QoS Evaluation of Prioritized Data Plane Service Employing Queueing Model

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***Abstract*—Software Defined Networking (SDN) is emerging as a new paradigm in which the control plane is decoupled from the data plane. SDN architectures enable the abstraction of network elements from the chaos of infrastructures to be service resources. The deployment of applications and network services can be largely simplified by taking advantage of the standardized open Application Program Interface (API). In the open literature, many efforts have been taken to evaluate the forwarding performance of the data plane. Jackson model is frequently employed to characterize the feature of such architectures. Further, network traffic frequently exhibits self-similar characteristic that has got a universal recognition. Analytical models without taking the traffic self-similarity into account may lead to unexpected results. To this end, this paper has proposed an analytical model to evaluate the Quality of Service (QoS) of SDN data plane with self-similar input traffic. Priority service is employed in data plane to decrease the sojourn time of the packets not matched. This is because packets traveled across the control plane are more sensitive to stringent delay bound. The QoS of the model can be evaluated by a decomposition approach. Extensive experimental results suggest that our model has a great accuracy and applicability.**

***Index Terms*—QoS evaluation; SDN model; data plane; prioritized service; self-similar**

I. Introduction

The Internet has brought us into a digital life. However, some obstacles caused by the inflexibility of predefined policies and the diversity of dedicated devices have come into the sights of researchers and engineers. In traditional networks, the tight coupling of the forwarding plane and the control plane makes any change to be difficult. Some new applications and protocols are hard to employ since they must be implemented directly into infrastructures. The variety of infrastructure devices makes the existed networks difficult to manage or upgrade. Thus, the programmable network and the concept of Software Defined Networking (SDN) is proposed [1], [2].

SDN is a new paradigm to facilitate network evolution. The abstract of underlying infrastructure dramatically simplifies the management, maintenance and upgrades of networks. On one hand, administrators can add suitable features using standard open API without changing the data plane. On the other hand, engineers can enhance the devices deployed in the data plane without changing control plane. The programmable nature of SDN gives network designers a chance to adopt new network protocols and policies. The centralized control makes a promise of a more flexible management on different applications. For example, if a traffic flow is considered to be abnormal, it is easy to be stopped. Since the flexible control over network services can be achieved with common programming languages, the network can adapt itself to users requirements. OpenFlow (OF) protocol follows the principles of SDN well and has established its place in the communication between the control plane and the data plane [3]. Consequently, the research and the employment of SDN are greatly promoted. Google has announced that their full scaled data center WAN had run as SDN. However, QoS of SDN is a matter of concern and has not been fully investigated.

Many efforts have been taken to explore the QoS of SDN architecture. In the existing research works, different research methods are employed to study the QoS of SDN. Lots of studies have been carried out directly on simulations or experiments to study SDN performance [4], [5]. Albeit useful, analytical model could be an efficient tool especially for SDN design and deployment. Thus, network calculus is utilized as a choice by some researchers to obtain the performance bound [6]. Yet, the analysis model of the performance used in [6] has a basis closely related to the queueing system. To our best knowledge, approaches base on queueing model are mostly utilized to characterize the performance of the control plane and the data plane. According to the works done by Long Yao et al. [7], the control plane is modeled as an $M^k/M/1$ queue to research controller capacity. In other related studies [8], [9], researchers model the controller as an $M/M/1$ queue and the data plane as a Jackson network. Useful SDN models with multiple switch nodes based on queueing theory have been exhibited [8], [9]. However, the arrival traffic employed in these models is indicated to be subjected to exponential distribution. While the self-similar nature of the network traffic has got an extensive investigation and been proved a broad existence. Self-similarity plays an important role in analysis of network QoS. Analytical model of SDN QoS without taking the self-similarity into account may lead to unexpected results. To fill this gap, we propose an analytical model based on a queueing system in which the self-similar traffic is utilized as the input traffic.

