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Hybrid Scheduling for Quality of Service Guarantee in Software Defined Networks to support Multimedia Cloud Services

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***Abstract*—This paper proposes a hybrid scheduling scheme to combine the priority queueing and Packet General Processor Sharing (PGPS) algorithm for Multimedia Cloud Services in Software Defined Network (SDN). The network calculus theory is employed to develop modeling and analysis techniques for evaluating the QoS performance of the proposed scheduling scheme. Both analytical and numerical results obtained in this paper show that the proposed scheme can provide QoS guarantee for meeting diverse requirements of multimedia applications.**

***Keywords*-Service scheduling, QoS, Software Defined Network, network calculus, performance analysis**

I. Introduction

One of the key challenges for support multimedia Cloud services lies in the QoS guarantees to heterogeneous multimedia applications in a Cloud data center [1]. Software Defined Network (SDN) is an emerging networking paradigm, which has been widely adopted for data centers networks in the Cloud infrastructure [2], [3] as well as for inter-Cloud data communications. The centralized control plane and flow-based packet forwarding enabled by SDN offer a promising approach to providing the required QoS guarantee to support multimedia applications in future networks. Therefore, SDN is expected to significantly improving network performance for supporting diverse applications in a Cloud data center.

Although much encouraging progress has been made toward QoS provisioning in SDN, these studies have not fully addressed the challenges brought in by the heterogeneous traffic flows of multimedia applications with diverse performance requirements. The QoS control in SDN, especially the queuing and scheduling mechanisms in OpenFlow (OF) switches should be able to not only meet the performance requirements of heterogeneous multimedia data flows but also achieve high utilization of network resources by fairly sharing spare bandwidth among best-effort flows. A single level scheduling scheme, such as Packet General Processor Share (PGPS) or Weighted Fair Queuing (WFQ), cannot fully meet such requirements.

In order to address this challenging issue, we propose a hybrid scheduling scheme that combines priority queues and PGPS scheduling for QoS guarantee of multimedia data flows in SDN. In order to obtain a deep insight about QoS capability of the hybrid scheduling scheme, we apply network calculus in this paper to develop a model and analysis technique to evaluate delay and backlog performance of this scheme. Application of network calculus in this paper makes the developed modeling and analysis techniques general and flexible to be applicable to QoS control in OF switches with diverse implementations to support various heterogeneous data flows of multimedia applications.

II. Hybrid Scheduling Model

We propose a hybrid scheduling model for multimedia flows in SDN, which combines the PGPS algorithm and the preemptive priority queueing algorithm. We also use the leaky bucket to shape the traffic, ensuring that the low-priority data also has an upper bounded determined performance, and avoiding the starvation phenomenon.

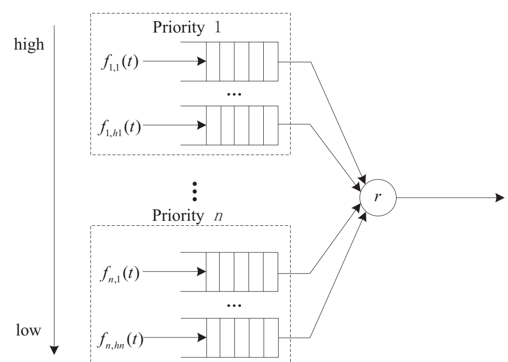

Figure 1. Hybrid Scheduling Model.

The scheme of hybrid scheduling is depicted in Figure 1, and the frequently used notations associated with the network calculus are shown in Table 1. There are n different types of priorities and for each priority level there are h_i flows with the same level of priority. This configuration is used to differentiate the heterogeneous flows in SDN and to improve the QoS for multimedia flow communications.

When data flows arrive at a node, they will be classified by their priorities first. Preemptive scheduling is applied

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to high-priority flows to meet their real-time transmission requirements, and PGPS is applied to the flows within the same rank of priority to ensure the fairness. Thus, both service distinctions and service fairness are handled in the hybrid scheduling model.

