

Route Optimization in SDNs: Incorporating Link Quality Estimation and Critical Switch Awareness

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Abstract

Software-Defined Networks (SDNs) have revolutionized network architecture, centralizing control, and introducing unparalleled levels of flexibility and programmability. Within this transformative landscape, the optimization of routing has emerged as a fundamental element in network management, a crucial factor in fully realizing the potential of SDNs. This study introduces an innovative approach that seamlessly integrates two critical components—link quality estimation and critical switch awareness—into the route path selection process, with the primary objective of elevating forwarding performance within SDNs. A noteworthy development in route selection is the concept of routing based on the identification of critical switches. At the heart of this research lies the imperative question: How can routes be optimized effectively and dynamically within the dynamic realm of SDNs? Implementing link quality estimation stands out as a pivotal catalyst for the enhancement of network performance. Our method consistently elevates the efficiency of data transmission, reduces latency, and upholds elevated levels of Quality of Service (QoS) by selecting routes based on real-time assessments of crucial link metrics, including latency, packet loss, and available bandwidth. This work introduces a multi-constraint iteration of Route Path Selection Optimization (RPSO), which integrates parameters such as Link Latency and Link Delivery Ratio, both in relation to the links and the switches themselves. These parameters advocate for a route selection strategy that prioritizes routes with a reduced count of critical switches and an emphasis on high link quality. The experimental results are compelling, showcasing a substantial 55.73% increase in throughput when utilizing the proposed scheme. Furthermore, the packet delivery ratio experiences a notable increase of 12.5%, while the path stretch is appreciably reduced by 37%.

Keywords: Route optimization, software defined networks, link quality, switch awareness, Route Path Selection Optimisation.

1. Introduction

The exponential advancement of contemporary networking has resulted in a growing need for network management solutions that are adaptable, effective, and intelligent. Considering this requirement, Software-Defined Networks (SDNs) have emerged as a transformative technology that separates the control plane from the data plane, providing exceptional levels of agility, scalability, and programmability [1]. SDNs have revolutionised the field of network architecture by enabling network administrators to exercise centralised control and management over network resources. This capability empowers administrators to

effectively adapt to dynamic conditions and optimise network performance.

Although SDNs have brought about significant advancements, they have also posed novel difficulties in terms of enhancing the efficiency of data flow routing within the network. Route optimisation is a crucial aspect of network management, as it involves the selection of the most appropriate path for data transmission to achieve specific performance goals [2]. In the context of conventional networking, the optimisation of routes commonly depends on the utilisation of routing protocols such as OSPF (Open Shortest Path First) or BGP (Border Gateway

Protocol). Nevertheless, it is common for these protocols to exhibit a deficiency in their ability to possess the requisite level of intelligence required for making timely and adaptable decisions that are contingent upon the present condition of the network [3].

This paper discusses the urgent requirement for effective and adaptable route optimisation in SDNs, with a specific emphasis on integrating link quality estimation and critical switch awareness into the decision-making procedure. Through the utilisation of these methodologies, our objective is to augment the comprehensive efficacy, dependability, and calibre of service within SDNs.

A. Context of Software-Defined Networks

Traditional network architectures are distinguished by their tightly integrated control and data planes, which are dispersed across numerous network devices. Modifications or adjustments to network behaviour frequently necessitate intricate and manual configurations of these devices, leading to restricted flexibility and scalability [4]. SDNs are characterised by a significant change in approach, as they separate the control plane from the data plane. SDNs employ a centralised control plane, wherein network devices within the data plane assume the role of straightforward forwarding elements that conform to the directives issued by the controller.

The process of centralising network control provides administrators with the ability to dynamically adjust the network in response to changing conditions and traffic patterns, thereby facilitating the optimisation of the network. SDNs utilise OpenFlow, a standardised communication protocol that facilitates the interaction between the controller and the data plane devices, enabling efficient management of network flows [5]. The division of control facilitates the advancement of network services that can be programmed, simplifies the process of identifying and resolving issues, and enhances the efficiency of network administration.

B. Motivation for Route Optimization in SDNs

SDNs have significantly transformed the landscape of network management, yet they have also introduced novel complexities pertaining to routing and path selection. Conventional routing protocols, such as OSPF and BGP, are not optimally compatible

with the dynamic and adaptable characteristics of SDNs. In the context of SDNs, the determination of paths is no longer exclusively reliant on static routing tables. Instead, paths can be flexibly modified in response to real-time network conditions, application requirements, and policy alterations. The inherent dynamism of SDNs underscores the imperative for the advancement of sophisticated route optimisation techniques. Optimizing routes in SDNs is essential for several reasons.

