SPRED: Active Queue Management Mechanism for Wide-Area Networks

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Abstract

AQM (Active Queue Management) mechanism is a congestion control mechanism at a router for controlling the number of packets in the router's buffer by actively discarding an arriving packet. AQM mechanism can shorter the average delay in the router's buffer, and can also achieve high throughput. RED (Random Early Detection) is a representative AQM mechanism, which probabilistically discards an arriving packet. However, it is reported that the performance of RED degrades in a wide-area network with a large propagation delay. In this paper, we therefore propose an AQM mechanism called SPRED (Smith Predictor for Random Early Detection) *for wide-area networks. The notable feature of SPRED is realizing high steady-state and transient-state performance by using a delay compensator called* Smith Predictor *for compensating a large feedback delay. In this paper, we show the effectiveness of SPRED by both analysis and simulation experiments.*

1 Introduction

AQM (Active Queue Management) mechanism is a congestion control mechanism at a router, which assists end-to-end TCP (Transmission Control Protocol) congestion control [2]. AQM mechanism controls the number of packets in the buffer of a router (i.e., queue length) by actively discarding arriving packets, lest the buffer of the router should overflow. It is therefore expected for AQM mechanism to achieve a better performance in comparison to a conventional DropTail router. For example, AQM mechanism can shorten the average queue length at a router, avoiding throughput degradation due to the buffer overflow of the router.

Thus far, various AQM mechanisms have been proposed [6, 5, 4, 3]. RED (Random Early Detection) [6], which is the most representative AQM mechanism, probabilistically discards packets that arrive at a router to control the queue length of the router. However, several problems have been pointed out with RED: e.g., (1) substantial care is required in tuning the parameters of RED to achieve reasonable performance; (2) the average queue length of a RED router in steady-state relies on the number of TCP connections [4, 9].

Additionally, the recent tendency of networks to widen and grow in scale has revealed the limitation of RED in a network with a large propagation delay [10]. In such a network, RED fails to quickly respond to the change of the queue length of the router. Therefore, the queue length of the router becomes unstable, causing overflow and underflow of the buffer.

Several control mechanisms have been proposed for a network with a large propagation delay. In [11], the authors proposed a method that applies a delay compensator in control theory (i.e., Smith Predictor) to a rate controller for ATM (Asynchronous Transfer Mode) networks. The delay compensator is a mechanism that compensates for control delay (i.e., virtually diminishes the effect of control delay) by using a mathematical model of a controlled system even in conditions where the propagation delay is large [8]. The rate control mechanism proposed in [11] keeps the number of packets in the buffer of the bottleneck ATM switch constant. In this mechanism, a Smith Predictor is utilized in order to compensate for the impact of the delay of feedback information from the ATM switch to the sender host due to propagation delay.

In [13], the authors proposed a dynamic resource control mechanism for wide-area Grid computing, which also utilized a delay compensator. In wide-area Grid computing, available resources fluctuate over time and the propagation delay of a network is significant. The dynamic resource control method proposed in [13] realizes effective dynamic resource control in wide-area Grid computing with a large propagation delay by using a delay compensator.

It is indeed effective to apply a delay compensator in control theory to control a network with a large propagation delay. However, to implement the control methods proposed in [11, 13], all sender hosts need to be modified.

In this paper, we therefore propose an AQM mechanism called SPRED (Smith Predictor for Random Early Detection), which achieves high performance even in a wide-area network. Our proposed SPRED is a mechanism in which a Smith Predictor is implemented in a representative AQM mechanism, RED. The notable feature of SPRED is that it achieves high steady-state and transient-state performance in a network with a large propagation delay by using a delay compensator in classical control theory (Smith Predictor) [15]. SPRED is distinctive in that only the bottleneck router needs to be modified when implementing it; i.e., the other end hosts or routers do not require modification.

As a mathematical model of a controlled system used by a Smith Predictor in SPRED, we adopt the fluid-flow models of a TCP connection and the buffer of a router, which were derived in [12]. More specifically, we model each of the TCP congestion control mechanisms and the buffer of the router as a continuous-time system using the modeling method proposed in [12]. By combining these two individual models, we construct a model of the system of the TCP connection and the buffer of the SPRED router. We then investigate the characteristics of the SPRED router. We demonstrate that SPRED achieves good steady-state and transient-state performance in a wide-area network.