Till now most analytical models for SDN QoS keep the focus on the control plane and the packets sojourn time. A study shows that in the perspective of network users, the distance between the two planes can cause an apparent influence on the QoS [5]. Delay is inevitable for communication between the control plane and the data plane, and the centralized strategy may lead to an aggregate load. Reports published by Global

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SDN Certified Testing Center also imply a bottleneck of the relatively limited capability of controllers. Packets in networks always have a stringent delay bound. Thus, the probability of packet loss may have a sharp rise due to the large delay in control plane. In this work, we deal this problem with paying our attention to the characteristics of data plane forwarding. A priority queue is utilized in the data plane to reduce the sojourn time of unmatched packets which always endure an extremely huge time cost in control plane.

Then extensive experiments are carried out to verify the accuracy of our analytical model by adjusting the parameters such as mean arrival rate and probability of match failure. Distribution function of queue length and delay is utilized to character the QoS of prioritized service model. The experimental results indicate that our analytical model has a great accuracy and adaptability.

Throughout this paper, we make the following contributions.

a. The analytical model of SDN data plane QoS is improved from two aspects. First, the input traffic is typically exponential distributed in the existing SDN models. While in our work, the self-similar traffic is utilized to characterize the SDN QoS. Secondly, to our best knowledge, the data plane is usually modeled as a single queue single service system in the existing SDN models. While in our work, a priority queue is utilized in the data plane to decrease the sojourn time of unmatched packets. The attempt to improve QoS is made from the perspective of data plane rather than the control plane.

b. In the most of existing SDN models, the QoS is usually analyzed via the mean queue length or mean sojourn time. While in this paper, a comprehensive study is performed by taking advantages of a mount of metrics such as the queue length, delay and the "transmission" delay. To character QoS of SDN data plane clearly, distribution function of these metrics are employed.

The remainder of this paper is organized as follows. Section II describes the preliminaries of this study. First, the self-similarity is introduced briefly. Then, the structure of the proposed Prioritized Service Model (PSM) is introduced. In Section III, concepts of the "queueing" and "transmission" are defined to simplify analysis. Next, the Quality of Service of the data plane is analyzed by the utilization of queue length and delay. As a supplement, the transmission delay is utilized to analyze the effect of the high priority queue added in the data plane. Section IV compares the results between the analysis and the simulation to validate the accuracy and feasibility of the Prioritized Service Model. And the efficiency of the priority queue added in data plane is valued by simulation results. Finally, the paper is concluded in Section V.

II. Preliminaries and Related Work

An aggregated time series may exhibit an apparent scaling behavior, which is widely recognized as the "self-similarity". Some pioneer investigations of this statistical nature of network traffic have shown evidence that the observed traffic is distinctly non-Poisson. Thus, numerous novel traffic modeling methods have been employed to characterize this scaling behavior.

A. Self-similarity arrival

The Self-similarity of the network traffic is a significant and familiar phenomenon in a variety of modern communication networks, which plays an important role in exploring the Quality of Service of networks. A straightaway expression of self-similar process is that, in statistics, the parts of the process present the same statistical properties at different scales. The Hurst parameter is an important parameter which is on behalf of the degree of the self-similarity. A series has no self-similarity if the value of the Hurst parameter is 0.5. The closer H is to 1, the greater the degree of persistence. Several efficient methods to measure the self-similar degree have been proposed. Among them, the Rescaled Range (R/S) estimator has been adopted for many years. The original aim of R/S estimator is to provide an assessment of how the apparent variability of a series changes with the length of the time-period being considered. And soon it is applied to the analysis of fractional Gaussian noises in water resources research. Variance Time estimator which has a better convergence speed is another frequently used means to calculate the Hurst parameter.