III. End-to-End Performance Analysis

By Figure 1, we assume that when a flow arrives at the queue and cannot be immediately serviced, it will be saved in sufficiently-larger buffers so that no packets will be dropped. Also, we assume that all services will be conducted at rate r. Our end-to-end deterministic performance analysis is split into two cases: single-hop and multi-hop.

A. Single-Hop Case

1) Service Curve: The following theorem presents the service curve for single-hop case.

Theorem 1: Suppose that data flow $f_{i,m}$ is the m-th data flow with priority i, and $f_{i,m}$ is constrained by the arrival curve $\alpha_{i,m}(t) = r_{i,m}t + b_{i,m}$, $1 \leq i \leq n$ and $1 \leq m \leq h_i$. Also, assume that the total service curve is $\beta(t) = r[t-0]^+$. Then, the service curve $\beta_{R_{i,m},T_{i,m}}(t)$ for $f_{i,m}$ is

$$\beta_{R_{i,m},T_{i,m}}(t) = R_{i,m}[t - T_{i,m}]^+, \tag{1}$$

where $R_{i,m} = w_{i,m} \cdot \frac{R'_{i,m}}{\sum\limits_{k=1}^{h_i} w_{i,k}}$, $T_{i,m} = T'_{i,m} + \frac{L_{i,\max}}{R'_{i,m}} + \frac{L_{i,m,\max}}{R_{i,m}}$, $R'_{i,m} = r - \sum\limits_{i<j}\sum\limits_{l=1}^{h_j} r_{j,l}$, and $T'_{i,m} = \frac{\sum\limits_{i<j}\sum\limits_{l=1}^{h_j} b_{j,l}}{R'_{i,m}}$.

Proof: Let s_i be the time that priority i data flow start to backlog, $(s_i, t]$ be the busy period. Thus the node output over this period of time is $r(t - s_i)$. With the preemptive scheduling, data in the highest priority queue will be serviced first, and when a higher priority data flow arrives, the service for low priority data will be interrupted immediately and the service will be transferred to the higher priority data. As a result, starting from s_i, the data with priority i will have to wait, at most, for all higher-priority services to finish. Therefore we have

$$R_i^*(t) - R_i^*(s_i) = r(t - s_i) - \sum_{i<j}(R_j(t) - R_j(s_i)), \tag{2}$$

where $R_i^*(t)$ and $R_j(t)$ denote the output accumulation function of the flow with priority i and input accumulation function of the flow with priority j over the time interval $[0, t]$, respectively. We also have

$$\begin{aligned} 0 &\leq R_i^*(t) - R_i^*(s_i) = R_i^*(t) - R_i(s_i) \\ &\leq R_i(t) - R_i(s_i) \leq \alpha_i(t - s_i). \end{aligned} \tag{3}$$

Combining equation (2) and inequality (3) give us the following

$$\begin{aligned} R_i^*(t) &\geq R_i(s_i) + K_i(t - s_i) \\ &\geq \inf_{0\leq s_i \leq t}\{R_i(s_i) + K_i(t - s_i)\} \\ &= (R_i \otimes K_i)(t), \end{aligned} \tag{4}$$

where $K_i(t-s_i) = \left[r(t-s_i) - \sum_{i<j}\sum\limits_{l=1}^{h_j}\alpha_{j,l}(t-s_i)\right]^+$.

The service curve of data flow with priority i would be $K_i(t-s_i)$, if $K_i(t-s_i)$ is a wide-sense increasing function. Hence, we can represent the service curve as a rate-latency function

$$\beta_i(t) = R'_{i,m}[t - T'_{i,m}]^+, \tag{5}$$

where $R'_{i,m} = r - \sum\limits_{i<j}\sum\limits_{l=1}^{h_j} r_{j,l}$ and $T'_{i,m} = \frac{\sum\limits_{i<j}\sum\limits_{l=1}^{h_j} b_{j,l}}{R'_{i,m}}$.

