IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 16 February 2026, accepted 11 March 2026, date of publication 13 March 2026, date of current version 20 March 2026.

Digital Object Identifier 10.1109/ACCESS.2026.3673921

RESEARCH ARTICLE

SD-GPON: A Dynamic Prioritization for Efficient Traffic Management Based on Controlling DSCP

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ABSTRACT Existing Gigabit Passive Optical Network (GPON) networks exhibit weaknesses in their traffic management abilities, specifically in the dynamic prioritization of data flow according to the policy constraints imposed by network administrators. In legacy GPON, the real-time priority process is achieved between the Optical Line Terminal (OLT) and Optical Network Unit (ONU) to manage different types of traffic like voice and video. The precedence process in GPON could be complicated to manage, particularly in networks with multiple traffic types. As a result, latency may adversely affect network performance. To tackle these shortcomings, we introduced a Software-Defined GPON (SD-GPON) approach by taking benefits of the SDN and virtualization techniques to manage data flow prioritization dynamically. Our proposal permits an entire control prioritization of data flow by modifying the Differentiated Service Code Points (DSCP) classes via a central vision of the Software-Defined Networking (SDN) controller to forward data based on its flow tables. In addition, we used Python programming language to virtualize the OLT to facilitate traffic management by the SDN Controller (SDNc), Mininet simulation to emulate the proposed network, and the ONOS platform controller to apply instances on the proposed network. The analysis of the proposed scheme revealed the superiority of the SD-GPON over GPON networks upstream and downstream for audio and video traffic by approximately 36%.

INDEX TERMS SDN, NFV, GPON, priority, SDCP value, traffic engineering.

I. INTRODUCTION

The exploding growth of the Internet in the last decades caused fast-growing capacity demands in bandwidth as copper-based technologies face their fundamental bandwidth limitations [1]. Moreover, interactive applications such as Telemedicine, E-learning, electronic banking, and the emerging IPTV services push toward a high transmission rate. The optical fibers, being the key, possess features such as a vast bandwidth, high-speed transmission, lowered susceptibility to signal degradation, and immunity to electromagnetic interference [2]. Access strategies based on optical fibers are earning more and more concentration as they deliver the ultimate solution of providing different services to the end client premises. Broadband access network operators increasingly considered Passive Optical Networks (PONs) the preferred technology for Fiber-To-The-Home, curb, building, and allocation point (FTTx) architectures [3]. In contrast, PON technology consumes effort and time for management, especially with increasing PON network distribution. Therefore, to meet the provision of next-generation networks with admission to security, intelligence, efficient control, and priority management as well as reducing Capital Expenditures (CAPEX) and Operating Expenses (OPEX), Software-Defined-Networking (SDN) is becoming increasingly influential in overcoming the challenges via its integration with PONs [4]. With SDN, the software controls the network instead of hardware, utilizing software applications and typical protocols like OpenFlow to control the network centrally [5]. The SDN architecture relies

The associate editor coordinating the review of this manuscript and approving it for publication was Xueqin Jiang.

on the distinction between the data plane, which contains network devices such as access points, routers, and switches responsible for data forwarding, and the control plane, which holds the network operating system that administrates the management functionalities of the underneath data plane physical devices. This separation enables the SDN control to provide centralized management of the network data plane device within the SDN framework, enabling flexible network administration. Furthermore, it facilitates the coexisting operation of diverse PON infrastructures from various providers due to the capability of its protocols to interact transparently with multiple types of hardware. Consequently, Internet Service Providers (ISP) and network operators effectively manage different Gigabit PON based on the Gigabit standard (GPON) devices via a programmable interface [6]. As a result, operators can supervise, manage, and update the whole network, irrespective of the underlying technology. Furthermore, SDN provides additional benefits in access networks, particularly in the case of GPONs. One representative of this is its ability to facilitate rapid control and reconfiguration of Quality of Service (QoS) requirements and applications for residential clients according to its provision of a shared programmable interface and a harmonious touchpoint for control, policy, and management [7]. SDN enables the rapid creation and alteration of QoS since there is no necessity for the synchronization of GPON equipment whenever a network configuration is altered. So, the impact of SDN on GPON implementation, particularly in QoS aspects, is notably promising [8]. While GPON stays satisfactory for traditional real-time traffic management, its QoS mechanism is increasingly unsatisfactory for the diverse, dynamic, and ultra-responsive real-time demands of current applications. The integration of GPON with real-time applications can lead to increased latency due to the shared medium of PON combined with the scheduling requirements. This combination complicates the maintenance of precise timing across different network domains, highlighting the challenges in synchronizing operations effectively. Additionally, managing traffic to ensure QoS and deterministic performance across PON technologies presents significant complexity [9]. Furthermore, traditional GPON utilizes static T-CONT genres and a particular Dynamic Bandwidth Allocation (DBA) [10], making it inflexible for various real-time services. Traditional DBA systems encounter numerous challenges, especially in latency, due to their dependence on centralized OLT decisions for bandwidth allocation. This centralized technique needs frequent and continuous transmission between OLT and ONUs, which worsens latency during periods of high network load or swiftly fluctuating traffic conditions. Furthermore, conventional DBA finds it difficult to adapt effectively to changes in traffic demand, leading to inefficient bandwidth distribution and reduced QoS [11]. The necessity of the SD-GPON solution derives from fundamental constraints in traditional GPON architectures when handling modern network demands, particularly of QoS traffic management, dynamic service provisioning, and integration with 5G/edge computing. While legacy GPON provides basic broadband access, it lacks the agility, visibility, and centralized control required in today's converged, cloud-native, and latency-sensitive environments.

The pivotal contributions of this article are as follows:

- 1. Providing a new mechanism to facilitate the flexible assignment of traffic prioritization levels by enforcing DSCP values, executed in the SDN controller to support runtime redefinition of traffic classes and their associated bandwidth assurances.
- 1. Prioritizing VoIP, Video streaming, and bulk data traffic flows through modifying DSCP values and precedence classes (dynamically and in real-time) according to the network administrator's policies and scope.
- Integrating GPON, SDN, and NFV for governing the assignment of priority to selected data for real-time traffic without manual reconfiguration to elevate QoS for mission-critical real-time data.