- *Resource Efficiency*: Optimized routing can help allocate network resources efficiently, reducing congestion and improving overall network utilization.

- *Quality of Service (QoS)*: Ensuring the desired level of QoS is a fundamental requirement for many applications and services. Optimized routes can help meet these QoS expectations.

- *Reliability*: Effective route optimization can enhance network reliability by providing redundant paths and rerouting traffic in case of failures or degradation.

- *Network Security*: Route optimization can be leveraged to enhance network security by avoiding malicious paths and isolating compromised network segments.

- *Reducing Latency*: Minimizing latency is crucial for applications with low-latency requirements, such as real-time communication and online gaming.

C. Problem Statement and Research Objectives

This research focuses on addressing the issue of optimising routes in SDNs by incorporating two key factors: link quality estimation and critical switch awareness. In the context of SDNs, conventional approaches to route optimisation typically employ simplistic shortest path algorithms. These algorithms, however, fail to account for the performance characteristics of the links traversed by the chosen path or the significance of the switches within the network. As a result, these methodologies may not consistently yield the most appropriate routes for transmitting data, thereby resulting in network performance that is less than optimal. Our research aims to develop a novel route optimization scheme that incorporates two key elements:

- *Link Quality Estimation*: We propose the integration of link quality metrics into the route

selection process. By assessing the quality of links based on parameters such as latency, packet loss, and bandwidth, our scheme can dynamically adapt to changing network conditions and select routes that optimize performance.

- *Critical Switch Awareness*: Recognizing the importance of switches in network stability, we introduce critical switch awareness. By identifying and considering the criticality of switches in the network, our scheme can choose paths that enhance network resilience and reliability

The main aim of this study is to develop, execute, and assess a route optimisation strategy that utilises link quality estimation and critical switch awareness to improve the performance of SDNs. It is posited that the proposed methodology will make a valuable contribution to the advancement of intelligent, efficient, and adaptable SDNs. This is particularly relevant given the pressing demand for sophisticated route optimisation techniques within the constantly evolving networking landscape.

2. Related Works

The current approach to selecting route paths takes into account only one metric during the path selection process. However, it fails to optimise the switch update operation, which is primarily due to subpar link quality and the increased frequency of update operations in the switch flow table. Numerous studies have been conducted on path selection, with a primary focus on routing metrics such as shortest distance [6], link latency [7], and link bandwidth [8]. The metrics currently in use are inadequate and unsuitable for meeting the demanding Service-Level Agreement (SLA) requirements of time-sensitive applications. While the restoration approach offers greater flexibility in the management of real-time flows. Therefore, it is unable to fulfil carrier-grade demands in a vast network that caters to numerous data streams [9]. On the contrary, protection mechanisms may exhibit superior forwarding performance, albeit at the expense of flow table capacity. Finding the optimal routing path is a complex task due to the need to balance the costs associated with flow table operations and path selection [10]. The authors of the study conducted by [11,12] introduced a localised restoration strategy that aims to minimise the number of flow operations required in disaster

scenarios. The proposed scheme aims to reduce the expenses associated with flow table update operations and minimise the number of hops, both of which are determined by a predefined threshold value.

The authors in reference [13] took into account the factors of latency and packet loss when formulating their approach to path selection. To optimise network performance, delay-sensitive flows are directed along a path that minimises delay, while other flows are directed along a path that minimises packet loss. In a similar vein, the authors [14] introduced a path selection algorithm that prioritises QoS considerations to expedite the rerouting of time-sensitive flows for real-time applications. This algorithm specifically targets bottleneck links that hinder the feasibility of scheduling. However, the previous study conducted in the range of [15] failed to take into account the impact of switch load when making decisions regarding path selection. To ensure the quality of the selected link, it is important to take into account both link latency and the ratio of link delivery. The authors of [16] proposed a QoS-driven and SDN-assisted MPTCP path selection scheme (QSMPS) to enhance the quality of transmission service.