As a fair service scheduling algorithm for heterogeneous flows, PGPS primarily simulates the ideal GPS scheduling algorithm and operates in a similar manner with GPS. In other words, when the data flows arrive, PGPS will schedule them in the same way as GPS does. By comparing the sending time of PGPS and of GPS, we can find that the sending rate of PGPS may be slower than that of GPS, with one data packet being delayed at most whose maximum size is $L_{i,max}$ [4]. Since we have obtained that the minimum service rate for priority flows is $R'_{i,m}$, the ending time for PGPS is at most the finishing time of GPS plus $\frac{L_{i,\max}}{R'_{i,m}}$. When the sending time of PGPS is later than the sending time of GPS, the cumulative function of PGPS would be at most $L_{i,m,\max}$ packets less than that of GPS. Considering that the slowest service rate for data flow $L_{i,m,\max}$, is $R_{i,m} = w_{i,m} \cdot \frac{R'_{i,m}}{\sum\limits_{k=1}^{h_i} w_{i,k}}$ [5], which is the same as that for GPS, we can see that the delay function under the worst circumstance is $\frac{L_{i,\max}}{R'_{i,m}} + \frac{L_{i,m,\max}}{R_{i,m}}$.

In summary, the minimum service rate of data flow $f_{i,m}$ is $R_{i,m}$ and the latency is $T_{i,m} = T'_{i,m} + \frac{L_{i,\max}}{R'_{i,m}} + \frac{L_{i,m,\max}}{R_{i,m}}$. Hence the service curve of data flow $f_{i,m}$ is $\beta_{R_{i,m},T_{i,m}}(t) = R_{i,m}[t - T_{i,m}]^+$. This completes the proof. ■

2) Performance Bounds: Using the service curves obtained in the previous section, we can derive the delay upper bound and the backlog upper bound. To this end, we assume that the arrival rate and the service rate satisfy the constraint $\sum\limits_{i=1}^{n}\sum\limits_{m=1}^{h_i} r_{i,m} \leq r$.

Theorem 2: The delay upper bound of data flow $f_{i,m}$, in the case of single-hop, is given as follows:

$$D_{i,m}(t) = \frac{b_{i,m} + L_{i,m,\max}}{\frac{w_{i,m}}{\sum\limits_{k=1}^{h_i} w_{i,k}}(r - \sum\limits_{i<j}\sum\limits_{l=1}^{h_j} r_{j,l})} + \frac{\sum\limits_{i<j}\sum\limits_{l=1}^{h_j} b_{j,l} + L_{i,\max}}{r - \sum\limits_{i<j}\sum\limits_{l=1}^{h_j} r_{j,l}}. \tag{6}$$

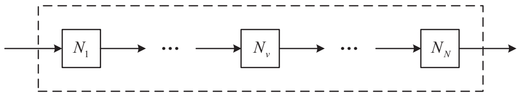


Figure 2. Multi-Hop Network Model.

Proof: By Theorem 1, we know that the delay upper bound is the horizontal deviation between the arrival curve $\alpha_{i,m}(t) = r_{i,m}t + b_{i,m}$ and the service curve $\beta_{R_{i,m},T_{i,m}}(t)$. Thus,

$$\begin{aligned}
D_{i,m}(t) &= h(\alpha_{i,m}, \beta_{R_{i,m},T_{i,m}}) \\
&= \sup_{t\geq 0}\{\inf\{d \geq 0 : \alpha_{i,m}(t) \\
&\leq \beta_{R_{i,m},T_{i,m}}(t+d)\}\} \\
&= \inf\{d \geq 0 : \alpha_{i,m}(0) \leq \beta_{R_{i,m},T_{i,m}}(d)\} \\
&= \inf\{d \geq 0 : b_{i,m} \leq R_{i,m} \cdot d - \frac{R_{i,m} \cdot \sum\limits_{i<j}\sum\limits_{l=1}^{h_j} b_{j,l}}{R'_{i,m}} \\
&- \frac{R_{i,m} \cdot L_{i,\max}}{R'_{i,m}} - L_{i,m,\max}\} \\
&= \inf\{d \geq 0 : d \geq \frac{b_{i,m} + L_{i,m,\max}}{R_{i,m}} \\
&+ \frac{\sum\limits_{i<j}\sum\limits_{l=1}^{h_j} b_{j,l} + L_{i,\max}}{R'_{i,m}}\} \\
&= \frac{b_{i,m} + L_{i,m,\max}}{\frac{w_{i,m}}{\sum_{k=1}^{h_i} w_{i,k}}(r - \sum\limits_{i<j}\sum\limits_{l=1}^{h_j} r_{j,l})} + \frac{\sum\limits_{i<j}\sum\limits_{l=1}^{h_j} b_{j,l} + L_{i,\max}}{r - \sum\limits_{i<j}\sum\limits_{l=1}^{h_j} r_{j,l}}.
\end{aligned} \tag{7}$$