Our proposal provides an approach to flexible management for the selected traffic types and governs the assigned priority level by modifying the DSCP values to forward this traffic. To achieve this proposal, we utilized sophisticated networking technologies such as SDN and NFV [12] to emulate and simulate the proposed network and its functions. The manuscript is organized as follows. Section II defines GPON, SDN, and NFV technologies and their corporation. Section III presents the proposed network and traffic prioritizing mechanism. Section IV discusses the performance and findings. The conclusion is presented in Section V.

II. BACKGROUND AND RELATED WORK

This section offers an overview of the foundational concepts of networking technologies and relevant research studies conducted on GPON, SDN, and NFV technologies. Specifically focused on works that aimed to enhance network performance and benefit from the transition from traditional to virtualized structure of communication networks, and to collaborate various techniques and platforms.

A. GPON

Optical transmission utilizes light signals to convey information, typically via fiber optic cables or free-space optical media. However, electrical communications use electrical signals to deliver data through wireless or copper wire. The advantages of optical communication are high data transmission rates, long distances, and more security. Widely using GPON in Fiber-to-the-Home (FTTH) deployments because it is cheaper to deploy than point-to-point fiber links. Access techniques established on optical fiber are gaining additional attention as they deliver the ultimate solution in offering different services to subscribers. Due to the shortage of active units in the light path, the GPON architecture is cost-effective, simple, and presents bandwidth that is hard to achieve by other access strategies [13].

It is a point-to-multipoint, bidirectional, high-rate optical network for data transmissions. This network has no active components in the Optical Distribution Networks; therefore, it is called passive. GPONs solve the access network bandwidth jam by delivering a flexible, cost-effective, and high-bandwidth solution [14]. Moreover, a GPON consists of an Optical Line Terminal (OLT) linked to an Optical Network Unit (ONU) at the user end by optical fiber, which splits up at a passive optical splitter. The OLT exists at the local exchange and attaches access to the metro backbone. ONU is located when the fiber terminates in the subscriber's homes or businesses [15]. The authors in [16] focused on the ITU-T GPON criteria, there will still be a reference to IEEE GPON as they work to provide as much commonality between essential aspects of GPON standards to underestimate divergence and facilitate convergence, and ease the use of the physical layer optical components by adopting identical wavelength plans. To take advantage of the increased capacity of 5G wireless networks, supported by identical high-capacity fixed networks for the fronthaul and backhaul transport, [17] discussed an elaborating approach by ITU-T Q2/SG15 to employ GPON technologies in different operational wireless networks architecture for the transport links as multiple small cells are placed next to macro-cells. As bandwidth needs continue to increase, it is expected that the next-generation optical access network require 100G or 200G per wavelength and beyond. Therefore, Zhang et al. in [14] introduced a Coherent GPON (C-PON) based on Digital Signal Processing (DSP) and multi-access coherent optics as a promising single-wavelength PON.

B. SDN

Software-Defined Networking (SDN) separates the control plane from the data plane of the forwarding devices. This split provides several advantages, including network management simplification and control. The rule of routers/switches is generally implemented at a controller [18]. The OpenFlow switches protocol has a consistent programming interface based on the OpenFlow protocol and the ability to monitor and forward the network data traffic flows according to the rules defined by the controller. In general, the SDN vision architecture comprises of four principal components [19]:

1) The application layer involves applications software that governs traffic engineering, configures load balancing, manages traffic flows, and applies traffic priority policy.
2) The control layer is an essential component of the SDN architecture, primarily described by the SDNc. It serves as a negotiator between the application layer, which restricts the intended network demeanor, and the data plane, which forwards data according to given commands. This layer supports the network with programmability and intelligence, permitting network administrators to set policies and manage network functions dynamically.
3) The Application Program Interface (API) defines the protocols of communication between diverse software parts. It serves as a vital bridge that links and interacts between the different layers of the SDN architecture, particularly between the data layer, control layer, and application layer. Moreover, APIs allow the applications, controllers, and other network administration tools to programmatically configure, optimize, and control the network resources based on real-time conditions.
4) The data plane (also known as the data layer or forwarding layer) plays an important function in the basic data traffic forwarding of a network. It is responsible for driving the packets that move via the network, following decisions about how the packet should be routed, and ensuring that data reaches its intended destination.

Over the past few years, many studies have been presented to guarantee a high Quality of Service (QoS) considering end-to-end latency, bandwidth, and packet loss. In [20], the authors proposed a traffic control system as a priority-based flow control by minimizing the complexity of the traffic change method in SDN switches by adjusting the priority of flow controls to reduce the consuming time on the control plane processing. To emphasize the significance of containing flow priority while updating the data plane of an SDN, researchers in [21] proposed an architecture for consistency, continuity, and priority management when scheduling the forwarded rule updates based on the programmability and flexibility offered by the SDN.

C. NFV

The advent of the Network Functions Virtualization (NFV) concept highlights its significance in the context of networking. This concept focuses on the substituting of classic network hardware with virtualized solutions. Rather than utilizing physical devices like routers or firewalls, we can implement these operations as software on virtual machines. This transition from hardware to software contributes to improved network flexibility and scalability [22]. NFV is the general architecture for virtualizing network functions, while Virtualized Network Functions VNF refers to the distinct models of those virtualized functions. For instance, a firewall could be implemented as software in an NFV environment as a VNF [23]. The authors [24] presented a softwarized platform for four ports PON to serve and assess real-time throughput, power consumption, and latency. They used pollinated data transmission and multitasking. We utilized these concepts to mimic the OLT and its functions to integrate SDN, NFV, and GPON technologies to advance our proposal. In other words, GPON is the preferred choice for most service providers due to its higher data rates, and it supports multiple services to end-users. This choice requires dedicated physical hardware such as switches, OLT, splitter, etc. However, in SD-GPON, the functions of physical network devices can be achieved by virtualizing these functions through software to simulate hardware operations. This procedure reduces the cost and effort of network configuration, in addition to flexible network management and programmability. With the benefits of NFV the network administrator can configure and apply its rules and policies in real-time to affect the network behavior simultaneously.