The fractional Brownian motion (fBm) process has been proved as a useful model in generating self-similar traffic [10]. Thus, in this study, the fBm process is used to model the cumulative self-similar arrival inputs (A_r) of the system. A self-similar traffic flow can be formulated as follows

$$A_r(t) = mt + F(t) \tag{1}$$

where $A_r(t)$ is the cumulative arrival inputs, m is the mean arrival rate and $F(t)$ can be formulated as

$$F(t) = \sqrt{v_c m}\overline{F}(t) \tag{2}$$

Here v_c is the variance coefficient. And $\overline{F}(t)$ is a centred fBm with variance

$$\overline{v}(t) = var\overline{F}(t) = t^{2H} \tag{3}$$

H is the Hurst parameter which on behalf of the degree of self-similar characteristic. Further, the variance of $F(t)$ can be obtained as follows

$$v(t) = v_c m\overline{v}(t) = v_c m t^{2H} \tag{4}$$

B. Jackson Model

The Internet ossification is largely attributed to the tight coupling between the data plane and the control plane. In traditional networks, decisions about data flow forwarding are made by independent network elements. Hence, the congestion control and the fault diagnosis usually become hard as there is no efficient measure to adjust the behavior of networks. What's more, it is nontrivial to deploy new network functionality or applications as they need to be implemented directly into the

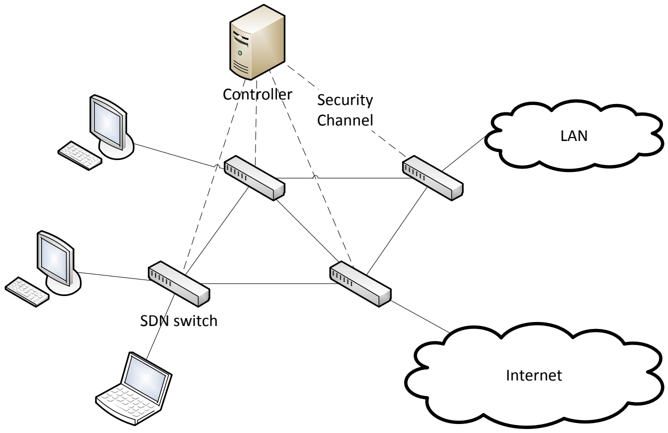


Fig. 1. SDN Architecture

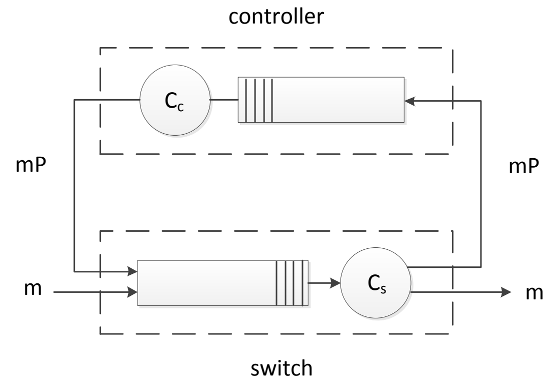


Fig. 2. A Primary SDN Model (PrM)

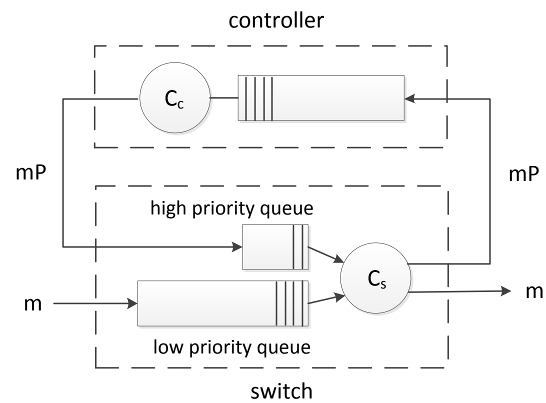


Fig. 3. Prioritized Service model (PSM)

infrastructure. Thus, one of the most important features of SDN is the separation of the control plane from the data plane, as visualized in Fig. 1. The separation of the network control from the forwarding elements allows easier network visualization and management. Consequently, the deployment of new protocols and applications becomes easier due to the convenient interface supported by the controllers. The centralized controllers also bring the capacities of middle-boxes integration, network behavior supervision and traffic controls.