This completes the proof. ■

Theorem 3: The backlog upper bound of data flow $f_{i,m}$, in the case of single-hop, is given as follows:

$$\begin{aligned}
Q_{i,m}(t) = b_{i,m} + r_{i,m} \cdot [&\frac{\sum\limits_{i<j}\sum\limits_{l=1}^{h_j} b_{j,l} + L_{i,\max}}{r - \sum\limits_{i<j}\sum\limits_{l=1}^{h_j} r_{j,l}} \\
&+ \frac{L_{i,m,\max}}{\frac{w_{i,m}}{\sum_{k=1}^{h_i} w_{i,k}}(r - \sum\limits_{i<j}\sum\limits_{l=1}^{h_j} r_{j,l})}].
\end{aligned} \tag{8}$$

Proof: By Theorem 2, we know that the backlog upper bound is the vertical deviation between the arrival curve $\alpha_{i,m}(t) = r_{i,m}t + b_{i,m}$ and the service curve $\beta_{R_{i,m},T_{i,m}}(t)$. Thus,

$$\begin{aligned}
Q_{i,m}(t) &= R_{i,m}(t) - R^*_{i,m}(t) \\
&\leq \sup_{t\geq 0}\{\alpha_{i,m}(t) - \beta_{R_{i,m},T_{i,m}}(t)\} \\
&= \alpha_{i,m}(T_{i,m}) - \beta_{R_{i,m},T_{i,m}}(T_{i,m}) \\
&= \alpha_{i,m}(T_{i,m}) \\
&= b_{i,m} + r_{i,m} \cdot [\frac{\sum\limits_{i<j}\sum\limits_{l=1}^{h_j} b_{j,l} + L_{i,\max}}{r - \sum\limits_{i<j}\sum\limits_{l=1}^{h_j} r_{j,l}} \\
&+ \frac{L_{i,m,\max}}{\frac{w_{i,m}}{\sum_{k=1}^{h_i} w_{i,k}}(r - \sum\limits_{i<j}\sum\limits_{l=1}^{h_j} r_{j,l})}].
\end{aligned} \tag{9}$$

This completes the proof. ■

B. Multi-Hop Case

Let us proceed to analyze the performance for multi-hop case.

1) Service Curve: Delivering multimedia Cloud service over SDN may need to go through the network with multiple hops. This means that many underlaying nodes need to cooperate to complete the transmission of a data flow. All data collected by senor nodes will be forwarded to sink nodes by relay, and then to management nodes in the network. Thus, performance analysis for multi-hop case is natural and necessary.

We analyze the properties of multi-hop data transmissions by means of the pay-bursts-only-once property in Network Calculus [6]. Since this property deals with the overall latency, it can deliver a tighter upper bound analysis than that when each individual node latency is considered. As shown in Figure 4, we assume that the nodes which a data flow needs to go through are , and the service curve provided by each node is $\beta_{N_v}(t) = r_v[t-0]^+, (v = 1, \cdots, N)$. The delays between two consecutive nodes are $d_1, \cdots, d_{N-1}$. According to pay-bursts-only-once property, the multi-hop of nodes is equivalent to a node with the service curve

