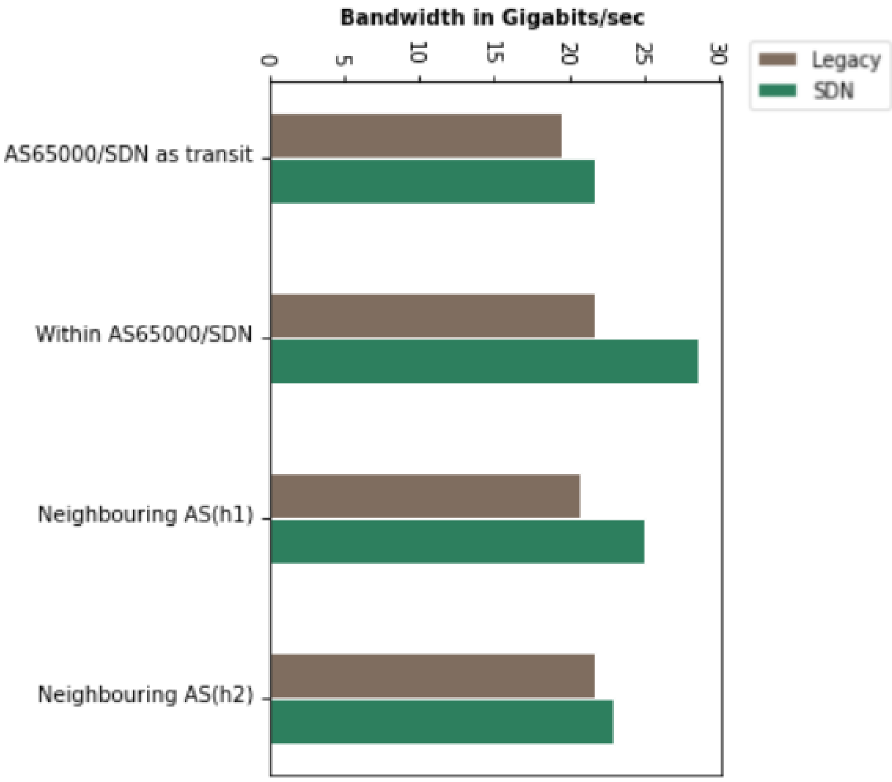

Figure 7. Bandwidth capacity for SDN and legacy network

The results for PTR obtained indicate that the total time taken by both network topologies for a given number of packets is almost equal. It is noted that both networks are active for same amount of time interval to execute the command.

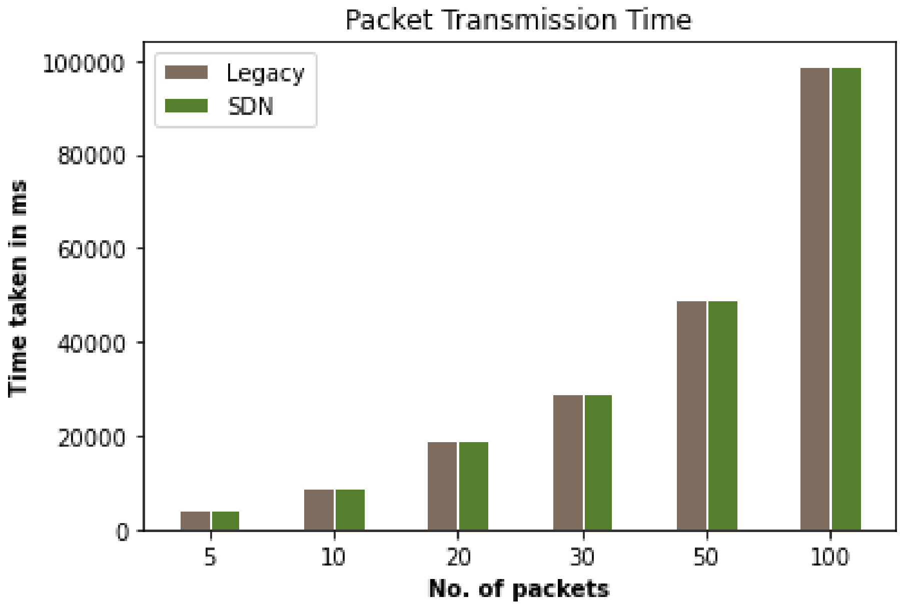

Figure 8. PTR for AS65000/SDN as transit network

4.1.3. Round trip time (RTT)

Next we compare the delay between nodes in each network. *'PING'* command was executed to obtain the RTT between the source and the destination nodes. The topologies were compared on the basis of the variance of RTT, and minimum and maximum values of RTT.