In some related studies about SDN [8], [9], researchers model the controller as an $M/M/1$ queue and the data plane as a Jackson network. As Fig. 2 shows, a Primary SDN Model (PrM) based on queueing system have been established. The mean service time of the controller and the switch can be express by T_c and T_s respectively, which are usually exponentially distributed. Then the capacity of the controller and the switch can be marked by mean service rates with value $C_c = E(1/T_c)$ and $C_s = E(1/T_s)$ respectively. The parameter m is the mean arrival rate of the input traffic which determines the departure rate of the output traffic to have a same value.

For an OpenFlow switch, if the packets of the external traffic have a match failure probability with value P, then the traffic in security channel will have a mean arrival rate with parameter mP, since the packets come from the control plane will inevitably matched in the same switch.

C. Prioritized Service Model (PSM)

However, the model presented by Fig. 2 is not very efficient as the packets come from the controller have an equal priority with new coming packets.

According to our investigation, the mainstream products of the SDN switches have a great packet processing capacity. Lots of these switches can complete a packet forwarding operation within a microsecond. Unfortunately, the capacities of controllers are not so satisfied. A RYU controller performance test report published in March, 3, 2016 by Global SDN Certified Testing Center implied that the controller processing capacity may still a bottleneck in SDN. The report shows that the controller could not fully process the packet-in messages when the packet-in messages have an arrival rate greater than thousands of packets per second. That means the time cost of the service of a packet-in message could be several milliseconds.

The controller usually spends a lot of time to compute a new forwarding path. Thus, a not matched packet could be more sensitive to the stringent delay bound than matched packets. Therefore, a Prioritized Service Model (PSM) is proposed in this paper as is demonstrated in Fig. 3. A priority queue is employed in the data plane to separate packets that have calculated forwarding path from those new comers.

The pattern of the input traffic has an important effect on the analytical model of SDN QoS. Poisson traffic is usually used to study the performance of SDN in previous work. However, self-similar nature has been proved as an significant phenomenon in networks and rarely been studied in SDN. To fill this gap, in our PSM, we take advantage of the outstanding studies about self-similar nature. Then, a comprehensive analysis about data plane QoS is presented.

Merging and splitting are two basic network operations in SDN analytical models. According to Y. Fan and N. Georganass' works [11], if $Z_i(i = 1, 2,)$ are self-similar processes with parameters H_i and these processes are mutually independent, then the merging process of Z_i is a H-ss process iff $H_i = H(i = 1, 2, ..., n)$. On the contrary, if a self-similar process Y with parameter H is split into two sub-processes Y_1 and Y_2 by an independent splitting operation, then Y_1 and Y_2 are also self-similar processes with parameter H. These properties are pretty suit in PSM and bring a great convenience for our analysis.

Mininet is a useful virtual network simulator which supports SDN well. The virtualization of the networks is lightweight so that we can simulate a SDN network with a controller, a switch and several hosts on one personal computer. The simulation can be established within several seconds. And the virtual devices (e.g. the controller, switches, hosts and network links) can perform as efficiently as the real devices.

III. QoS EVALUATION OF THE PRIORITIZED SERVICE MODEL

In this section, firstly the famous Large Deviation Principle (LDP) is briefly introduced to derive the probability distribution of the queue length. And the Empty Buffer Approximation (EBA) and a decomposition method are introduced to support the analysis of the proposed PSM [12]. Then, the definitions of "queueing" and "transmission" are given in order to simplify the analysis of the data plane performance. After that, the QoS of "queueing" and "transmission" are analyzed.