The structure of this paper is as follows. Section 2 explains the outline and the operational algorithm of our proposed AQM mechanism, SPRED. Section 3 evaluates the performance of SPRED through analysis and simulation experiments. Lastly, Section 4 describes a summary of this paper and future tasks.

2 SPRED (Smith Predictor for Random Early Detection)

The proposed SPRED utilizes a delay compensator in classical control theory (Smith Predictor) to compensate for feedback delay. In particular, we apply the Smith Predictor to a representative AQM mechanism, RED. We employ the fluid-flow models of TCP connection and of the buffer of the router, which were proposed in [12], as a model of the controlled system (i.e., TCP connection and the buffer of the router for the AQM mechanism) used by the Smith Predictor. SPRED predicts the queue length after a feedback delay, by using the Smith Predictor to achieve high steady-state and transient-state performance even in a network with a large propagation delay.

The delay compensator is a mechanism for feedback control to improve the performance of a system with a control delay [8]. In a controlled system with an intrinsic delay, the feedback delay tends to be so large that it becomes difficult to control the system by responding to its fluctuation. As a result, the system becomes unstable, and performance significantly deteriorates. The delay compensator can compensate for the delay in the controlled system and therefore is expected to enable the system to achieve high steady-state and transient-state performance.

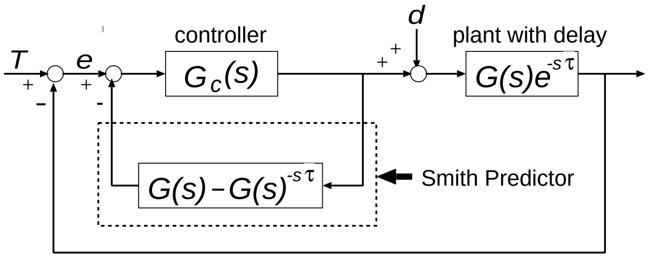

Figure 1: Block diagram of Smith Predictor

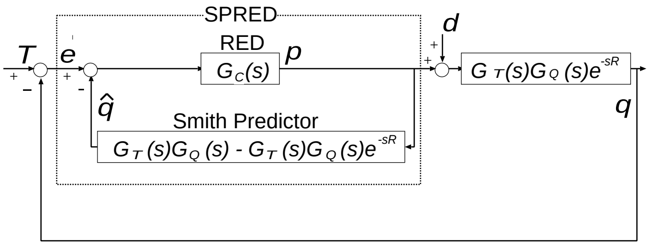

Figure 2: Block diagram of SPRED (Smith Predictor for Random Early Detection)

The Smith Predictor is a representative delay compensator in classical control theory [15]. Figure 1 shows the block diagram of the Smith Predictor. The Smith Predictor predicts future output by using the mathematical model of controlled system without control delays, $G(s)$, to eliminate the impact of the feedback delay, $e^{-s\tau}$. To function successfully, the Smith Predictor requires both the precise mathematical model of the controlled system, $G(s)$, and an accurate estimate of the delay in the controlled system, τ.

In the following, we explain the algorithm of the AQM mechanism, SPRED. The block diagram of SPRED is shown in Fig. 2. The algorithm of SPRED is basically the same as that of RED. However, instead of the actual current queue length of the router, q, the adjusted value, p, based on the current queue length predicted by the Smith Predictor is used to calculate the packet marking probability, $\hat{q}$.

Each time a packet arrives at the router, SPRED executes the following procedure:

1. To calculate the estimate of the queue length, $\hat{q}$, by using the mathematical models of the controlled system: i.e., $G_T(S)$ for the TCP connection and $G_Q(S)$ for the buffer of the router.

2. To correct the current queue length of the router, q, based on the above queue length estimate, $\hat{q}$, and, using a similar algorithm to that of RED, calculate both the average queue length, $\overline{q}$, and the packet marking probability, p.

3. To probabilistically discard an arriving packet, using the similar algorithm to that of RED based on the above packet marking probability, p.

In SPRED, the models of a TCP congestion control mechanism and of the buffer of the router derived in [12] are used.

In [12], the fluctuation of the transfer rate from TCP sender hosts is modeled as follows:

$$\dot{y} = \frac{x(t)}{y(t)R^2} - \frac{2}{3}y(t)\{y(t-R) - x(t)\}, \qquad (1)$$

where $x(t)$ is the arrival rate of ACK packets to sender hosts, $y(t)$ is the packet sending rate, and R is the round-trip time of a TCP connection.