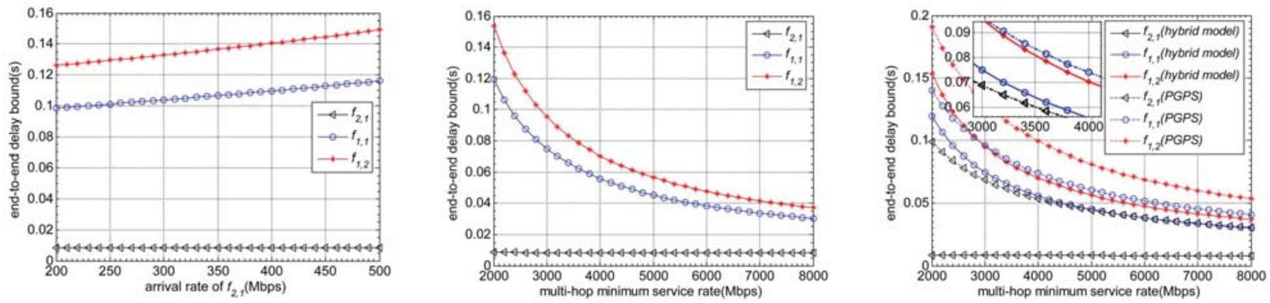
$$\beta^N_{R_{i,m},T_{i,m}} = \beta^{N_1}_{R_{i,m},T_{i,m}} \otimes \cdots \otimes \beta^{N_N}_{R_{i,m},T_{i,m}}. \tag{10}$$

By above equation, we can see that

$$\beta^N_{R_{i,m},T_{i,m}} = \min\{R^{N_1}_{i,m}, \cdots R^{N_N}_{i,m}\}[t - \sum_{v=1}^{N} T^{N_v}_{i,m} - \sum_{v=1}^{N-1} d_v]^+, \tag{11}$$

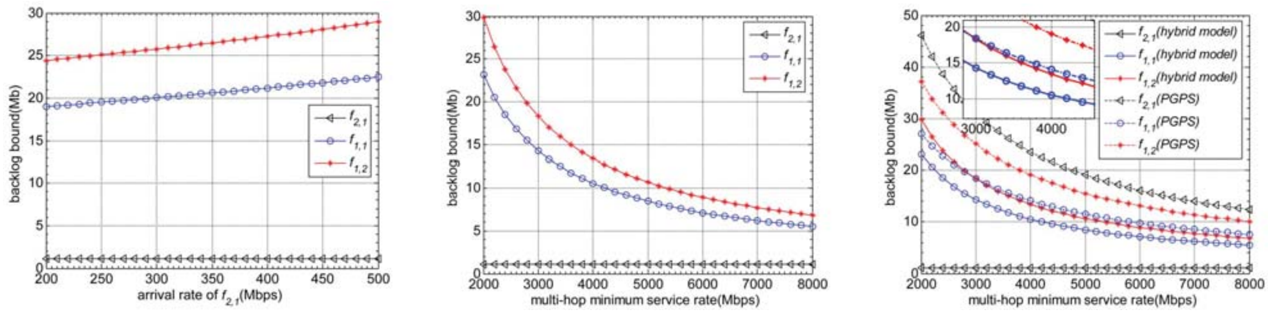
where $R^{N_v}_{i,m} = \frac{w_{i,m}}{\sum_{k=1}^{h_i} w_{i,k}}(r_v - \sum\limits_{i<j}\sum\limits_{l=1}^{h_j} r_{j,l})$, and

$$T^v_{i,m} = \frac{\sum_{i<j}\sum_{l=1}^{h_j} b_{j,l} + L_{i,\max}}{r_v - \sum_{i<j}\sum_{l=1}^{h_j} r_{j,l}} + \frac{L_{i,m,\max}}{R_{N_v}} .$$



(a) $r = 2Gbps, r_{1,1} = r_{1,2} = 200Mbps, r_{2,1} \in [200, 500]Mbps$ (b) $r_{2,1} = 500Mbps, r_{1,1} = r_{1,2} = 200Mbps, r \in [2000, 8000]Mbps$ (c) $r_{2,1} = 500Mbps, r_{1,1} = r_{1,2} = 200Mbps, r \in [2000, 8000]Mbps$

Figure 3. Delay upper bounds in the multi-hop case.