A. Self-similar traffic in priority queueing system

In a queueing system with self-similar input traffic, the Large Deviation Principle (LDP) is a typically employed method to derive the probability distribution of queue length. For a sequence of random variables subject to self-similarity, LDP could give the asymptotic upper and lower bounds of the probability distributions. Relevant studies have show that the geometric mean value of the limiting behaviors is a well estimator, then we can obtain the approximate function of the queue length distribution [13]:

$$P(Q > x) \approx \frac{e^{-G(\hat{t})/2}}{\sqrt[4]{2\pi\left(1+\sqrt{G(\hat{t})}\right)^2}} \tag{5}$$

Where the $\hat{t}$ is a time instant that minimizes function $G(t)$ [13]:

$$G(t) = \frac{\left(-x + \left(C_s - \sum_{i=1}^{N} m_i\right)t\right)^2}{\sum_{i=1}^{N} v(t)_i} \tag{6}$$

Empty Buffer Approximation (EBA) is proposed as a well-known method for analyzing the queue length of the low priority buffer in a prioritized queueing system. When the server has adequate capability, the high priority queue is negligible compared to the low priority queue because it is almost an empty buffer at most time. In such a priority system, the high priority traffic seems like accumulate to the low priority buffer. The EBA suggests that the total queue is almost composed of the low priority queue alone. As a consequence, the QoS of the low priority queue should be approximately analyzed using the total input traffic. The validity of the EBA has been empirically proven. Following the priority queueing principle, this decomposition approach can be utilized to analyze the QoS of the data plane of PSM.

B. Definitions of "queueing" and "transmission"

Packets in SDN may have different experiences. A new arrival packet always has to wait for a period time in the buffer after it arrives at a switch. We define this waiting behavior as "Queueing". Then, if this packet is matched with the flow table, it can be processed immediately and will departure this switch. On contrary, if a packet is not matched in the switch, the packet-in message will be handed up to a controller to ask for the instruction. Then, the message with instructions will be sent back to switch. Thus, we define "Transmission" as the stage from the time epoch when the packet-in message is pushed into the security channel to the time epoch when the switch deals this packet another time.

C. Performance analysis in PSM

1) Queueing length in PSM: Queue length is one of the most important indicators in QoS analysis of networks. On one hand, the memory is always precious for any network device. When the queue length exceeds a preset threshold, some packets have to be dropped on the basis of some strategy. On the other hand, the queue length always has a direct influence on the waiting time of packets. Thus, the queue length, especially the distribution of the queue length, is the first indicator we study in our work.

As aforementioned, splitting and merging operations in PSM do not change the nature of self-similar traffic. Assuming the match failure probability (P) is stable when the Software Defined Networking runs stably. The aggregated flow pushed into a switch server should be a self-similar traffic with the arrival rate to be $m(1 + P)$. Since the high priority queue is almost an empty buffer at most time in a prioritized queueing system, the queue length of the low priority queue can be approximately obtained using (5) where $G(t)$ is expressed as:

$$G(t) = \frac{(-x + (C_s - (1+P)m)t)^2}{a(1+P)mt^{2H}} \tag{7}$$

Then minimize $G(t)$, we can derive that:

$$\hat{t} = \frac{Hx}{(C_s - m - mp)(H-1)} \tag{8}$$

2) Queueing delay in PSM: Queueing Delay (D_q) is also a vital statistic which is closely related to the Queueing length. Delay not only determines the QoS of some applications such as video conference, but also has an important effect on the probability of packet loss. Packets that transmitted in modern networks usually have stringent delay bounds. If a packet takes too much time to wait in buffers, the packet loss may occur which would lead to retransmissions.