RTT variance: here the standard deviation of values of RTT for both the topologies are plotted in a graph. This is done for source and destination nodes within an AS, in neighbouring AS, and when AS65000 and SDN network are used as transit networks.

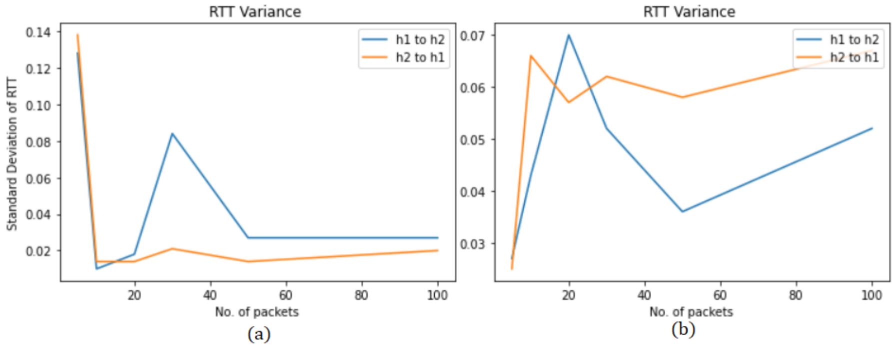

Figure 9. RTT Variance, (a) AS65000/SDN as Transit in SDN, and (b) in Legacy

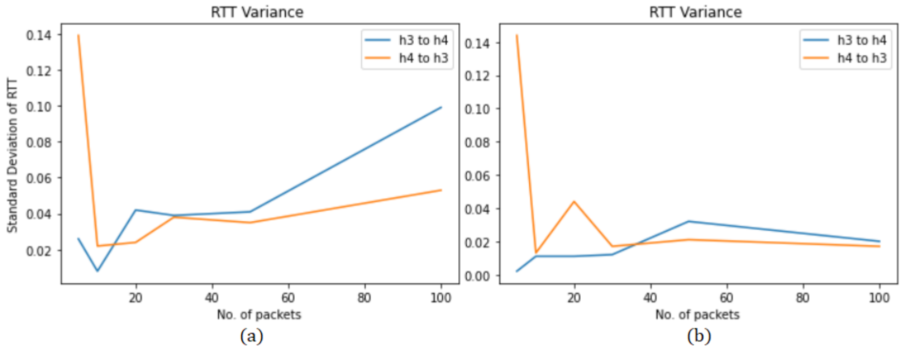

Figure 10. RTT Variance, (a) Within AS65000/SDN in Legacy, and (b) SDN

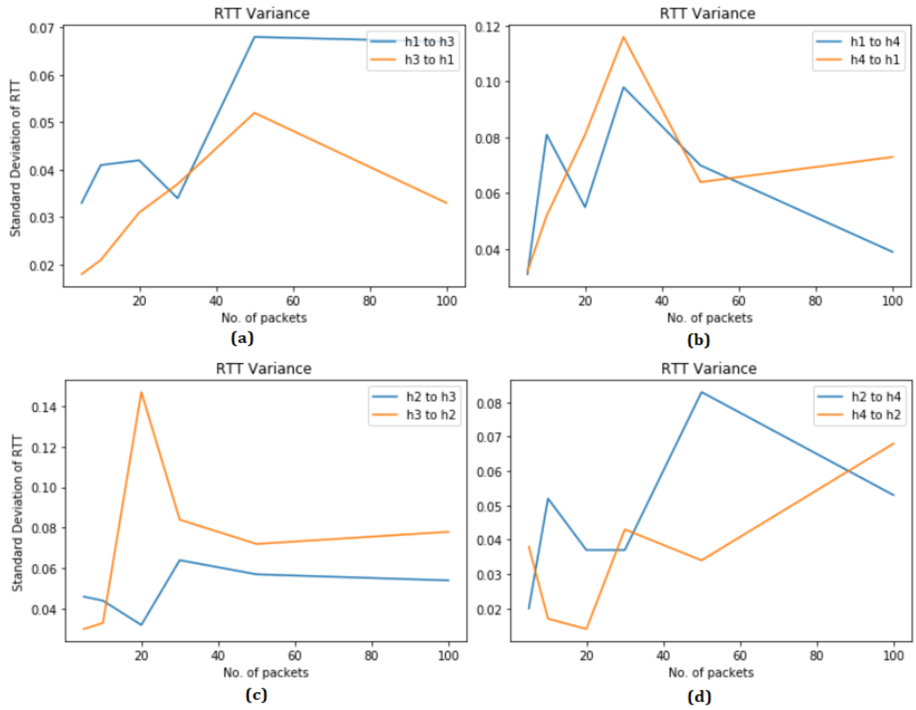

Figure 11. RTT Variance for Neighbouring AS of Legacy Network, (a) h1<->h3, (b) h1<->h4, (c) h2<->h3, and (d) h2<->h4

Since, standard deviation is simply the average of how far each RTT value is from the mean RTT. It shows how variable the round trip time is overtime. Higher variability in RTT value results in a more unstable network. As shown in the plots of Figures 9a,b, 10a,b,11a,b,c,d, and 12a,b,c,d, the standard deviation values with varying number of packets for SDN network is lesser than legacy network, which signifies that SDN can be more reliable and stable than their legacy counterparts.