D. INTEGRATION OF SDN AND GPON

Despite the significant acceptance of SDN resolutions in various network architectures, the integration of SDN in GPONs has a remarkable impact since it is a widely deployed access architecture. SDN allows the invention and modification of services transparently, contrary to the strategies implemented in access networks, as GPON equipment needs to be synchronized when any modification in its configuration is accomplished. Furthermore, SDN permits the coexistence of numerous GPON infrastructures from different agents because the SDN protocols can interact smoothly with diverse equipment. Then, network operators or ISPs can efficiently control GPON devices using a typical programmable interface. Also, SDN makes it more manageable to apply automatized and centralized responses to network QoS without affecting the regular network operation. As a result, many proposals are concentrating on controlling residential networks using SDN approaches. Khalili, et al. in [25] proposed an SDN architecture for Ethernet PON (EPON) to virtualize the OLT task and place it within an external controller while maintaining the remaining PON capabilities near an OpenFlow switch to improve management of the bandwidth allocation, power consumption management, and QoS enforcement and monitoring. The authors in [26] present an SDN architecture to manage traffic QoS, scheduling, and energy-saving elements to Time and Wavelength Division Multiplexing GPONs considering laser tuning span and real constraints in the multiwavelength GPON. A hierarchical framework is proposed in [27] to build an automated, visualized, and smart GPON through an SDN-enabled PON controller admitting round and Real-Time (RT) vision of network services to realize the decision-making capabilities for industrial GPON networks. While in [4] outlined OpenFlow SDN mechanism design and implementation for administrating and managing ten-gigabit symmetric PON (XGS-PON). The SDN agent establishes communication with the controller via the functioning of the OpenFlow protocol, concurrently maintaining direct contact with OLT through the application programming interface to eliminate the necessity of simulating SDN in hardware appliances.

Traditional GPON technology relies on a fixed, pre-assigned bandwidth, and making any modifications or changes is complex, challenging, and time-consuming. That is, GPON cannot dynamically adapt to changing traffic patterns due to a shortage of centralized management and real-time programmability of a network to enforce dynamic QoS policy and prioritize various traffic types. The proposed SD-GPON architecture provides the flexibility and programmability required to handle the dynamic diverse traffic demands of networks. This leads to enhanced efficiency and performance when compared to standard GPON.

All the research papers mentioned above presented proposals about collaborating SDN and PON without enforcing neither precedence level for specific traffic, nor regulating bandwidth allocation for different data types. Whereas our proposal governs the DSCP to prioritize diverse traffic flows and control the assignment of bandwidth to different types of data. This collaboration aims to prioritize various traffic flows effectively and regulate bandwidth allocation by using SDN, NFV, and VNF. The findings suggest that such an approach can significantly improve network performance by ensuring that diverse traffic demands are met efficiently, thereby optimizing resource utilization and enhancing overall service quality.

III. PROPOSED SD-GPON

We validate an SDN and OpenFlow access network administration proposal over GPON with virtualizing OLT to deliver efficient and highest control on the access network, guaranteeing the fulfillment of QoS essentials to the subscribers and exhibiting the entire functionality of the legacy GPONs as shown in Figure 1. In particular, we present a solution to managing traffic flow precedence by controlling and defining network resources to provide temporarily dynamic services and manage priority.

A. BUSINESS APPLICATION LAYER FUNCTIONALITY

This layer allows the network administrator to control different network data flows and adjust services according to the ISP requirements by reserving a selected flow with the highest allocated bandwidth and priority. The administrator can control the bandwidth and priority by modifying the Traffic Class (TC) and Flow Label (FL) fields of the IPv6 packet header field bits. Figure 2 illustrates the TC (priority) bits representing Differentiated Service Code Point (DSCP) bits and FL. The last two bits of the TC field are designated for Explicit Congestion Notification (ECN). It enables a mechanism for permitting network devices to communicate without resorting to drop packets, rather than discarding packets when congestion occurs. This is true in traditional GPON where ECN-enabled network devices can observe packets to indicate that they are undergoing congestion. While in SD-GPON the role of ECN is less important due to the SDN concept implicates the capability to handle load balancing efficiently in case congestion occurs [25]. In simple words, ECN within the IPv6 TC field supports network devices to intercommunicate congestion information, then each device decides to tackle this congestion according to its vision. SD-GPON if this problem occurs, the SDN controller will solve this dilemma based on its central vision of the whole network. Both TC and FL are fields in the IPv6 header, although they function for different goals in network traffic management. TC is used to prioritize packets

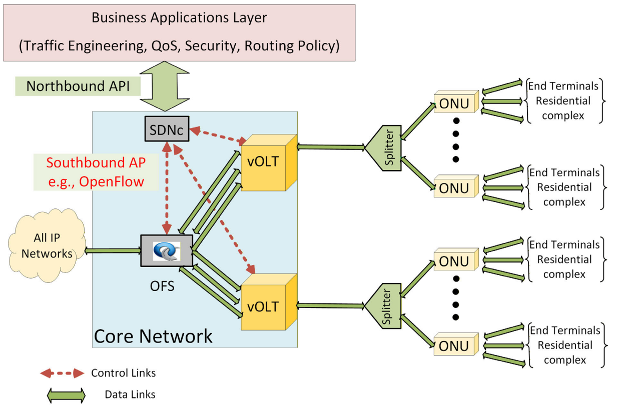

FIGURE 1. SD-GPON proposed network model.