If the queueing length is x, the queueing delay is easy to obtain by $E(D_q) = x/E(C_s)$ especially when the queue length is fairly long. Then we have:

$$P(D > d) \approx \frac{e^{-G(\hat{t})/2}}{\sqrt[4]{2\pi\left(1+\sqrt{G(\hat{t})}\right)^2}} \tag{9}$$

Where $\hat{t}$ is the value which minimizes the function:

$$G(t) = \frac{(-C_s d + (C_s - (1+P)m)t)^2}{a(1+P)mt^{2H}} \tag{10}$$

3) Improvement on the transmission delay: Packets in controller always endure a high time cost for routing computation, while the time costs are much smaller when processed in switch. Compared to PrM, the PSM utilized a priority queue to reduce the transmission time. Thus, the packet loss may decrease and a better QoS may be obtained. In this part, we focus on the difference of transmission delay (D_{tr}) between PrM and PSM.

As mentioned, a "transmission" contains several parts. Thus, transmission delay ($D_{tr}(M)$) consists of communication time (T_{com}) that messages spend in security channel, delay in controller buffer (D_c), service time (T_c) cost by the controller server, and another queueing delay (D'_q) in switch buffer. Therefore, we define Transmission Delay as:

$$D_{tr}(M) := T_{com} + D_c + T_c + D'_q(M) \tag{11}$$

where the parameter M represents the type of analytical model (i.e. PrM or PSM). As the high priority queue is almost an empty buffer at most time, it is obvious that we have $D'_q(PSM) < D'_q(PrM)$. Thus, we can obtain that

$$D_{tr}(PSM) < D_{tr}(PrM) \tag{12}$$

In SDN switch, the sojourn time of not matched packet is much greater than that of matched packet. Thus, these not matched packets are more sensitive to the stringent delay bound. By taking advantage of the priority service policy, the sojourn time of not matched packets could be shortened. Further, the packet loss and retransmission events may decrease.

IV. Validation of the PSM

In this section, the extensive experiments are carried out to verify the analysis results of section III. The capacity of the controller must be power enough to deal with the aggregated arrivals. If we set the capacity of the switch (C_s) to be 10 packets per unit time, it is obvious that the capacity of the controller must be larger than 1 packets per unit time, or the congestion will be inevitable in controller. Many factors have inevitable influences on the Quality of Service of this queueing system. We pay our attention to some factors closely related to the scenario of SDN, such as the mean arrival rate (m) of input flows. More details of parameter setting are presented according to TABLE I. The unit time in our simulation is set to be 10 microseconds.

TABLE I
PARAMETER IN 4 CASES

	H	v_c	C_s	**m**	**P**
Case 1	0.80	1	10	8.5	1%
Case 2	0.80	1	10	9.0	1%

A. Queueing length in PSM

In Fig. 4, experiment results of the 2 cases presented the queueing length performance under different workload. In Case 1 and Case 2, the mean arrival rates (m) are set to be 8.0 and 8.5 packets per unit time respectively. As Fig. 4 demonstrated, when the mean arrival rate increase from 8.0 to 8.5, the queueing length has a huge rise. When the mean arrival rate is 8.0, the probability of queue length greater than 500 is about 1% (i.e. $P(Q > 500) = 1\%$). When the mean arrival rate is set to be 8.5, the queueing length relevant to the same probability is about 5000 (i.e. $P(Q > 5000) = 1\%$).

B. Queueing delay in PSM

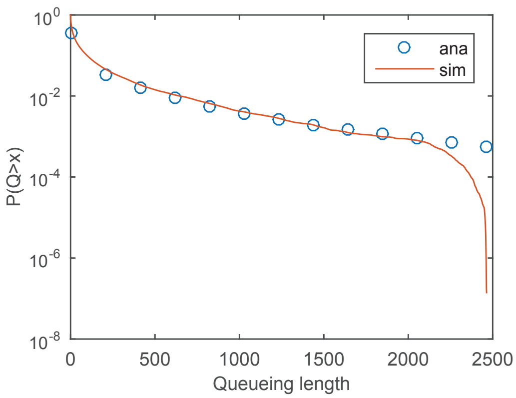
The queueing delay distributions of Case 1 and Case 2 are presented in Fig. 5. The queueing length distribution has a significant influence on the performance of queuing delay. Comparing Fig. 5 and Fig. 4, we can see that the trends are quite similar between the queueing length and the queueing delay. As we have utilized the formula: $E(D_q) = x/E(C_s)$, it is understandable that the scale of x-axis in Fig. 5 is only one-tenth compared to that in Fig. 4. This indicates that the service rate of the switch is stable enough.