In addition, the fluctuation of the queue length of a router is modeled as follows:

$$\dot{q} = \begin{cases} x(t) - c & \text{if } q(t) > 0 \\ (x(t) - c)^+ & \text{otherwise} \end{cases}, \qquad (2)$$

where $(x)^+ \equiv \max(x, 0)$, $x(t)$ is the packet arrival rate at the router, and c is the router's processing capacity.

By combining these models, the fluid-flow approximation model of the controlled system (i.e., the buffer of the router and the TCP connection) for the AQM mechanism is obtained as described below.

$$\dot{q}(t) = \begin{cases} \sum_{i=1}^{N} x_i(t) - c & \text{if } q(t) > 0 \\ \left(\sum_{i=1}^{N} x_i(t) - c\right)^+ & \text{otherwise} \end{cases} \qquad (3)$$

$$\dot{y_i}(t) = \frac{x_i(t)}{y_i(t)R_i^2} - \frac{2}{3}y_i(t)\{y_i(t-R_i) - x_i(t)\}, \qquad (4)$$

where N is the number of active TCP connections and R_i is the round-trip time of the i-th TCP connection. In SPRED, assuming that N TCP connections are equivalent in terms of their probabilistic behavior, we use the following equations as the fluid-flow approximation models of the controlled system:

$$\dot{q}(t) = \begin{cases} Nx(t) - c & \text{if } q(t) > 0 \\ (Nx(t) - c)^+ & \text{otherwise} \end{cases} \qquad (5)$$

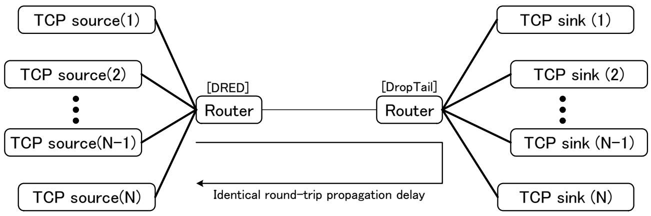

Figure 3: Network topology used in analysis and simulation

$$\dot{y}(t) = \frac{x(t)}{y(t)\overline{R}^2} - \frac{2}{3}y(t)\{y(t-\overline{R}) - x(t)\}, \qquad (6)$$

where $\overline{R}$ is the average round-trip time of TCP connections. Equation (5) is the model of the buffer of a router, $G_Q(s)$, whereas Eq. (6) is the model of a TCP connection, $G_T(s)$.

In the last part of this section, we discuss how the number of active TCP connections, N, and the average round-trip time of TCP connections, $\overline{R}$, can be estimated at a router. Both the number of active TCP connections, N, and the average round-trip time of TCP connections, $\overline{R}$, should be accurately estimated for the Smith Predictor to function accurately. The number of active TCP connections can be estimated by using the method proposed in [14, 7] without identifying all TCP flows. Although it is not straightforward to measure the average round-trip time of TCP connections in general, it can be estimated by identifying SYN packets and SYN ACK packets at the router.

3 Performance Evaluation

In this section, we clarify the effectiveness of our proposed AQM mechanism, SPRED, through analysis and simulation experiments.

Figure 3 depicts the topology of the network used for the analysis and simulation experiments. Several TCP connections with the same propagation delay share a single RED or SPRED router. In Fig. 3, the bandwidth of the links between TCP sender/receiver hosts and the routers are significantly larger than that of the link between the routers. Thus, the link between the routers is the bottleneck.

The analysis and simulation experiments were conducted by changing the parameters such as the propagation delay of the bottleneck link and the number of TCP connections in Fig. 3. For the analysis, in addition to the mathematical models of the controlled system explained in Section 2 (i.e., Eqs. (5) and (6)), the mathematical model of RED in [12] was used. The numerical simulation experiments were conducted with various configurations of the parameters in Eqs. (5) and (6) including the number of TCP connections, N, the processing capacity of the router, c, and the

Table 1. Parameter configuration used in analysis and simulation

Bandwidth of bottleneck link	10	[Mbit/s]
Propagation delay of bottleneck link	100	[ms]
Buffer size of router	600	[packets]
Packet length	1000	[bytes]
The number of TCP connections	50	
Minimum threshold of RED router	100	[packets]
Maximum threshold of RED router	300	[packets]
Maximum packet drop rate of RED router	0.1	
Exponential moving average of RED router	0.04	

average round-trip time, $\overline{R}$. MATLAB/Simulink [16] and a modified version of ns-2 (version 2.28) [1] were used for the analysis and the simulation experiments, respectively. Table 1 lists the parameter configuration used in the analysis and simulation experiments. The parameters in Tab. 1 are used in the following, unless stated otherwise.