The Video Path Selection Algorithm (VPSA) for multimedia flows was introduced in reference [17]. The VPSA system utilises the historical and real-time data on link bandwidth usage, which is gathered by the controller, to determine an appropriate path. The acceptance or rejection of video streams is contingent upon the presence of a viable pathway. In a similar vein, authors [18] employ the notion of monitoring to extract statistical data and compute the load of the port. The routing of flows is directed towards a path with lower congestion. Nevertheless, the regular monitoring of past and current link bandwidth usage or port in [19] can have a notable impact on the time required for topology learning and discovery. This, in turn, leads to an increase in the latency of path setup [20]. The author employed a specialised packet provided by the controller to gauge the round-trip time of packets returning to the controller. To calculate the total path setup latency, the time is added to each path.

In a network that undergoes dynamic changes, the quality of links is significantly impacted, leading to

frequent occurrences of link failure within the network. Hence, it is crucial to take into account the quality of links and the parameters of switch resources when making decisions regarding routing path selection. The issue at hand is of significant complexity since the quality of links and the availability of switch resources play a crucial role in determining the network's capacity to accommodate increasing demands as it undergoes changes over time.

3. Methodology

This section presents the methodology employed for the development and implementation of a route optimisation scheme in SDNs, which integrates link quality estimation and critical switch awareness. The "Route Path Selection Optimisation" (RPSO) scheme is designed (see Figure 1) to choose a path that maximises the quality of links and efficiently allocates resources from the source to the destination in a SDN environment. The selection of quality links takes into account multiple constraints, and the focus is on identifying a minimal set of critical switches from the perspective of the switches.

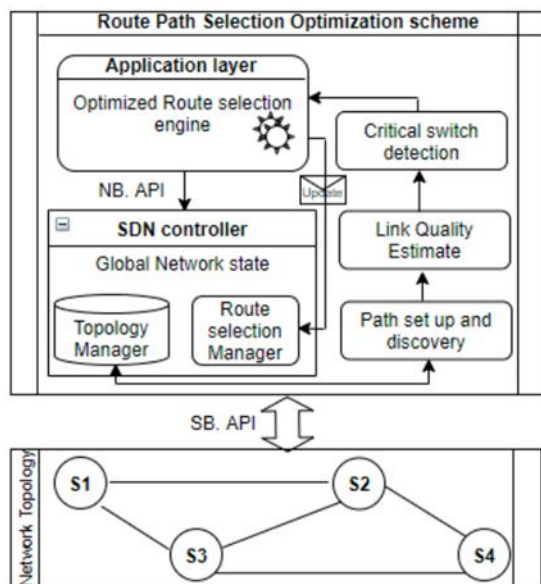


Figure 1. Proposed RPSO Architecture

Any manipulation or alteration in network topology has the potential to directly impact the services provided by the SDN controller. Hence, the SDN controller employs the Link-Layer Discovery Protocol (LLDP) message for the purpose of identifying the network forwarding components,

including switches, links, and hosts, at a given time t_i . In this context, the SDN controller initiates a Packet-Out event to transmit LLDP advertisements to every operational switch. As a reciprocal action, the switch will transmit the link information by encapsulating the LLDP message within the Packet-In event. In this investigation, we measure the time it takes for the controller to send and receive specially crafted Eco_Ping packets using Internet Protocol (IP) and Medium Access Control (MAC) addresses. This allowed the Ethernet frame to be sent to neighbouring switches S_1 via Packet-Out, with the packet's creation time and port number included in the payload. On the flip side, if the Ethernet type encounters an entry-miss at S_2 , the Packet-In event will relay Eco_Ping back to the controller.

To assess the quality of links within the SDN, a set of metrics is defined. These metrics encompass factors that directly impact the performance of data transmission across the network. The key metrics include:

1. *Latency*: The round-trip delay in communication between network nodes, representing the time taken for a packet to travel from the source to the destination.
2. *Packet Loss Rate*: The percentage of packets lost during transmission, which indicates the reliability of a link.
3. *Available Bandwidth*: The maximum data rate that a link can support, providing insights into the link's capacity.

To collect data for the defined link quality metrics, the scheme employs various techniques:

1. *Passive Monitoring*: Utilizing passive monitoring tools, the network continuously collects data related to latency and packet loss rate. These tools may be integrated into the SDN controller or distributed strategically within the network.
2. *Active Probing*: Periodic active probing is conducted to measure available bandwidth. This is achieved by sending test packets across network links and monitoring their delivery times.