Fig. 4 and Fig. 5 have given a comprehensive display of performance of the prioritized SDN data plane. It presented the accuracy of the decomposition approach using EBA under self-similar traffic. The results between extensive simulations and the analysis have shown that our analytical model has a satisfactory accuracy and applicability.

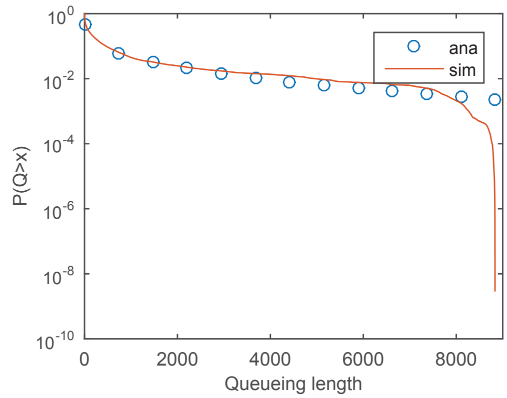
V. Conclusion

Software Defined Networking (SDN) may pave the right way to the future networks. In recent years, Jackeson model is frequently employed to study SDN performance. However, Network traffic usually exhibits apparent self-similar characteristics. Analytical model without taking the self-similar nature into account may lead to unexpected results. Packets always have a stringent delay bound. According to our investigations, packets not matched in the SDN switch always spent a much longer time than matched packets. Thus, a not matched packet may be more sensitive to the stringent delay bound than matched packets. To decrease the sojourn time of not matched packet, we proposed the Prioritized Service Model (PSM). And the self-similar traffic is employed to study characteristics of the data plane.

A decomposition approach has been utilized in our work to analyze the QoS of the data plane. Experiments on queueing length and queueing delay demonstrated the QoS of SDN data plane under self-similar traffic. The results show that the analytical result can match the simulation result well.

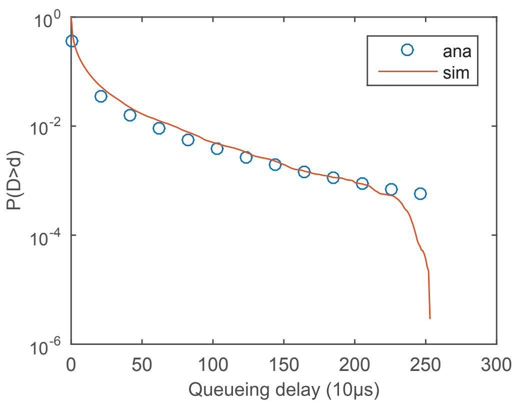


(a) Queueing length of Case 1

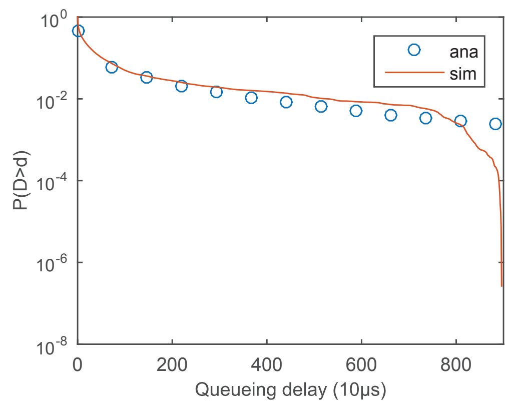


(b) Queueing length of Case 2

Fig. 4. Queue length of the low priority queue in PSM



(a) Queueing delay of Case 1



(b) Queueing delay of Case 2

Fig. 5. Queueing delay of the low priority queue in PSM

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