As the performance metrics of RED and SPRED, the average and the standard deviation of the queue length of the router were measured: The average queue length represents the steady-state of the router, whereas the standard deviation of the queue length represents its fluctuation. We conducted numerical analysis and simulation experiments of 100 seconds to measure these performance indicators.

3.1 Impact of Propagation Delay

We first focus on the impact of network propagation delay on the average and standard deviation of the queue length of the SPRED router. Thereby, we demonstrate that SPRED can stabilize the queue length of a router in a wide-area network.

We first show results with numerical analysis. Figure 4 shows the average queue length of both the RED router and the SPRED router when the TCP round-trip time, R, was changed from 1 to 500 [ms]; Fig. 5 shows their standard deviation.

From Fig. 4, we can see that the average queue length of the SPRED router is larger than that of the RED router when the round-trip time of TCP connections is large. Moreover, the average queue length of the RED router is less than the minimum threshold, min_{th}, when the round-trip time is 300 [ms] or larger. It is assumed that this result was obtained because the operation of the RED router became unstable when the round-trip time of TCP connections was large. On the other hand, the average queue length of the SPRED router is larger than min_{th}. Therefore, it can be assumed that SPRED stably operated even when the round-trip time of TCP connections was large. Figure 5, which

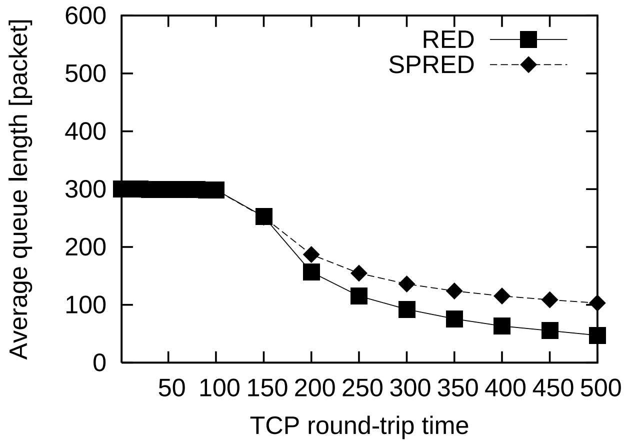

Figure 4: Average queue length of RED and SPRED routers for R = 1–500 [ms] (numerical analysis)

shows the standard deviation of the queue length, supports these assumptions.

In particular, Fig. 5 shows that the standard deviation of the queue length of the RED router is larger than that of the SPRED router when the round-trip time becomes large. This means that the queue length of the RED router significantly fluctuates, indicating that overflow and underflow of the buffer occur when the round-trip time is large. In contrast, the queue length of the SPRED router is stable; its standard deviation is at most 50 [packets] even when the round-trip time is 500 [ms].

3.2 Impact of the number of TCP connections

Next, let us look at the impact of the number of TCP connections, N, on the average and standard deviation of the queue length of the SPRED router. We demonstrate that SPRED can better stabilize the queue length of a router than RED regardless of the number of TCP connections.

Figure 6 shows the average queue length of the RED and SPRED routers when the number of TCP connections changed from 1 to 100; Fig. 7 shows their standard deviation.

It can be seen from Fig. 6 that the queue length of both the RED router and the SPRED router falls below the minimum threshold, min_{th}, when the number of TCP connections is small. However, the queue length of the RED router is less than min_{th} for $N < 25$, while that of the SPRED router is less than min_{th} for $N < 10$. As in the previous case, it can be assumed that this has resulted from the fact that the operation of SPRED is more stable than that of

