Journal of Network and Computer Applications 83 (2017) 89–100

Contents lists available at ScienceDirect

Journal of Network and Computer Applications

journal homepage: www.elsevier.com/locate/jnca

Modeling and performance analysis for multimedia data flows scheduling in software defined networks

Jun Huang[a,b,*], Liqian Xu[a], Qiang Duan[c], Cong-cong Xing[d], Jiangtao Luo[b], Shui Yu[e]

[a] School of Communications and Information Engineering, Chongqing University of Posts and Telecommunications, Chongqing 400065, China
[b] Institute of Electronic Engineering and Networking, Chongqing University of Posts and Telecom, Chongqing 400065 China
[c] Department of Information Science and Technology, The Pennsylvania State University, Abington, PA 19001, USA
[d] Department of Mathematics and Computer Science, Nicholls State University, Thibodaux 70310, USA
[e] School of Information Technology, Deakin University, Melbourne 3125, Australia

ARTICLE INFO

Keywords:
Heterogeneous multimedia flow
Software Defined Network
Multi-priority scheduling
Network calculus
Performance analysis

ABSTRACT

Supporting diverse Quality of Service (QoS) performance for data flows generated by multimedia applications has been a challenging issue in Software Defined Network (SDN). However, the current available QoS provision mechanisms proposed for SDN have not fully considered the heterogeneity and performance diversity for multimedia data flows. To this end, this work presents a hybrid scheduling model by combining priority queueing with a packet general-processor sharing to provide diverse QoS guarantees for multimedia applications in SDN. *Network Calculus* is applied to develop modeling and analysis techniques to evaluate the QoS performance of the proposed scheme. Performance bounds guaranteed by the proposed scheme for heterogeneous data flows, including their worst-case end-to-end delay and queueing backlog, are thus determined. Both analytical and simulation results show that the modeling and analysis techniques are general and flexible thus are fully capable of modeling QoS for diverse requirements of multimedia applications in SDN.

1. Introduction

Recent proliferation in computing and networking technologies has enabled the rapid development of a wide spectrum of network-based multimedia applications (Lu et al., 2015; Yuan et al., 2015). WebTV, video on demand, online gaming, and video conference are becoming exceedingly popular over the Internet. Internet multimedia applications bring in new challenges to networking technologies as such applications usually expect more bandwidth, little or no packet drop, low packet delay, and small delay variation. The diversity in multimedia applications, which have different traffic characteristics and performance requirements, further complicates the network control for supporting both multimedia and best-effort traffic coexisting in the Internet (Che et al., 2015). Therefore, more flexible network architectures and more effective network control mechanisms are required to achieve diverse service provisioning with Quality of Service (QoS) guarantees.

Traditional networking technologies lack sufficient capabilities to address the above challenges. The IP-based Internet architecture with tightly-coupled data forwarding and routing functions suffers from the ossification that constrains flexible on-demand service provisioning. Tremendous amount of efforts have been made by both academic and industrial researchers for enhancing Internet QoS, resulting in, for example, IntServ (Braden et al.), DiffServ (Carlson et al.), and MPLS (Awduche and Jabbari, 2002). However, the currently available mechanisms are quite limited in several aspects, such as the scalability issue of IntServ, coarse-grain traffic classification of DiffServ, and complex configuration, management, and troubleshoot of MPLS. QoS provisioning for heterogeneous data flows to meet multimedia application requirements remains an open issue.

Software-Defined Network (SDN) as an emerging networking paradigm brings new hope to address this challenging issue. SDN architecture decouples network control and data forwarding functions, thus enabling network control to be directly programmable by upper layer applications (Wang et al., 2016, 2015; Chang et al., 2015; Li et al., 2014; ONF). Its key features include separated control and data planes, a logically centralized network controller, programmability of the control plane, and standard application programming interfaces (APIs). DN provides greater flexibility and finer granularity on traffic control for meeting the diverse performance requirements of multimedia data flows. Flow tables in SDN switches allow network traffic to be segregated into flows using a wide variety of criteria, including MAC addresses, IP addresses, TCP port numbers, etc. The SDN controller may specify various packet processing actions for steering the traffic of

* Corresponding author at: Institute of Electronic Engineering and Networking, Chongqing University of Posts and Telecommunications, Chongqing 400065, China.
E-mail address: xiaoniuadmin@gmail.com (J. Huang).

http://dx.doi.org/10.1016/j.jnca.2017.01.032
Received 24 December 2015; Received in revised form 11 November 2016; Accepted 24 January 2017
Available online 29 January 2017

different flows. In addition, the centralized control plane in SDN allows a single controller to obtain a global view of the entire network domain and perform end-to-end flow-level traffic control across multiple switches, which may significantly enhance the capability of QoS provisioning.

While numerous works have been done for QoS provisioning in SDN from the control and management perspective, QoS performance guarantee in SDN requires effective scheduling models for flow forwarding in data plane switches. Flow scheduling in SDN witches for supporting multimedia applications must handle a wide variety of data flows with highly diverse traffic load features to meet different levels of QoS requirements. In addition, the scheduling model should also be able to achieve high network resource utilization for both multimedia data flows and best-effort traffic in SDN. However, none of the currently available single packet scheduling scheme can meet all these requirements. Therefore, a hybrid scheduling model is necessary. Although hierarchical packet scheduling algorithms have been developed for Internet QoS provisioning (Bennett and Zhang, 1997; Stoica et al., 2000), hybrid packet scheduling employed in SDN switches for supporting multimedia data flows is still an open issue that has not been sufficiently studied yet. In this work, we propose a hybrid scheduling model for multimedia flows in SDN to address this issue.

