Congestion Propagation among Routers with TCP Flows *

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Abstract

In recent years, various non-linear phenomena of the Internet have been discovered. For instance, it is reported that congestion of a router propagates to neighboring routers like a wave. Several researches on congestion propagation among routers have been performed. However, in these researches, cause of congestion propagation and condition that congestion propagation occurs have not been sufficiently investigated. In this paper, we reveal a cause of congestion propagation, and also investigate under what conditions congestion propagation is observed. Consequently, we show that speed of congestion propagation is affected by the bandwidth and the propagation delay of links, and that periodicity of congestion propagation becomes less obvious as randomness of network traffic increases.

Keywords

Congestion Propagation, TCP (Transmission Control Protocol), Router, Nonlinear Phenomena, Ring Network

1 Introduction

The Internet is a huge non-linear system, and non-linear dynamics of the Internet has been attracting attention. In recent years, it has been reported that various non-linear phenomena are observed in the Internet. For instance, it has been reported that the Ethernet traffic in the Internet has self-similarity [1, 2], time variation of TCP flow's window size exhibits a chaotic behavior [3], and congestion of a router propagates to neighboring routers like a wave [4].

Congestion propagation among routers is a phenomenon that congestion propagates from a congested router to neighboring non-congested routers like a wave. An example of congestion propagation is illustrated in Fig. 1. Once the router 1 is congested, routers 2, 3, 4, and 5 will be soon congested and the congestion of the router 1 will be relieved. Similarly routers 6, 7, 8, and 9 will then be congested and congestion of routers 2, 3, 4, and 5 will be relieved.

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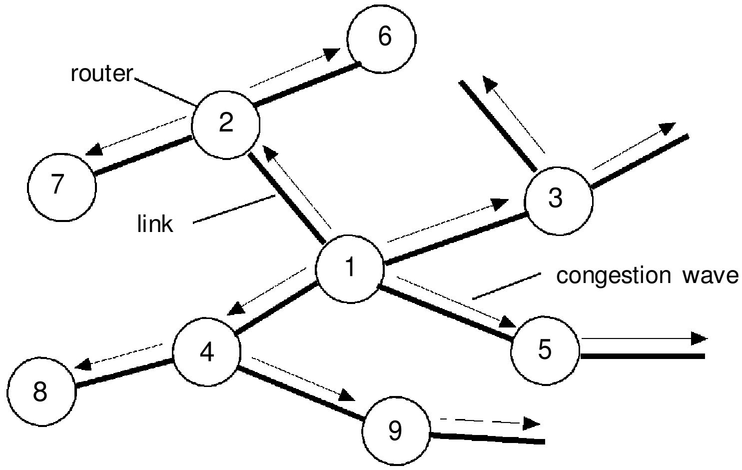

Figure 1: Example of congestion propagation in the Internet

Several researches regarding congestion propagation among routers in the Internet have been performed [5, 6]. The authors of [5] observed congestion propagation in a real network. In [5], using ICMP packets, round-trip times between an end host and every router are measured. Congestion level of each router is estimated from the measured round-trip times. It is shown in [5] that correlation exists between congestion levels at a router and its neighboring routers. It is also shown that congestion propagates to neighboring routers. The authors of [6] investigate congestion propagation through simulation experiments. As shown in Fig. 2, continuous TCP traffic is generated from router i $(1 \leq i \leq N)$ to router $i - 1$ (and from router 1 to router N) in a ring network where nodes are connected by unidirectional links. It is shown in [6] that congestion propagation is observed, and that each TCP flow's transmission rate fluctuates periodically. In these researches, however, it has not been revealed why congestion propagation occurs and under what conditions congestion propagation occurs.

In this paper, we therefore reveal a cause of congestion propagation among routers, and also investigate under what conditions congestion propagation is observed. We use the same ring network with that in [6]. To clarify conditions that congestion propagation occurs, we perform simulations while changing several network parameters and system parameters. In particular, we clarify the effect of system parameters (i.e., link bandwidth, propagation delay, and router buffer size) and network protocols (i.e., queue management mechanism such as DropTail and RED, and TCP protocol version) on congestion propagation among routers.

In this paper, we will use a qualitative approach for investigating congestion propagation among routers. Namely, we visually examine evolutions of the queue length of each router and the transmission rate of each TCP flow for investigating a cause of congestion propagation among routers. We confirmed validity of our findings using a quantitative approach — spectral analysis [7] of the queue length of each router and the transmission rate of each TCP flow.