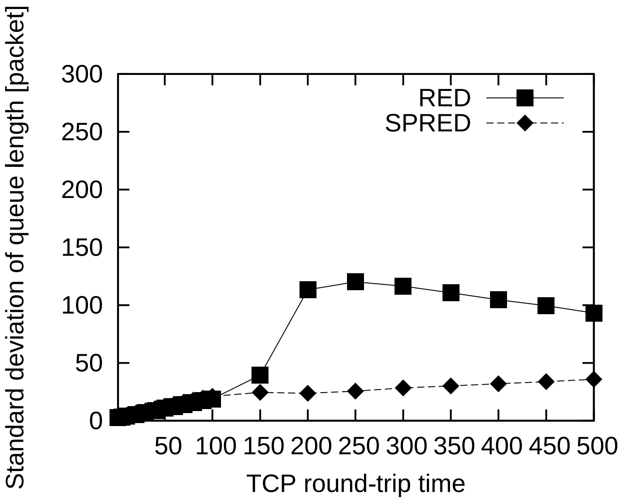

Figure 5: Standard deviation of queue length of RED and SPRED routers for R = 1–500 [ms] (numerical analysis)

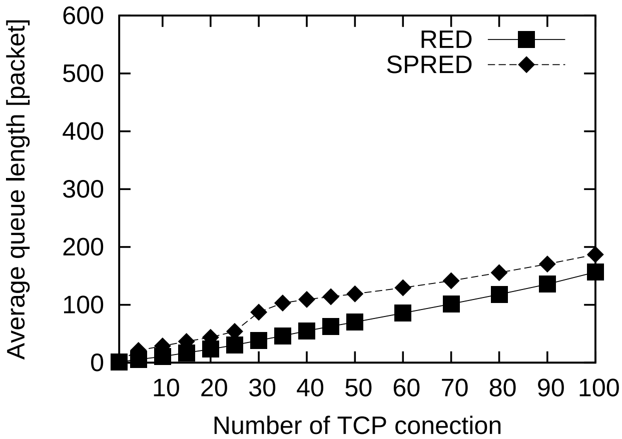

Figure 6: Average queue length of RED and SPRED routers for N = 1–50 (numerical analysis)

RED.

Indeed, their difference in the standard deviation shown in Fig. 7 suggests considerable discrepancy in performance between SPRED and RED. This figure clearly shows that the standard deviation of the queue length of the SPRED router is much smaller than that of the RED router. This means that the operation of SPRED is more stable in comparison with RED.

Figure 8 shows the time fluctuation of the queue length of the RED and SPRED routers under the parameter configuration described in Table 1. Figure 9 zoomed in Fig. 8 at the simulation results for 20–40 [s]. Figure 9 indicates that the SPRED router operates more stably than the RED router.

Figures 10 and 11 show the time fluctuation of the queue length of the RED and SPRED routers, when the propagation delay of the bottleneck link was set at 300 [ms] and 500 [ms], respectively. We can see from the comparison of these two figures that the change in the degree of fluctuation of queue length is more apparent for the RED router than for the SPRED router. The degree of fluctuation of the queue length of the SPRED router is smaller than that of the RED router when the propagation delay is large. In particular, Fig. 11 indicates that the SPRED router succeeded in avoiding buffer overflow, while the buffer of the RED router overflowed and its usage declined.

Thus, from the above results, we can conclude that SPRED is effective especially in the network with large propagation delays.

4 Summary and Future Tasks

In this paper, we have proposed an AQM mechanism called SPRED (Smith Predictor for Random Early Detection) which achieved high performance even in a wide-area network. SPRED has distinctive advantage of achieving high steady-state and transient-state performance in a network with a large propagation delay by using the Smith Predictor in classical control theory. We have evaluated the performance of SPRED by analysis and simulation experiments. The results have demonstrated that SPRED could stabilize the queue length of a router even when the network propagation delay was large.

As a future task, we will evaluate the performance of SPRED under realistic network configurations. In particular, we will evaluate its performance in a network in which propagation delays of TCP connections are different.

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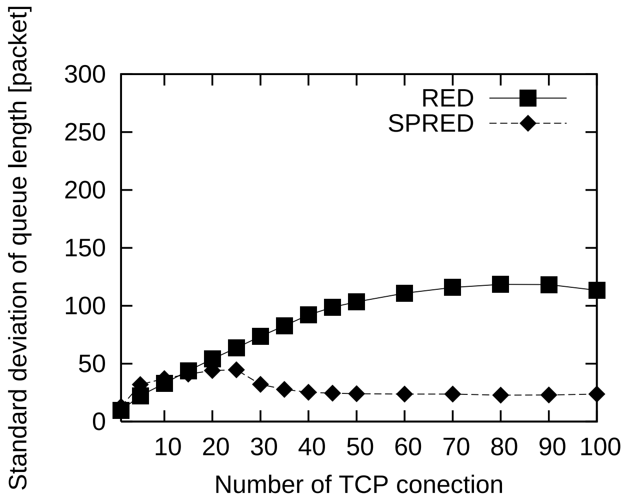