Maximum and minimum RTT: next the minimum and maximum values of RTT for both the topologies are plotted in a graph of Figures 13a,b,c,d, 14a,b,c,d, and 15a,b,c,d. This is done for source and destination nodes within an AS, in neighbouring AS, and when AS65000 and SDN network are used as transit networks.The traffic were captured at multiple rounds and more than one plots are provided in the Figures 13, 14, and 15.

From the plots of Figures 13a,b,c,d, 14a,b,c,d, 15a,b,c,d, and 16a,b,c,d, it can be observed that for varying number of packets, the minimum and maximum values of RTT are lesser in SDN compared to that of legacy network. Higher RTT value signifies more time taken for transmission of packets that can affect the speed and reliability of the network. Thus, it can be concluded that routing in SDN using ONOS/SDN-IP performs much better than legacy network in terms of speed and reliability.

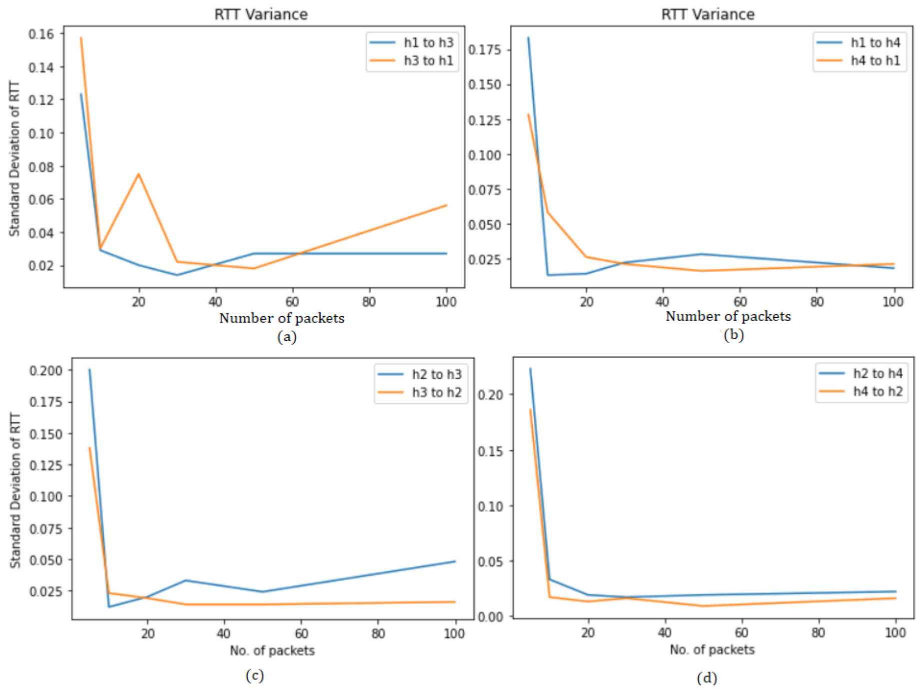

Figure 12. RTT variance for neighbouring AS of SDN, (a) h1<->h3, (b) h1<->h4, (c) h2<->h3, and (d) h2<->h4