The organization of this paper is as follows. In Section 2, we show an example of congestion propagation using simulation experiments. In Section 3, we discuss a cause of congestion

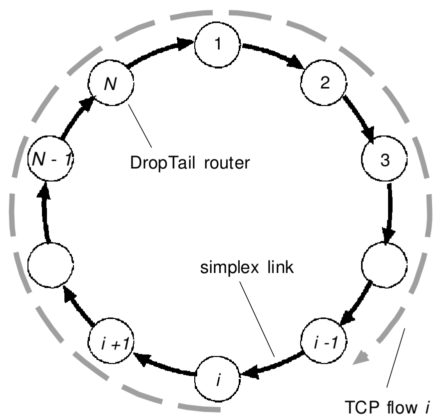

Figure 2: Simulation model

propagation among routers. In Section 4, we perform several simulations while changing network parameters and system parameters. Consequently, we reveal a cause and conditions of congestion propagation. Finally, in Section 5, we conclude this paper and discuss future work.

2 Congestion Propagation among Routers

The network model used for simulation is shown in Fig. 2. Similar to [6], we use a ring network where N routers are connected by unidirectional links. In what follows, i-th ($1 \le i \le N$) router is called *router* i. As shown in Fig. 2, TCP flow i ($1 \le i \le N$) continuously transfers data from the router i to the router $i - 1$ (and from the router 1 to the router N). Note that there are N TCP flows although only the TCP flow from the router i to the router $i - 1$ is shown in Fig. 2. For revealing a cause of congestion propagation among routers, and investigating under what conditions congestion propagation is observed, it is crucial to fully investigate fundamental characteristics of congestion propagation. For systematically investigating cause and effect of congestion propagation, we intentionally use one of simplest network models, a unidirectional ring network, for simulation experiments. It is because use of a simplified model is essential for examining nonlinear phenomena. We believe that simulation using a ring network is useful to reveal fundamental characteristics of congestion propagation since a ring network is quite simple. The parameter configuration used in simulation is shown in Tab. 1. Unless explicitly stated, parameters shown in Tab. 1 are used in the following simulations. ns-2 (version 2.28) [8] was used for simulation.

Figure 3 shows the evolution of the queue length (i.e., the number of packets in the buffer) of each router. In Fig. 3, the x-axis is time and the y-axis is router identifier i. In the figure, the queue length of the router measured every 10 [s] is shown with brightness of a color. This figure shows that the congestion of a router (i.e., increase/decrease of the queue length) repeatedly propagates to other routers. This figure also shows that variation in the queue length propagates from a downstream router to an upstream router (i.e., from router i to router $i - 1$). From these observations, we find that the congestion of a router regularly propagates from a downstream router

Table 1: Parameter configuration used in simulation

Number of nodes Link	N	10
bandwidth Propagation	B	10 [Mbit/s]
delay of a link Buffer size	τ	31 [ms]
of a router	L	300 [packet]
Queue management mechanism		DropTail
Packet length	S	552 [byte]
TCP version		TCP Tahoe

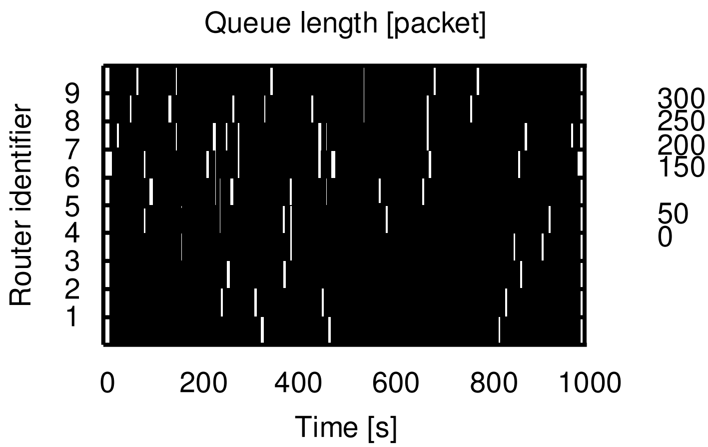

Figure 3: Evolution of queue length of routers (B = 10 [Mbit/s])

to an upstream router.