Figure 7: Standard deviation of queue length of RED and SPRED routers for N = 1–50 (numerical analysis)

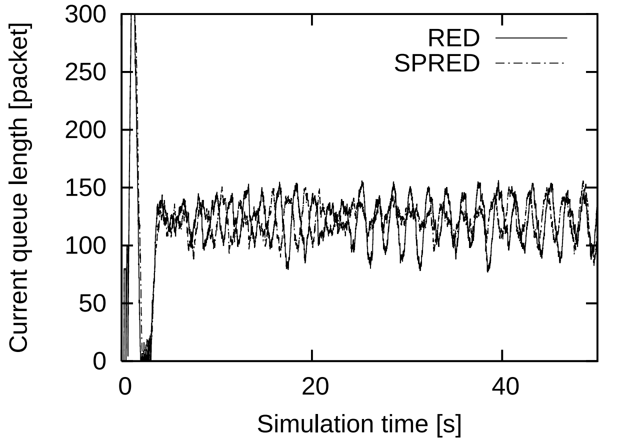

Figure 8: Time fluctuation of queue length of RED and SPRED routers for $\tau = 100$ [ms] (simulation)

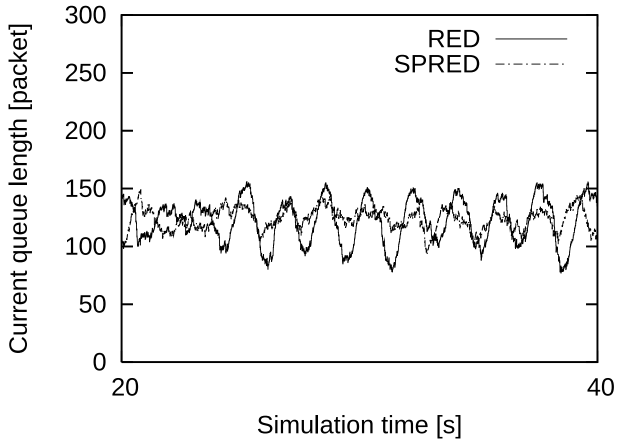

Figure 9: Time fluctuation of queue length of RED and SPRED routers for $\tau = 100$ [ms] (zoomed in at 20–40 [s]) (simulation)

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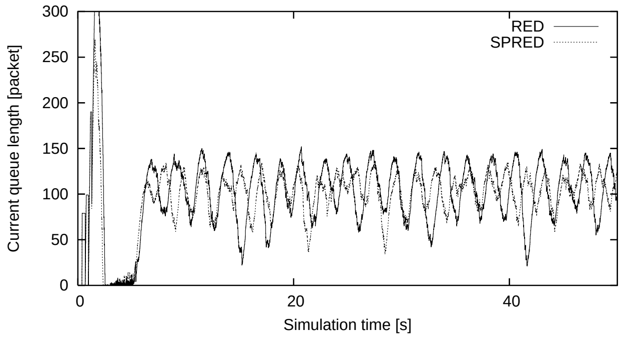

Figure 10: Time fluctuation of queue length of RED and SPRED routers for $\tau = 300$ [ms] (simulation)

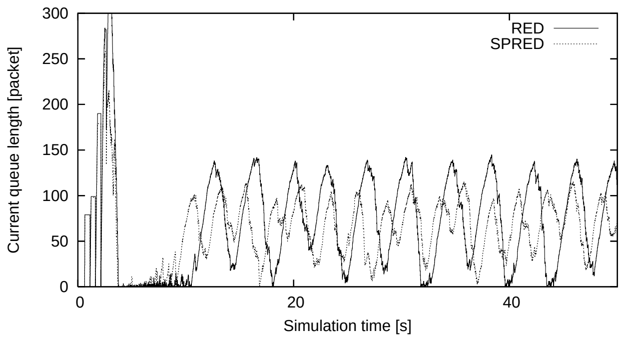

Figure 11: Time fluctuation of queue length of RED and SPRED routers for $\tau = 500$ [ms] (simulation)