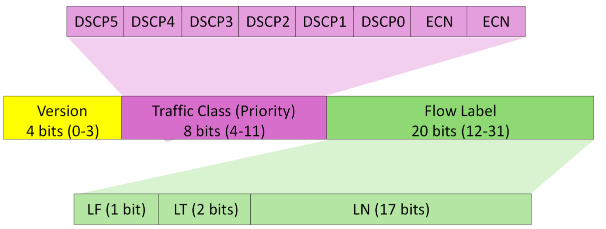

FIGURE 2. First 32 bits header of IPv6 specifying TC and FL bits.

based on their precedence or perceptiveness according to assigning a numerical value to the DSCP bits, indicating packet priority level. Network devices can employ this information to prioritize packet scheduling and forwarding. For instance, video streaming might use a higher traffic class level to ensure smooth playback, while a low-priority application such as email could utilize a lower traffic class level. In comparison, FL bits are used to pinpoint packets belonging to the same data flow or stream, by allocating a unique identifier to a distinct flow of packets between users. For example, a VoIP call or a video meeting would use a flow label to guarantee that packets are delivered in an accurate order and with lower latency. Specifically, the TC is an international means for prioritizing packets via a network. Nevertheless, the FL is a better-granulated mechanism for specifying and prioritizing distinct data flows of packets between a source and a destination. By effectively employing these fields, network administrators optimize network performance, improve QoS, and guarantee the efficient delivery of diverse classifications of data traffic. Table 1 illustrates the effects of controlling the selected bits from the TC field to manage the travel of packets through the networks via matching a differentiated services classifier using the first three bits (DSCP5, DSCP4, and DSCP3) to signify this. These bits determine the overall priority class categories only, excluding the specified priority level of each class. Apprehending and properly configuring the first three bits, DSCP5, DSCP4, and DSCP3, are crucial for effective QoS enactments in network environments. The FL bits control the packet flow priority mechanism by changing the specific bits

TABLE 1. DSCP coding for defining QoS classes.

	TC							
Priority Level	000	001	010	011	100	101	110	111
Classes	Best Effort	Class 1	Class 2	Class 3	Class 4	Express Forwarding	IP Routing	Keep Alive

from the 20 bits of the FL fields, which are divided into three parts:

- Label Flag (LF) a single bit, if LF is assigned to 1, the FL is enabled, and if 0 means is disabled.
- Label Type (LT) two bits that determine the FL type.
- Label Number (LN) 17-bits that supplies a unique identifier for packet flow.

TABLE 2. Function of LF, LT, and LN bits in flow lable field of IPv6.

FL		
LF	0	Disable
	1	Enable
LT	00	Flow label requested by source
	01	Flow label returned by destination
	10	Flow label for data delivery
	11	Flow label terminates connection
LN	Random number created by source	

Table 2 shows the flow label field of IPv6. The LF is dominant on the LT and LN fields, when the LF is set to 1 the LT and LN are influential. Otherwise, the entire field is ignored and the flow label is not used. Various values of the LT indicate different classes of data traffic or QoS conditions. The LN is assigned to a flow of packets by the source node. Network devices use this number to recognize and process packets belonging to the same traffic flow in a particular manner, such as fast forwarding or providing differentiated QoS. The main purpose of the FL field is to permit powerful packet processing and QoS by allocating a unique label to a data flow of packets. Network devices (routers) can fast-forward packets and reduce processing overhead. Network administrators use FL to configure routers to steer traffic flows via certain network paths. In summary, the TC prioritizes packets when moving them through the network devices from node to node. In contrast, the FL prioritizes packets belonging to a flow from source to destination (between end users).

B. DSCP CLASSES AND PRIORITY LEVELS

DSCP Classes use 6 bits in the IPv6 header field, permitting 64 values of priority levels ranging from 0 to 63 probable codepoints. These codepoints are divided into classes that specify how traffic should be forwarded to each network device. Expedited Forwarding (EF) is the highest priority in DSCP classes [5]. The EF is designed for the highest-reliability traffic, low latency, and low jitter, such as real-time applications (video and voice). The instructed DSCP codepoint for EF is decimal 46 or binary (101110) within network configurations. Routers and switches utilize the DSCP codepoint to identify EF traffic to apply QoS mechanisms, such as traffic shaping and priority queuing to guarantee that EF traffic flow is given a preferential forwarding process. Table 3 illustrates the DSCP classes and their precedences. We mapped the SD-GPON with dynamic DSCP rules that are governed by the SDN controller according to the administrator of network management policy, i.e., the SDN controller allows dynamic modification of both DSCP values and GPON Dynamic Bandwidth Allocation (DBA) parameters. In case of conflicts, the SD-GPON system can categorize traffic flow based on mixed parameters further DSCP including IP addresses for source and destination, port number (TCP or UDP), VLAN tag, and application type.

In GPON, the layered QoS scheduling, which usually applies combinations of Strict Priority (SP), Weighted Fair Queuing (WFQ), and Weighted Round Robin (WRR), can serve in both static and dynamic modes, relying on how they are set and executed [28]. The scheduling SP, WFQ, and WRR algorithms have already worked in GPON. Our proposed concept relies on the flexibility of selecting any traffic type to be handled with an enforced priority level that is applied by the administrator's network management policy. SDN controller can dynamically adjust scheduling parameters based on real-time network conditions. Moreover, SDN enables the implementation of sophisticated QoS policies, where scheduling decisions are driven by administrator-predefined rules. SD-GPON's priority improvements are a result of a coordinated effort, such as DSCP, which is used for traffic classification, and other GPON tools (T-CONT and DBA) for granular bandwidth control and for dynamic bandwidth allocation, respectively [29]. Whereas the SDN controller provides a centralized vision of the network, and dynamic management of these mechanisms.

TABLE 3. DSCP classes and priority levels.

Priority Level	Class Name	DSCP Value	Descrition
Highest Priority	Expedited Forwarding (EF)	46	Designated for Real-Time, Delay-Sensitive Traffic, Minimal Latency and Jitter.
High Priority	Assured Forwarding (AF)	AF1: 10, 12, 14 AF2: 18, 20 ,22 AF3: 26, 28 30 AF4: 34, 36, 38	Segmented into 4 subclasses (AF1 to AF4), each comprising three levels of drop precedence. Used to guarantee bandwidth, However, it is not as critical as EF.
Medium Priority	Class Selector (CS)	CS7: 56 CS6: 48 CS5: 40 CS4: 32 CS3: 24 CS2: 16 CS1: 8 CS0: 0	Higher CS values characterize higher priority. In this hierarchy, CS7 is the highest priority
Default Priority	Best Effort (BE)	0	For traffic that does not necessitate specific handling. Such traffic is managed according to a "best-effort" approach.