The data collected from the metrics and monitoring techniques are stored in a Link Quality Database. This database is updated in real-time, ensuring that the route optimization scheme has access to the latest information about link quality within the network. Critical switch identification is

a crucial component of the route optimization scheme. Criticality of switches is determined by evaluating multiple factors, including:

1. *Network Traffic*: Switches experiencing a higher volume of traffic are considered critical as they play a pivotal role in data transmission.
2. *Redundancy*: Switches that act as redundancy points to ensure network reliability are identified as critical components.
3. *Security Policies*: Switches enforcing security policies, such as access control or firewall rules, are deemed critical due to their impact on network security.

The scheme employs a combination of techniques to identify critical switches:

1. *Traffic Analysis*: Network traffic data is analysed to identify switches with high traffic loads. Such switches are more likely to be critical components.
2. *Redundancy Mapping*: By assessing network redundancy configurations, the scheme identifies switches that act as primary and secondary paths for data transmission.
3. *Policy Evaluation*: Network policies are evaluated to recognize switches responsible for implementing security policies or access control.

The data collected for identifying critical switches is stored in a Critical Switch Database. This database is continually updated to reflect changes in network conditions and policies.

3.1. Framework for Route Optimization

The route optimization scheme operates within a well-defined framework. The framework consists of the following stages:

1. *Network Topology Discovery*: The SDN controller periodically discovers the network's topology, identifying switches, links, and their characteristics.
2. *Link Quality Estimation*: Utilizing data from the Link Quality Database, the scheme calculates link quality metrics for available paths.
3. *Critical Switch Assessment*: The Critical Switch Database is consulted to evaluate the criticality of switches along potential routes.
4. *Path Selection Algorithm*: A path selection algorithm is employed to optimize route paths. This algorithm takes into account link quality metrics and critical switch information to make route selection decisions.

3.2. Integration of Link Quality Estimation and Critical Switch Awareness

The route optimization scheme integrates link quality estimation and critical switch awareness by considering both aspects during the route selection process. For each potential route, the algorithm evaluates the following:

1. **Link Quality Metrics**: It assesses the quality of links along the path, favouring paths with lower latency, minimal packet loss, and greater available bandwidth.
2. **Critical Switches**: It considers the criticality of switches along the path, prioritizing routes that avoid or utilize critical switches strategically.

The route selection algorithm employed in the scheme is based on a combination of heuristics and optimization techniques. This algorithm computes route paths that strike a balance between link quality and critical switch awareness, optimizing network performance while maintaining reliability. The route optimization scheme is implemented in a simulated SDN environment. This environment replicates a realistic SDN infrastructure with switches, controllers, and network applications. Data for link quality estimation and critical switch assessment are collected and processed using custom scripts and monitoring tools integrated into the SDN environment.

To evaluate the effectiveness of the route optimization scheme, a series of tests and validations are conducted. These include simulated network scenarios with varying traffic patterns, failures, and changes in network conditions. The scheme's performance is assessed based on criteria such as latency, packet loss, and network reliability.

4. Results and Discussion

The simulation is executed on a computing device with a processing speed of 3.60GHz and a memory capacity of 16GB. The device is equipped with a Ryu SDN controller and utilises Mininet version 2.2.2. The utilisation of the OpenVswitch software switch within the Mininet framework, operating on virtual machines. The OpenFlow switch is commonly characterised by its limited capacity, while the OpenVswitch can accommodate a larger number of entries. The study aims to enhance the functionality of OpenVswitch by enabling it to accommodate the limitations found in real OpenFlow switches. The term "path setup time" denotes the time required for establishing the complete path to

route flows from a source to a destination during the installation phase. The time taken for path installation shows an observable correlation with the path's length; it tends to increase with longer paths and decrease with shorter ones. Figure 2 presents data that makes it clear that Flow-based Security Language exhibits a slightly lengthier setup time compared to RPSO, whereas Reverse path forwarding indicates a longer setup time. Notably, the initial ping experiences a greater delay than subsequent pings. This delay is primarily due to the necessity of consulting the controller to compute the initial path for each ping and updating the corresponding switch flow table to facilitate the routing process.