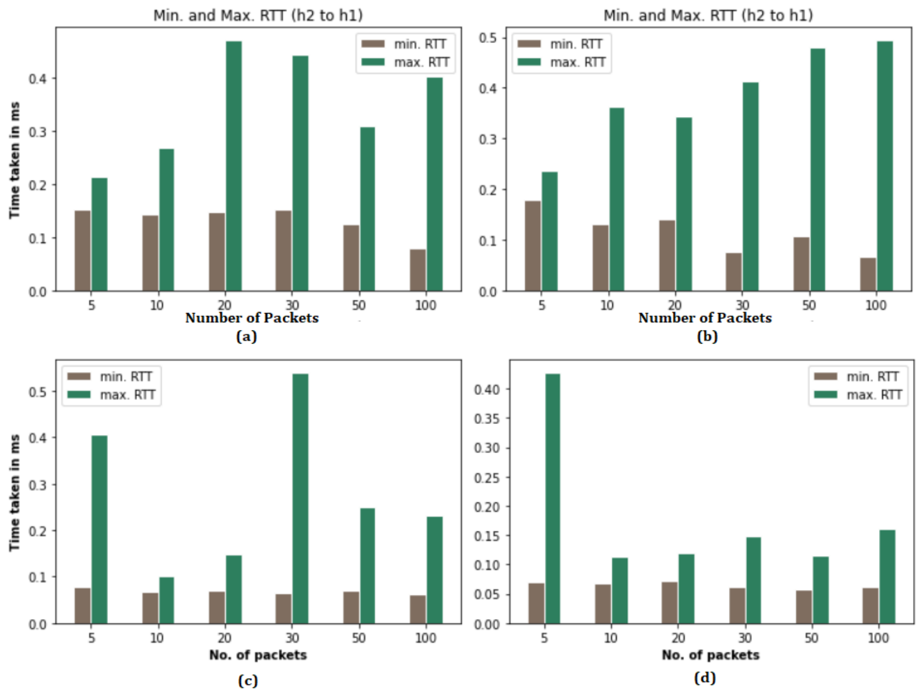

Figure 13. RTT variance between h2 and h1, (a)/(b) AS65000/SDN as transit in legacy, (c)/(d) RTT Variance between h2 and h1 in SDN

5. Discussion and Future Work

Virtualization features of SDN enables to have powerful APIs, which can be used to control many network functionalities with intelligence. The issues of backward compatibility of SDN with the legacy network enforces research communities to develop robust system for interoperability between SDN and legacy networks for smooth and low cost migration approaches. Hybrid SDN is the only solution to have smooth transition

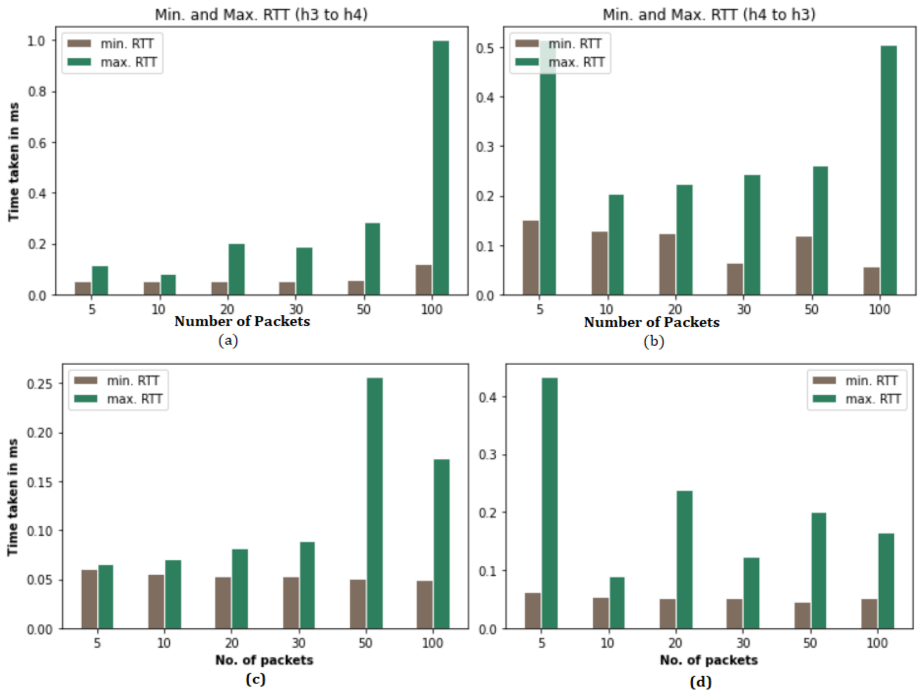

Figure 14. RTT variance, (a)/(b) Within AS65000/SDN in Legacy, and (c)/(d) in SDN