C. SDN AND CORE NETWORK

The core network comprises the SDNc, OpenFlow Switch (OFS), and virtual OLT (vOLT). The SDNc receives instructions and policy rules from the applications layer via the northbound API link, which contains the instances program to govern and manage the data traffic flows that pass through the core network according to the network administrator's requirements. In this network design, the SDNc can modify QoS in RT according to actual network traffic flow or user demands, thereby enabling more adaptable management of GPON functionalities. The SDNc manages the traffic flow QoS by modifying the DSCP5, DSCP4, and DSCP3 bits of the TC field, as well as the LF and LT of the FL bits. These bits are altered according to the ISP policy based on the user's requests at the business application layer, which allows the network manager to program rules and instructions to control traffic flow priority. These rules and instructions are sent to the SDNc via the northbound API. The core network is functioned by the SDNc, which has a complete seen to construct flow tables that govern forwarding data across the OFS and vOLT. The OFS is connected to each vOLT via three channels, each one dedicated to passing through a reserved port (RT traffic, Stream traffic, or bulk Data traffic) according to its classified applications. The OFS forwards classified traffic after checking its flow tables to direct the traffic flow to the appropriate vOLT ports. The SDNc creates the flow tables, which rely on the network administrator's priority policy. The OFS receives the flow tables through the southbound API link (control link). The flow tables contain information to forward prioritized data traffic to the appropriate port.

The ordinary GPON performs data traffic in two links with diverse wavelengths. The downstream link (from the OLT to ONUs) and the upstream link (from ONUs to the OLT) for each port. The SDNc should maintain deals with the data traffic in both links. So, the vOLT is programmed and configured to tuneable bandwidth and wavelength for the downstream and upstream traffic. For each traffic flow, the vOLT allocated a specific precedence level based on a scheduling algorithm to select the order of the transmitted traffic. Figure 3 illustrates the structure of the vOLT and its flow tables. The classified incoming flow traffic from the OFS will be forwarded by the vOLT based on the flow tables that were created by the SDNc according to the network administrator's management policy. The vOLT is programmed to give a prioritizing level to the selected wavelength that carries a specific data flow traffic that passes via the correct port. In each vOLT, the ingress/egress ports are aggregated by the Multiplexer/ Demultiplexer (Mul/Demul) equipment that connects to the ONUs through the splitter device.

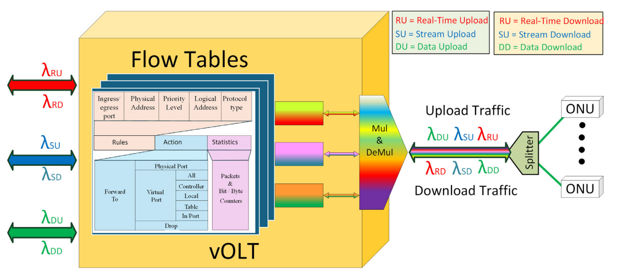

FIGURE 3. Proposed programmable functions of vOLT.

D. IMPLEMENTING SDN APPROACH OVER LEGACY GPON

We proposed incorporating an SDN technique over the GPON network, which allows configuration of the access network employing OFS using an external SDNc (SDNc). To turn legacy OLT into vOLT compatible with OpenFlow controllable devices, an SDN software and hardware conception layer must be implemented. Therefore, we propose to use OFS connected to the vOLTs and an external SDNc. We utilized the Open Network Operating System (ONOS) [30] platform as an external controller. ONOS supports the evolution from legacy network to SDN network. Moreover, it is designed to simplify the management of both traditional and modern networking infrastructures. ONOS also offers a robust framework that enables network administrators to move towards more agile and programmable environments.

Figure 1 explains the topology of the SD-GPON network scenario. The SDNc can dynamically adjust the priority services according to user requirements or real network traffic to allow traffic precedence elastic managing of GPON capabilities. By governing the TC and FL bits within the created flow tables by the SDNc, the OFS and vOLT will manage the priority for different data traffic passing through the network. To dynamically handle the proposed GPON approach, we implemented vOLT to execute the SDN layer and manipulate the priority levels for the upstream and downstream GPON channels. We have configured an SDN management layer that interacts with the vOLT to handle traffic priority. The SDNc is responsible for occasionally observing the requested bandwidth of subscribed users and involving RT policies to proficiently adjust the maximum bandwidth allocated to a particular traffic type.

For each vOLT, three pairs of wavelengths (uplink and downlink channels) are designated to manage traffic from/to OFS and from/to splitter. The Mul/Demul allows the vOLT to combine and split the wavelength signals. The passive splitter is used to distribute the feeder fiber link that carries the transmission signals to deliver multifarious traffic to the multiple ONUs. The ONU acts as the bridge between the user's devices and the fiber optic network architecture. It serves as the interface to deliver data traffic from and to end users. Additionally, the ONU function transforms optical signals received from the vOLT into electrical signals that can be utilized by end users' devices. This transformation procedure is necessary for enabling high-data-rate communication services. Figure 4 illustrates four scenarios for the priority service reconfiguration policy. First, when the SDNc identifies the type of traffic, it either modifies an existing flow table or creates a new one for each traffic type. If the traffic is classified as RT, it receives the highest priority by adjusting the TC field, specifically the DSCP3, DSCP4, and DSCP5 bits. The FL field, which includes the LF and LT bits, enables the vOLT to differentiate and prioritize various traffic flows, processing them individually based on their unique characteristics and the network administrator's policy. The second scenario is the SDNc, which is designed

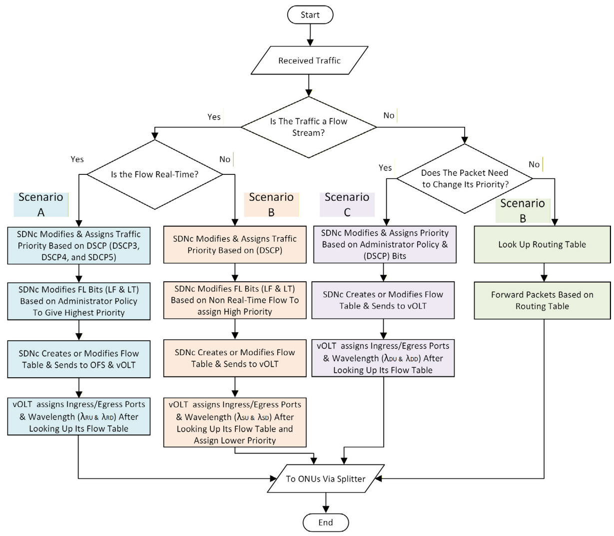

FIGURE 4. Traffic category and managing workflow in SD-GPON are divided into four functional scenarios: (A) Real-time high-priority, (B) Non-real-time high-priority, (C) Priority-change, and (D) Default best-effort. Classification relies on DSCP, timing, port, and policy; actions include FL-bit adaptation, flow-table updates, and vOLT wavelength/port assignment.