Figure 4 shows the evolution of the transmission rate of each TCP flow. In Fig. 4, the x-axis is time and the y-axis is TCP flow's identifier i. In the figure, TCP flow's transmission rate measured every 10 [s] is shown with brightness of a color. This figure shows that variation of TCP flow's transmission rate repeatedly propagates to other TCP flows. This figure also shows that variation in TCP flow's transmission rate propagates from a downstream flow to an upstream flow similar to the variation in the queue length of a router.

By comparing Figs. 3 and 4, one can find that both congestion propagation and TCP flow's transmission rate seem to fluctuate with the same cycle. We confirm validity of our finding that both congestion propagation and TCP flow's transmission rate fluctuate with the same cycle by using spectral analysis [7]. Figures 5 and 6 show the spectral density of evolution of queue length and TCP flow's transmission. These figures show that the spectral density of those have a large peak at the cycle of 110 [s]. This indicates that both queue length and TCP flow's transmission rate have the same periodicity. From these observations, it is expected that congestion propagation

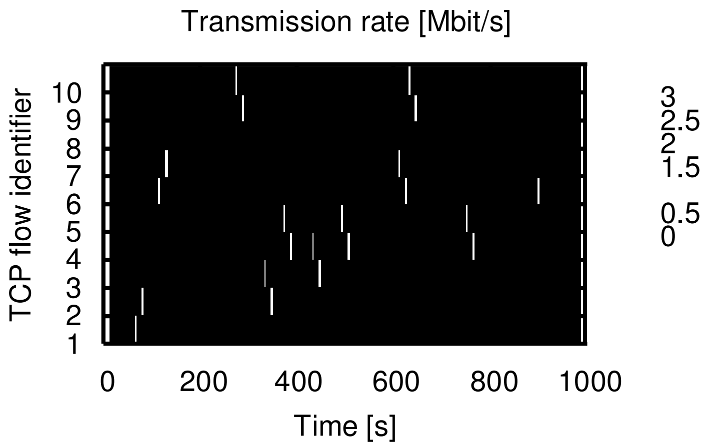

Figure 4: Evolution of TCP flow's transmission rate (B = 10 [Mbit/s])

might cause periodic variation of TCP flow's transmission rate, or vice versa.

In the next section, we will discuss a cause of congestion propagation in the ring network.

3 A Cause of Congestion Propagation

The evolutions of the queue length of the router 1 (Fig. 3) and TCP flow 1's transmission rate (Fig. 4) are shown in Fig. 7.

One can find from Fig. 7 that the queue length of a router and TCP flow's transmission rate fluctuate almost synchronously. One can also find that variation of TCP flow's transmission rate is slightly (approximately 10 [s]) earlier than that of the queue length of a router. From these observations, we expect that congestion propagation among routers is caused by periodic variation of TCP flow's transmission rate.

We then investigate why TCP flow's transmission rate fluctuates periodically. From Figs. 3 and 7, one can observe a strong positive correlation between the variation of TCP flow 1's transmission rate and the variation of the queue length of the router 1. This implies that when TCP flow 1's transmission rate is high, many packets sent from the TCP flow 1 are likely to be stored (i.e., buffered) in the queue of the router 1.

Let us assume that the TCP flow i has the largest transmission rate among all TCP flows. In this case, many packets sent from the TCP flow i are queued in the buffer of the router i. Hence, once the queue of the router i overflows, *packets sent from the TCP flow* i *are most likely to be discarded.*

When TCP flow i 's packet is discarded, the TCP flow i will decrease its transmission rate because of its window-based flow control. Since the TCP flow i 's transmission rate was largest just before the packet loss, when the TCP flow i decreases its transmission rate, the queue length