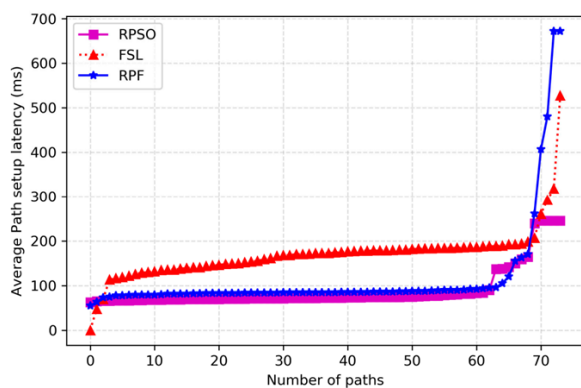


Figure 2. Path setup Latency

Throughput, in the context of data transmission, is the average number of successfully received data packets at the intended destination over a defined period, usually one second. Throughput measurements are typically taken following network events, such as the introduction of new data flows. As shown in Figure 3, the performance comparison between our proposed solution, referred to as RPSO, and an alternative method reveals a noteworthy improvement in throughput performance. Specifically, the RPSO algorithm demonstrates significant enhancements, achieving a 29.54% improvement compared to the Flow-based Security Language and a 55.73% improvement compared to the Reverse Path Forwarding techniques.

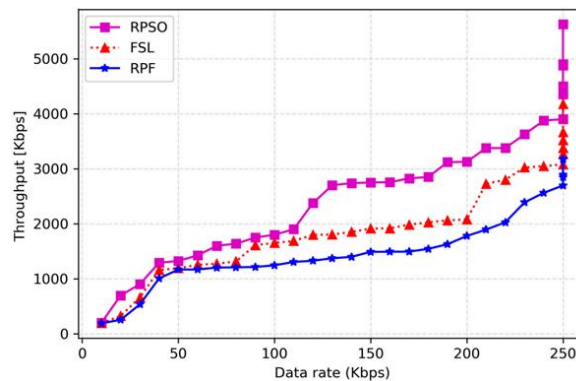


Figure 3. Throughput Comparison

The RPSO algorithm exhibited outstanding performance in the estimation of link quality, leading to an increased success rate in successfully delivering critical data packets to their designated destinations. This achievement remained consistent even as incoming traffic flows continued to grow.

The term "Packet Delivery Ratio" (PDR) pertains to the proportion of packets that are successfully received in relation to the total number of packets transmitted, with the average calculated across all flows. The evaluation of the transmission efficiency deployed in the network is significantly influenced by this factor. The PDR exhibits an upward trend in response to an increased incidence of packet drops resulting from network events, such as link failures. The observed (in Figure 4) rise in PDR signifies enhanced system performance, while RPSO demonstrates a consistent increase, ultimately reaching 100%.

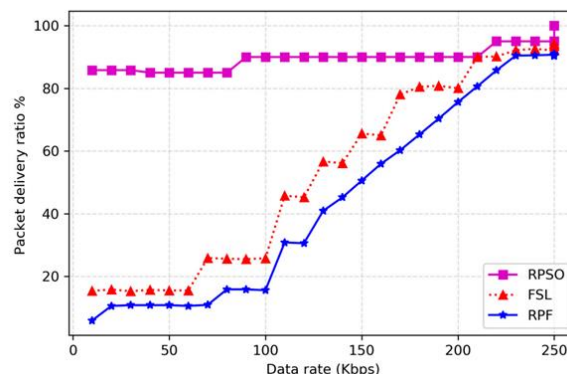


Figure 4. PDR Comparison

5. Conclusion

In this research, we introduce a novel approach aimed at enhancing forwarding performance by taking into account route path selection that

seamlessly integrates both link quality and critical switch awareness. A noteworthy contribution of this work is the development of critical switch-based routing, which streamlines the path selection process. The central goal of this study was to address the pressing need for efficient and adaptive route optimization within the dynamic realm of SDNs. The incorporation of link quality estimation has proven to yield significant improvements in network performance.

By making route selections based on real-time evaluations of link metrics, including factors like latency, packet loss, and available bandwidth, our scheme consistently demonstrated enhanced data transmission efficiency, reduced latency, and the sustained delivery of higher QoS levels. Critical switch awareness emerged as a pivotal factor in bolstering network reliability. By factoring in the criticality of switches during route selection, our scheme not only ensured that traffic traversed dependable network components but also provided redundancy options in the event of switch failures.

The real-time nature of our route optimization scheme allowed the SDN to swiftly adapt to evolving network conditions and shifting traffic patterns. While the findings presented in this study are indeed promising, ongoing research and practical implementations will be paramount in further validating the long-term benefits of this approach. We firmly believe that the fusion of link quality and critical switch awareness in route path selection will continue to drive the evolution of SDNs, equipping them to meet the ever-increasing demands of modern networking with heightened efficiency and adaptability.

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