TABLE 4. Experimental setup parameters.

Parameter Category	Parameter Name	Value	Units
Network devices	Number of vOLTs	2	-
Network devices	Number of ONUs	32	-
Network devices	Number of Split	2	-
Network devices	Split Ratio	1:32	-
Traffic Generation	Traffic Types	VoIP, Video, Data	-
Traffic Generation	Data	50 (bulk)	Mbps
Traffic Generation	VoIP Rate	100 (Aggregate)	Mbps
Traffic Generation	Video Rate	10 (Per Stream)	Mbps
Performance Measurement	Latency	-	ms
Performance Measurement	Packet Loss	-	Percentage
ONOS Controller	Controller IP	192.168.1.100	IP address
ONOS controller	QoS parameters	DSCP marking, Mapping prioritization	-
Container	Packet size	Max payload 1500 bytes	Byte
Upstream	Wavelengths	1310 & 1490	nm
Downstream	Wavelengths	11550 & 1625	nm

to give high priority to traffic that includes video or audio streams; however, this priority is still lower than that assigned to RT flows. The third strategy is that the data traffic is assigned a lower priority than RT and streaming flows. Finally, the data traffic will be forwarded according to the standard routing table.

IV. SD-GPON EVALUATION AND FINDINGS

The suggested architecture allows the administrator and ISP to configure GPON with the support of the ONOS platform to emulate the SD-GPON topology for system analysis. To execute our proposal, we employed the Mininet simulator [31] to provide an environment to construct a virtual network founded on the SDN technique. The ONOS platform allows for the implementation and experimentation of the SD-GPON network with various parameters on a single physical machine. The specifications of the host physical machine are 8 Core 1.7GHz Intel Xeon Bronze 3106 CPU, 3.8TB Intel SSD data storage, and 64GB DDR4 RAM. We used Python language to configure the vOLT, ONU, and wavelengths. Table 4 shows the experiment used parameters

```python
class ONU:
    def __init__(self, volt1):
        self.volt = volt1
        self.wavelength = None
        if not self.olt.assign_wavelength(self):
            raise ValueError("Failed to assign wavelength to ONU.")

    def send_data(self, data):
        if self.wavelength:
            self.volt.receive_data(self, data)
            logging.info(f"ONU {id(self)} sent data on wavelength {self.wavelength}: {data}")
        else:
            logging.error(f"ONU {id(self)} does not have a wavelength assigned.")

    def receive_data(self, data):
        logging.info(f"ONU {id(self)} received data: {data}")

# Main simulation
if __name__ == "__main__":
    # Define available wavelengths
    available_wavelengths = [1310, 1490, 1550, 1625]

    # Create an vOLT instance
    volt1 = vOLT1(available_wavelengths)

    # Create multiple ONUs
    onu1 = ONU(volt1)
    onu2 = ONU(volt1)
    onu3 = ONU(volt1)

    # ONUs send data to the vOLT
    onu1.send_data("Data from ONU 1")
    onu2.send_data("Data from ONU 2")
    onu3.send_data("Data from ONU 3")

    # vOLT transmits data back to ONUs
    volt1.transmit_data(onu1, "Response to ONU 1")
    volt1.transmit_data(onu2, "Response to ONU 2")
    volt1.transmit_data(onu3, "Response to ONU 3")
```

FIGURE 5. Identifying code for wavelengths and ONUs to vOLT.

```python
import logging

# Configure logging
logging.basicConfig(level=logging.INFO, format='%(asctime)s - %(levelname)s - %(message)s')

class vOLT:
    def __init__(self, wavelengths):
        self.wavelengths = wavelengths  # List of available wavelengths
        self.onus = {}                  # Dictionary to hold ONUs with their assigned wavelength
        self.data_received = {}         # Dictionary to hold data received from each ONU

    def assign_wavelength(self, onu):
        if not self.wavelengths:
            logging.error("No wavelengths available for assignment.")
            return False
        wavelength = self.wavelengths.pop(0)
        self.onus[onu] = wavelength
        logging.info(f"Wavelength {wavelength} assigned to ONU {id(onu)}")
        return True

    def receive_data(self, onu, data):
        wavelength = self.onus.get(onu)
        if wavelength:
            if wavelength in self.data_received:
                self.data_received[wavelength].append(data)
            else:
                self.data_received[wavelength] = [data]
            logging.info(f"Data received from ONU {id(onu)} on wavelength {wavelength}: {data}")
        else:
            logging.warning(f"ONU {id(onu)} is not assigned a wavelength.")

    def transmit_data(self, onu, data):
        wavelength = self.onus.get(onu)
        if wavelength:
            logging.info(f"Transmitting data to ONU {id(onu)} on wavelength {wavelength}: {data}")
        else:
            logging.warning(f"ONU {id(onu)} is not assigned a wavelength.")
```

FIGURE 6. Configuration code for vOLT and ONUs to assigned wavelength.

in the proposed system. Figures 5 and 6 show parts of the configuration code.