On the other hand, in order to evaluate the QoS capability of the proposed scheduling scheme we must face some new challenges brought in by SDN to network performance analysis. Traditional queueing theory-based analysis methods rely on some strong assumptions about the probabilistic attributes of the service process and arrival load for the studied network system. Nevertheless, decoupling of data and control planes in SDN introduces an abstraction of network infrastructure, which may consist of switches with heterogeneous implementations that are transparent to controllers. Besides, multimedia applications generate data flows with highly diverse traffic loads, and thus it is difficult to have an appropriate assumption about the distributions of packet service time and inter-arrival time in an SDN environment.

To attack this problem, we employ network calculus (Boudec and Thiran, 2012) in this paper as the mathematical tool for modeling and analyzing the proposed scheduling system. The network calculus-based analysis method may obtain the upper bounds of queueing delay and backlog guaranteed to each data flow in an SDN network without assuming any specific switch implementation or arrival traffic distribution. Therefore, application of network calculus makes our analysis agnostic to SDN switch implementations and applicable to various multimedia data flows with diverse traffic characteristics.

In summary, the main challenges we attempt to tackle in this paper lie in the diversity of QoS requirements for the data flows that must be supported simultaneously by SDN and the heterogeneity of switch implementations enabled by SDN data plane abstraction. The network calculus-based modeling and performance evaluation methods developed in this paper are general and flexible, thus are applicable to diverse multimedia data flows processed by heterogeneous switches in an SDN environment. Specifically, we make the following contributions in this paper.

- We propose to apply a hybrid scheduling mechanism in SDN switches for providing QoS guarantees to multimedia data flows.
- We develop a network calculus-based model for evaluating QoS capability of the proposed hybrid scheduling scheme in SDN switches.
- We determine the performance bounds, including the maximum queuing delay and backlog, guaranteed by the proposed scheduling scheme to each traffic flow, for both single hop and multi-hop cases.
- We conduct extensive simulation experiments to evaluate effectiveness of the proposed scheduling scheme and analyze the impacts of various queueing and scheduling parameter settings on its performance.

The rest of this paper is organized as follows. We review related works in Section 2 and present the hybrid scheduling that we propose to apply in SDN switches for supporting multimedia data flows in Section 3. Then in Section 4 we develop the network calculus-based performance analysis technique to evaluate the QoS capability of the proposed scheduling model. Numerical and simulation results are provided and discussed in Section 5. We draw conclusions and identify the possible future work in Section 6.

2. Related work

QoS provisioning in SDN has been studied from various aspects (Zinner et al., 2014). The centralized control plane enabled by SDN allows network programmability through an API between network controllers and upper layer applications. This API, often referred to as a northbound interface in SDN, allows applications to specify their QoS requirements, thereby enabling application-based QoS control. Gorlatch et al. (2014) described the specification of a northbound API that allows real-time interactive applications to specify their network requirements. Such an API facilitates QoS control in SDN for supporting multimedia applications. Zhong et al. (2014) evaluated potential QoS performance improvement gained by applying an application-based QoS control mechanism in SDN. Such a mechanism improves QoS performance in comparison with the traditional class-based approach to QoS provisioning.

The QoS requirements specified by applications must be transformed by a SDN controller to specific configuration of data plane switches in order to achieve the expected QoS guarantee. Initial design of SDN controllers such as NOX (Gude et al., 2008) lacked some necessary functions for QoS-guaranteed service provisioning. Jeong et al. presented a QoS-aware network operating system (QNOX) for SDN with generalized OpenFlow protocol (Jeong et al., 2012). In order to facilitate QoS management in SDN, Bueno et al. (2013) proposed a Network Control Layer (NCL) based on a Network-as-a-Service (NaaS) paradigm. The NCL enhances the functionality of SDN controllers to support dynamic QoS control. The NaaS paradigm has also been adopted to achieve end-to-end QoS provisioning across multiple network domains in SDN (Duan, 2014). Design of an OpenFlow controller that can perform optimal QoS routing for multimedia traffic delivery has been presented in Egilmez et al. (2012).

Currently OpenFlow (OF) is among the most widely adopted protocol between network controllers and data plane switches, i.e., the southbound interface, in SDN. Through OF, flow tables in data plane switches may be configured and updated to control packet forwarding operation for supporting QoS provisioning. However, queue configuration has not been clearly specified in the current OF protocol. OF-CONFIG has been developed as an auxiliary protocol of OF in order to facilitate configuration of OF switches. In Wendong et al. (2014), the authors presented an autonomic management mechanism for configuring various QoS features of switch queuing and scheduling functions through OF-CONFIG. The QoS architecture presented in Kim et al. (2010) adds a rate-limiter and queue mapping mechanism to map traffic flows to specific rate-limiters and priority queues in OF switches.

The aforementioned research mainly focused on the control and management aspect of QoS provisioning in SDN. In order to actually achieve QoS provisioning in SDN, the switches in the data plane must perform packet scheduling to fulfill the policies determined by the control plane. QoSFlow proposed in Ishimori et al. (2013) may control multiple packet schedulers, including hierarchical token bucket, random early detection, and stochastic fair queueing, in OF switches; however, this work is limited to Linux-based switch implementations and assumes each scheduler operates individually instead of forming a hybrid scheduling scheme. In this work we focus on our study on hybrid packet scheduling in OpenFlow switches for supporting QoS provisioning for multimedia flows in SDN. Although the OpenQoS controller proposed in Egilmez et al. (2012) is able to perform QoS