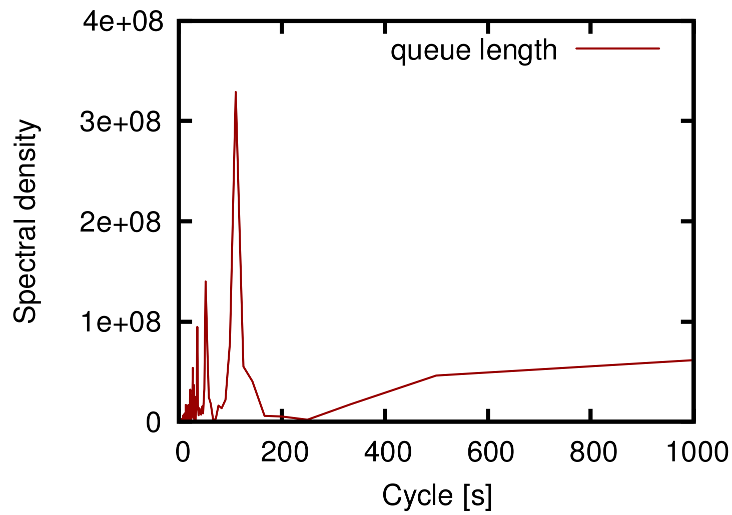

Figure 5: Spectral density of queue length of a router

of the router i will be decreased greatly. At this moment, *the TCP flow* $i - 1$*, which is closest to the router* i*, is more likely to queue more packets than other TCP flows.* Namely, among all TCP flows, the TCP flow $i - 1$ is most likely to increase its transmission rate after TCP flow i 's transmission rate decrease.

By repeating such procedures, variation of TCP flow i 's transmission rate propagates to the TCP flow $i - 1$. Thus, variation of TCP flow's transmission rate propagates from a downstream flow to an upstream flow.

4 Effect of System and Network Parameters on Congestion Propagation

In this section, we perform simulation experiments while changing various network parameters and system parameters. In particular, we clarify the effect of system parameters (i.e., link bandwidth, propagation delay of links, and router buffer size) and network protocols (i.e., queue management mechanism such as DropTail and RED, and TCP protocol version) on congestion propagation among routers.

4.1 Effect of System Parameters

We first investigate the effect of system parameters (i.e., link bandwidth, propagation delay of links, and router buffer size) on congestion propagation among routers.

Figures 8 and 9 show evolutions of the queue length of a router and TCP flow's transmission rate when link bandwidths of all links are uniformly set to $B = 1$ [Mbit/s].

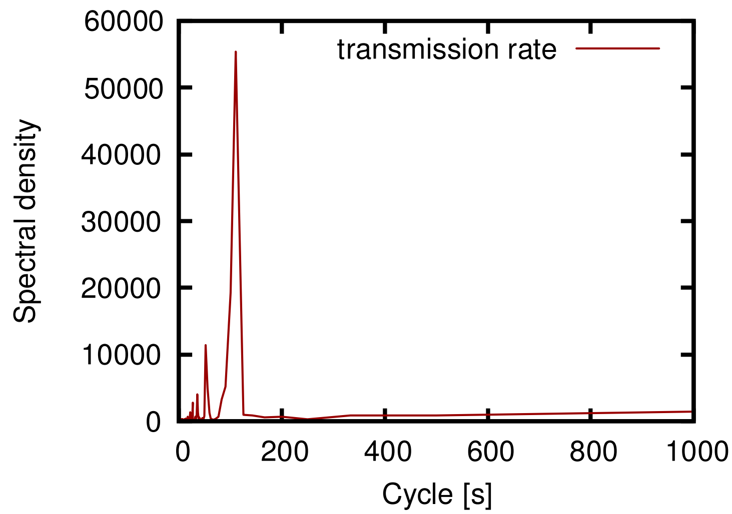

Figure 6: Spectral density of transmission rate of a TCP flow

In Figs. 3 (B $=$ 10 [Mbit/s]) and 8 (B $=$ 1 [Mbit/s]), the queue length of a router fluctuates periodically (i.e., congestion propagates to other routers) regardless of the link bandwidth. However, by comparing Figs.3 (B $=$ 10 [Mbit/s]) and 8 (B $=$ 1 [Mbit/s]), one can find that the cycle of congestion propagation among routers in Fig. 8 is seems as three times as that in Fig. 3. Similarly, the cycle of the variation of TCP flow's transmission rate in Fig. 9 is also as three times as that in Fig. 4.

Although results are not included in this paper due to space limitation, we confirmed validity of our finding using spectral analysis. The spectral density of evolution of queue length and TCP flow's transmission rate have a large peak at the cycles of 330 [s]. Such a difference is probably caused by the difference in TCP flow's round-trip times. Although results are not included due to space limitation, congestion propagation among routers was observed when the propagation delay is set to $\tau = 55$ [ms] and when the router buffer size is set to L $=$ 600 [packet]. However, the cycle of congestion propagation is different in every case. Such a difference in cycles of congestion propagation among routers is also caused by difference in TCP flow's round-trip times. Note that these results are in agreement with the analytic result in [6].

From these observations, we conclude that system parameters (i.e., link bandwidth, propagation delay, and router buffer size) do not affect occurrence of congestion propagation among routers and that the cycle of congestion propagation among routers is determined by TCP flow's round-trip time.