We programmed the vOLT to be under the control of the ONOS controller to manage network interactions, which is responsible for observing the required bandwidth of ONUs (users' traffic). Moreover, it implements RT guideline rules to effectively adjust the maximum allocated bandwidth for each service. Our proposal configures the traffic and its related highest bandwidth to end users based on RT bandwidth requirements using traffic flows controlled by the ONOS controller following the administrator policies. OpenFlow [32]presents numerous benefits for network administrators and ISPs. Primarily, while traditional OLT and ONU are designed to adhere to the GPON standard, the managing software and APIs supplied by various vendors for network configuration often vary enormously. This difference frequently leads to compatibility and inter-operability challenges among types of equipment from different manufacturers. Therefore, OpenFlow facilitates the management of legacy GPON devices of diverse vendors as all OLT and ONU comprehend the same protocol since each device follows the flow table that governs the forwarding

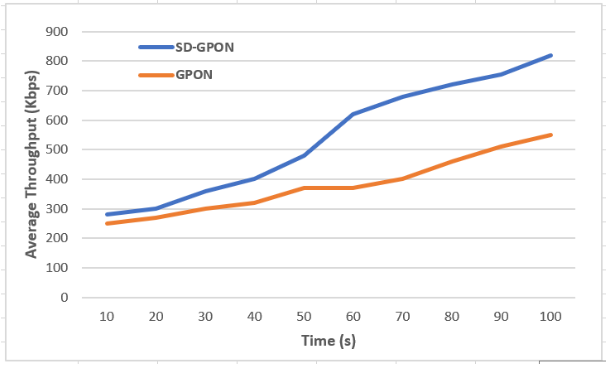

FIGURE 7. Average throughput for SD-GPON and GPON comparison.

traffic in the SDN network. Secondly, our suggestion permits simultaneously managing several vOLTs to prioritize traffic flows in centralized, dynamic, and efficient ways. In addition to handling and adjusting the assigned bandwidth for each traffic type.

The proposed SD-GPON network evaluation compares the network efficiency for handling the average throughput, channel utilization, RT priority, and packet drop based on controlling traffic priority for both traditional GPON and the proposed system. Figure 7 compares the average throughput performance between SD-GPON and GPON technologies. With the pre-configuration of the proposed traffic priority management for SD-GPON, the Figure shows that SD-GPON is superior to legacy GPON in the case of dynamic throughput demands. Overall, we can conclude that SD-GPON has greater efficiency and variability in throughput level without forcing priority rules for RT traffic. This comparison could indicate that SD-GPON could be satisfactorily suited for scenarios where increased throughput is needed, whereas the legacy GPON is less reliable for dynamic performance. Figure 8 demonstrates the examination of traffic controlling to set forced priority levels for selected flows. We applied the experiment to prioritize the video and audio traffic while keeping the same parameters for this experimentation. The GPON video scored a higher priority level than the GPON audio traffic by 39% because of applying the default GPON standard priority. Contrarily, the SD-GPON audio acquired a forced priority level via adjusting the TC field bits by setting the EF with a specific DSCP value, which is designed for high reliability and low latency traffic. Therefore, the SD-GPON audio traffic acquired a higher priority than the GPON video traffic. The SD-GPON video had the highest precedence level than the SD-GPON audio traffic by 21% due to the implementation of the proposed policy for managing non-standard priorities within the SD-GPON model. Notably, the SD-GPON audio priority class assigned by the ONOS controller is higher than that of the GPON video around 2%. Figure 9 compares the channel utilization for traffic flows pass via the channel for each type of traffic. Rising channel utilization can have a considerable impact on traffic priority, especially in network events where diverse types of traffic are allotted different priority classes. As can be

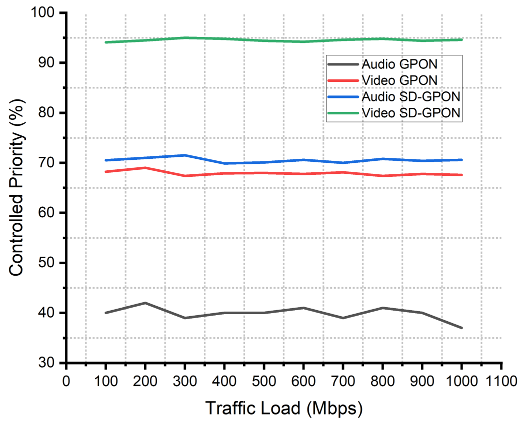

FIGURE 8. Comparison of forced priority levels of real-time flows for SD-GPON and GPON.

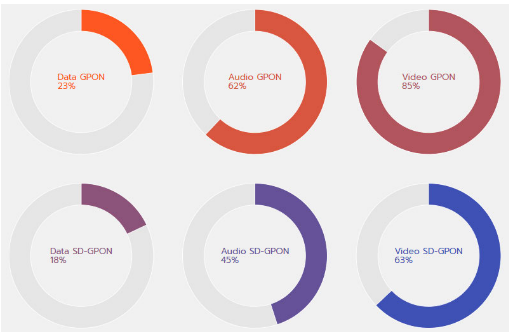

FIGURE 9. Average channel utilization for diverse traffics.

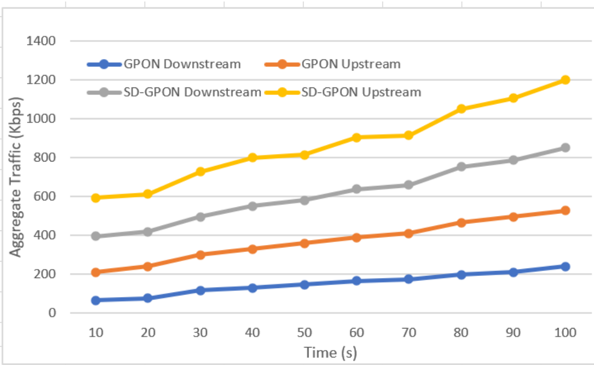

FIGURE 10. SD-GPON and GPON comparison for upstream and downstream in real-time traffic.

seen from the Figure, the pre-configured prioritizing for every traffic kind that passes through the network, the channel utilization decreased in SD-GPON for the data, audio, and video traffic over the GPON approach for the same network traffic circumstances. This enhancement in performance is yielded due to the dynamic pre-configuring of the traffic prioritization according to data types. In Figure 10 upstream represents the traffic sent from the vOLT to the splitter, whereas the downstream stands for the traffic received from the splitter to the vOLT. The Figure highlights a comparison between the SD-GPON and traditional GPON in both Upstream and Downstream directions for diverse RT traffic. Our proposal demonstrates a significant enhancement

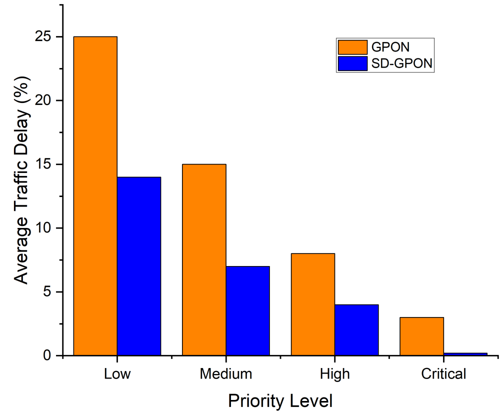

FIGURE 11. Comparison of forced priority levels versus averarge delay for real-time flows.

over the GPON by about 35.4% in the upstream direction, while in the downstream direction, the improvement is nearly 18.8%. This advancement is attributed to the prioritization control enforced in the SD-GPON approach.