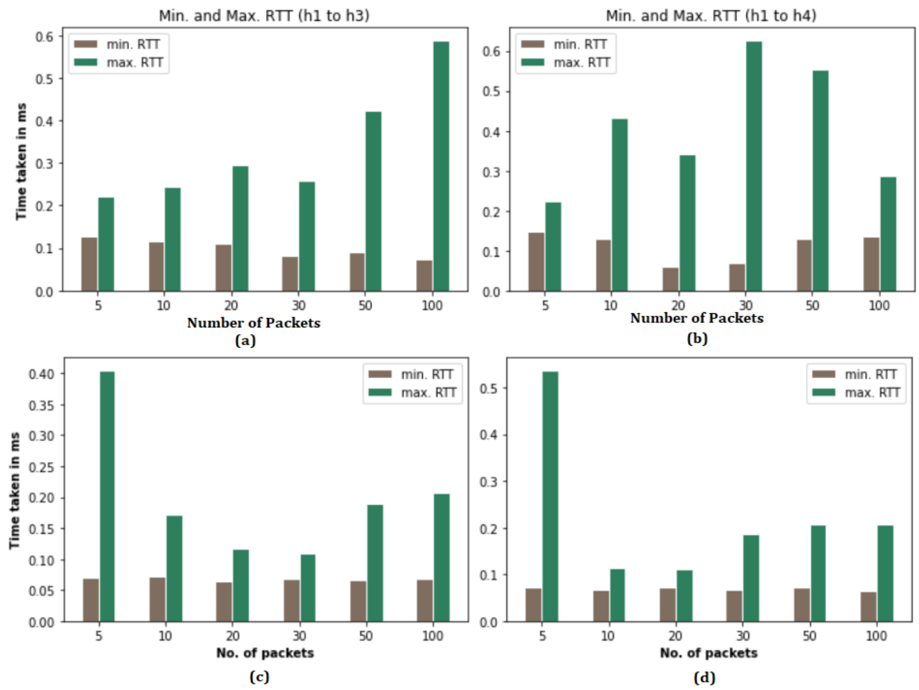

Figure 15. RTT variance for neighbouring AS for Host h1, (a)/(b) in Legacy, and (c)/(d) in SDN

to pure SDN for service providers so that customers can get uninterruptible services during the migration period. SDN-IP is an ONOS application that is used to peer SDN networks with external networks on the Internet using the standard BGP so that service providers can run hybrid SDN in their existing network for migration initiation. SDN-IP controlled network acts as a transit AS that interconnects different legacy IP networks considering each external network as a different AS domain and interfaces with the SDN network through its BGP-speaking border routers.