(a) $r = 2Gbps, r_{1,1} = r_{1,2} = 200Mbps, r_{2,1} \in [200, 500]Mbps$ (b) $r_{2,1} = 500Mbps, r_{1,1} = r_{1,2} = 200Mbps, r \in [2000, 8000]Mbps$ (c) $r_{2,1} = 500Mbps, r_{1,1} = r_{1,2} = 200Mbps, r \in [2000, 8000]Mbps$

Figure 4. Backlog upper bounds in the multi-hop case.

2) Performance Bounds: Delay upper bound and backlog upper bound in the case of multi-hop can be obtained in a similar path to that in the single-hop case.

Theorem 4: Assume that data flow $f_{i,m}$ goes through N nodes. The end-to-end delay upper bound of data flow $f_{i,m}$ in multi-hop case is

$$D_{i,m}^{N}(t) = \frac{b_{i,m}}{\min\{R_{i,m}^{N_1}, R_{i,m}^{N_2}, \cdots R_{i,m}^{N_N}\}} + \sum_{v=1}^{N} T_{i,m}^{N_v} + \sum_{v=1}^{N-1} d_v. \tag{12}$$

Proof: Similar to the proof of Theorem 4. ■

Theorem 5: Assume data flow $f_{i,m}$ goes through N nodes. The backlog upper bound of data flow $f_{i,m}$ in multi-hop case is

$$Q_{i,m}^{N}(t) = b_{i,m} + r_{i,m} \cdot (\sum_{v=1}^{N} T_{i,m}^{N_v} + \sum_{v=1}^{N-1} d_v). \tag{13}$$

Proof: Similar to the proof of Theorem 5. ■

IV. Numerical Results

In this section, we evaluate those performance bounds and discuss various aspects that may impact these performance bounds through numerical experiments. We assume that there are three data flows, $f_{1,1}$, $f_{1,2}$, and $f_{2,1}$. $f_{2,1}$ has higher priority than that of $f_{1,1}$ and of $f_{1,2}$. Also, according to [7], we assume that the maximum size of packet of a data flow is 1500 byte, and the burst data transfer parameter is 1.1Mb. In PGPS, $w_{i,k}$ of data flows are 0.3, 0.2, and 0.5. Note that preemptive scheme is used in the proposed hybrid scheduling model, and that lower-priority flows can be served only if there are no higher-priority flows being present, thus $w_{1,1}$ and $w_{1,2}$ are proportionally increased to 0.6 and 0.4 in our model.

Figures 3 and 4 respectively illustrate the end-to-end delay and backlog bounds of flows in the multi-hop case. As can be seen, the arrival rate and service rate both have a substantial impact on flows deterministic performance upper bound. The delay upper bound and backlog upper bound of low priority flows depend not only on the service rate but also on the arrival rate of higher priority flows. Under the same setting, flows with high priority perform clearly better than flows with low priority. Moreover, the delay upper bounds and backlog upper bounds of data flows exhibited in our hybrid scheduling model are lower than that in PGPS.

V. Conclusions

In this paper we have studied the problem of QoS guarantee in SDN-based data center networks to support multimedia Cloud services. We have proposed a hybrid scheduling model that combines the priority queueing scheme with preemptive PGPS scheduling algorithm. Applying network calculus theory in this paper, we have analyzed performance of the proposed hybrid scheduling model in both single-hop and multi-hop cases. Analysis results show that the hybrid scheduling model can provide deterministic QoS guarantees, including upper bounded maximum packet delay and queue backlog, for heterogeneous multimedia traffic flows. We also have conducted extensive simulation experiments to evaluate performance of the proposed scheduling scheme. Obtained numerical results indicate that the proposed hybrid scheduling is superior to PGPS in terms of both maximum packet delay and backlog upper bound.

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