Figure 11 shows the relation of the average traffic delay with priority level. In GPON, each network device is responsible for assigning the appropriate priority level for the received traffic that causes an increased average delay. In contrast, in the SD-GPON, the priority is determined and assigned by the ONOS controller, which centrally monitors and manages the whole network. Hence, the average delay time decreases for time-sensitive traffic such as video and audio streams in the proposed network.

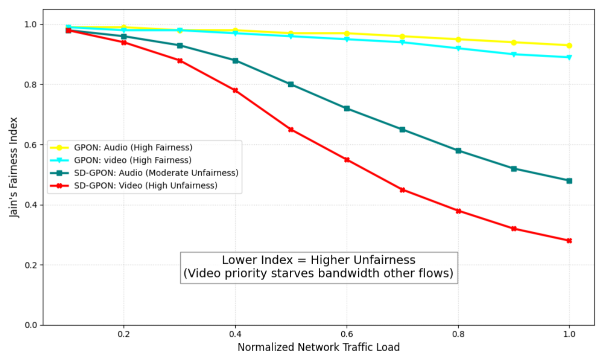

FIGURE 12. Jain's fairness index comparison under forcing different prioritization strategies.

Jain's fairness index [33] serves as a quantitative measure to assess whether system resources are allocated fairly among heterogeneous competing traffic flows. In the context of network resource allocation, our proposed system shows an unfair distribution of resources due to enforcing a prioritization level for a particular type of traffic flow in relation to others. Figure 12 illustrates Jain's fairness comparative analysis as a function of normalised network traffic load for audio and video. The figure shows that the GPON maintains a consistently high fairness index of about 0.9 across the entire load range. This indicates that the traditional DBA mechanism keeps a (work-conserving) nature that allocates residual bandwidth for various traffic flows, avoiding total starvation. While the SD-GPON architecture employs modifying traffic prioritization, which controls and adapts the DBA for selected specific traffic to be starved over other traffic flows. Therefore, fairness degradation in SD-GPON scenarios exhibits a greedy bandwidth behavior, which causes degradation in fairness as the network traffic increases. The video priority in SD-GPON gets the highest unfairness, approximately 0.28 at full network traffic load.

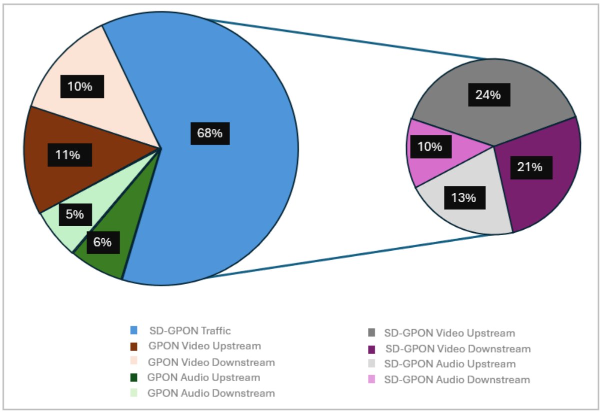

FIGURE 13. Forced priority levels of upstream and downstream for real-time traffic.

Figure 13 shows the relation of the average multiple types of traffic priority levels. The large circle represents all the traffic under testing; the blue sector characterizes the entire SD-GPON traffic. Other sectors describe the GPON traffic. The small circle defines the whole SD-GPON diverse traffic. In this test, we prioritized two types of traffic video and audio for SD-GPON in upstream and downstream directions while keeping the default GPON traffic priority policy. According to Table 3, we prioritized the 69% SD-GPON traffic portion to EF level (DSCP 46) to both video and audio upstreams only, and for video and audio downstream, the precedence level is Assured Forwarding (AF) as AF1. The data illustrated in the small circle hints that video upstream accounted for 24% of the SD-GPON traffic, while audio upstream described 13%. In contrast, video downstream occupied 21%, and audio downstream constituted 10%. The findings indicate that the audio upstream exceeded the video downstream, attributed to the highest priority level assigned to audio, which is classified as the EF priority level. In summary, the SD-GPON traffic surpasses the GPON traffic due to controlling the DSCP precedence levels.

V. CONCLUSION

Although the GPON network offers a satisfactory QoS for its traffic, it still suffers from the inability to fully control time-sensitive traffic. Audio traffic in the traditional mechanism for assigning priority levels can not get the highest priority level with existing video traffic. This drawback urges us to propose a network based on SDN to improve the legacy GPON infrastructure. Therefore, the hybrid network, which combines SDN and GPON, presents significant prospects for researchers to conceive innovative solutions. With the ability to virtualize networking functions for most physical network devices, the network administrator can easily control and manage the network efficiently and flexibly. DSCP bits in the packet header are responsible for setting the priority level for every packet and, consequently, every traffic flow. Our suggestion qualifies a mechanism for an entire governance prioritization of traffic flow by adjusting the DSCP levels through a central concept to forward data based on flow tables that are created by the SDNc. Furthermore, we employed the Python language to build a virtual representation of the OLT, thereby improving traffic priority management through the SDNc. We utilized Mininet simulation to replicate the proposed network and implemented the ONOS controller to deploy instructions within the suggested network. The evaluation of the proposed network showed that the SD-GPON exhibits a considerable advantage over GPON in handling audio and video traffic, achieving approximately 36% better performance in both upstream and downstream directions.

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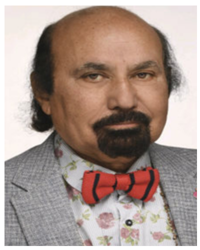

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