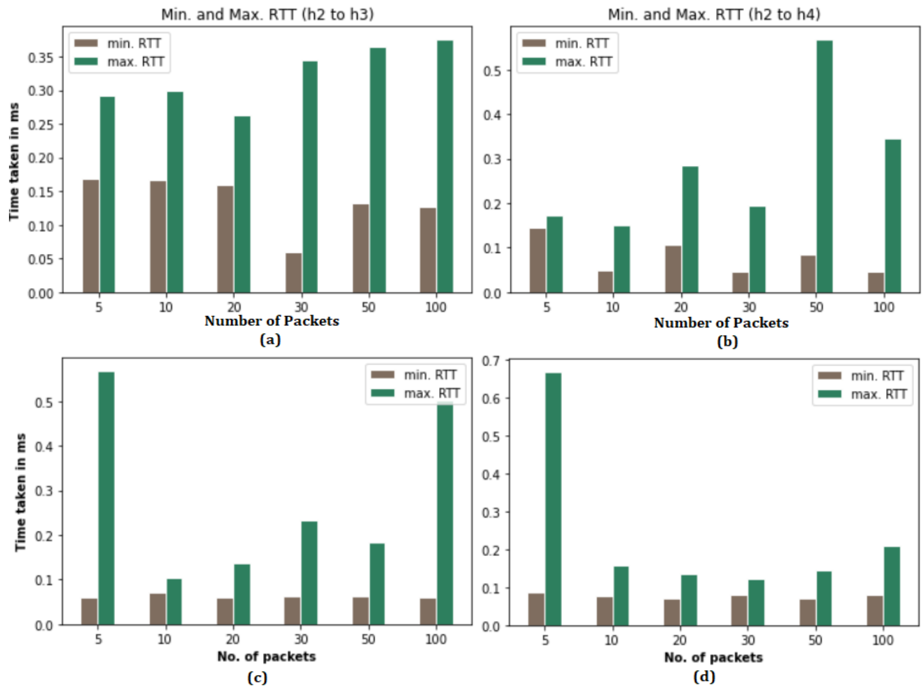

Figure 16. RTT variance for neighbouring AS for host h2, (a)/(b) for Host h1 in legacy, and (c)/(d) in SDN

In this study, an SDN integrated network was created with Mininet and experimental tests were done to ensure successful communication of the hosts in different ASes. The output of the tests show smooth transmission of data between hosts thus, providing testament to the possibilities of interoperability between two different networking paradigms. A similar legacy network was also created and observed to note the difference in characteristics of an integrated SDN and legacy network.

The comparison between legacy and SDN integrated network aimed at verifying the speculations of SDN performing better than legacy networks. By studying both the networks based on key performance indicators such as bandwidth capacity, packet transmission rate, and round trip time, it is observed that the performance of SDN network is much better than its legacy counterpart. Similarly, the exploratory data analysis of the values of QoS parameters collected from the network provided us with insights about the network.

The scope of this experimental analysis was limited to IPv4 addressing network only. routing performance analysis with the networks enabled with IPv6 addresses could further help to establish the significance and prospects of SDN implementation with future networking technologies. Additionally, this study was limited to compare the performance of hybrid SDN and legacy network to determine the feasibility of migration of the legacy networks into SDN. Routing implementations over hybrid SDN with multiple controllers and their placement, large and varying number of data plane devices etc. could be the future works to reflect the situations of carrier grade large ISP networks when implemented into reality. A single instance of ONOS controller is used in the present study. Multiple instances can be run at the same time for high availability services. Multiple instances help in load balancing of the whole network and adds reliability to the network. Additionally, other available network controllers can be used to replicate the results for comparison in addition with ONOS.

To give statistical significance to this experiment, correlation coefficients of the QoS parameters were determined. These values can be further utilized with artificial intelligence technologies or develop machine learning models or rules about the network. These insights can be useful in wide areas of applications such as traffic classification, routing optimization, quality of service and quality of experience prediction, resource management, security enhancement, and many other purposes.

6. Conclusions

Implementation of SDN is the only solution meet the modern age communication requirements and to avoid the issues in legacy networks. The devices that support the SDN network use OpenFlow protocol. But the devices generally already in use these days do not support OpenFlow protocol. The replacement of the existing networking devices at once by the OpenFlow supporting devices is not feasible and hence, a phase-wise migration is the only feasible solution. The features of SDN are compelling enough to encourage the migration of larger networks of ISPs from Legacy to SDN. This research has aimed towards demonstration of successful integration of SDN networks with legacy networks to show the possibilities of smooth migration and interoperability. The test results shown are contributory to verify the seamless interoperability of legacy and SDN networks so that service providers can be confident towards the SDN implementation in their ISP and Telcos networks.The experimental analysis is also a testament to SDN-integrated networks performing better than traditional legacy networks based on QOS parameters viz. bandwidth, PTR, and RTT.

Supplementary Materials: N/A

Author Contributions: Conceptualization, B.R.D., S.R.J.; Methodology, B.R.D; Software, A.T.,R.G.,D.L., and S.P.U.; Validation, B.R.D., and S.R.J.; Formal Analysis, B.R.D., A.T.,R.G.,D.L., and S.P.U.; Investigation, B.R.D., S.R.J.; Resources, B.R.D., S.R.J.; Data Curation, B.R.D, A.T., R.G., D.L., and S.P.U.; Writing—Original Draft Preparation, B.R.D., A.T., R.G., D.L., and S.P.U.; Writing—Review and Editing, B.R.D, and S.R.J.; Visualization, A.T., R.G., D.L., and S.P.U.; Supervision, B.R.D., and S.R.J.; Project Administration, B.R.D. and S.R.J.; Funding Acquisition, B.R.D. All authors have read and agreed to the published version of the manuscript.

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