4.2 Effect of TCP Traffic Randomness

When multiple TCP flows are accommodated in a DropTail router, a phenomenon such that behaviors of TCP flows synchronize (i.e., phase effect) is known [9]. It is known that the phase effect disappears when TCP traffic has some randomness [9]. For instance, when the timing of packet

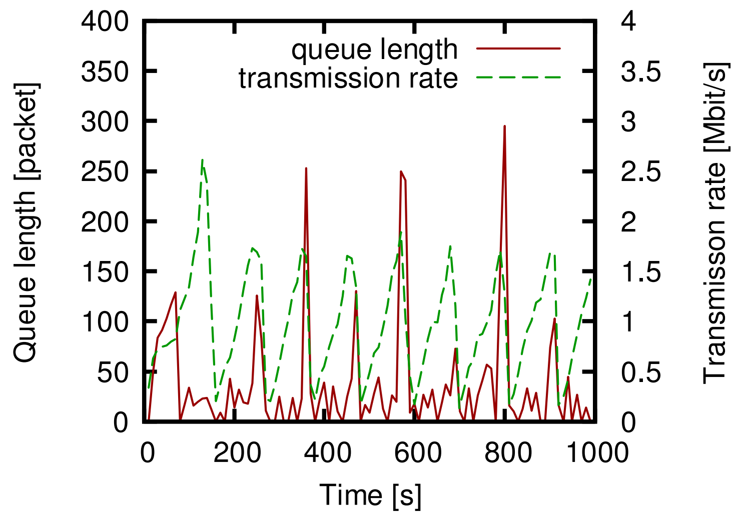

Figure 7: Evolutions of queue length of router 1 and TCP flow 1's transmission rate

transmission from TCP source hosts is randomly delayed, the phase effect disappears.

As we have discovered in Section 3, congestion propagation among routers is caused by the periodic variation of TCP flow's transmission rate. If the periodicity of TCP flow's transmission rate disappears by adding randomness to TCP traffic, it is expected that congestion propagation among routers may disappear.

We therefore performed simulation by adding a random delay to the timing of packet transmission from a TCP source host. Specifically, a random delay of 0 – 0.1 [s] was added at the time of packet transmission from TCP source hosts. Figures 10 and 11 show evolutions of the queue length of a router and TCP flow's transmission rate. By comparing Figs. 3 and 10, one can find that although congestion propagation among routers can still be observed, periodicity in Fig. 10 is less obvious than in Fig. 3.

Figures 12 and 13 show the spectral density of evolution of queue length and TCP flow's transmission. These figures show that the spectral density of evolution of queue length and TCP flow's transmission do not have a large peak.

From these observations, we conclude that although the periodicity of congestion propagation among routers becomes less obvious by adding randomness to TCP traffic, congestion propagation does not disappear.

4.3 Effect of Router's Queue Management Mechanism

As another method for preventing the phase effect with a DropTail router, active queue management mechanisms such as RED (Random Early Detection) have been proposed [10–13]. We performed simulation by changing queue management mechanism of a router from DropTail to RED.

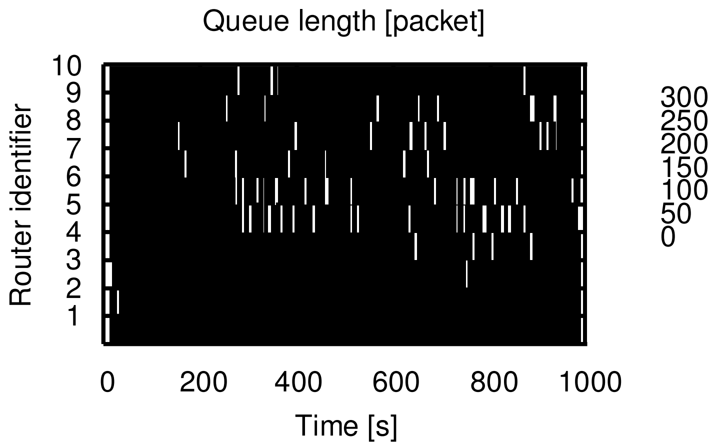

Figure 8: Evolution of queue length of routers (B = 1 [Mbit/s])

In the case with RED routers, evolutions of the queue length of a router and TCP flow's transmission rate are shown in Figs. 14 and 15, respectively. By comparing Figs. 3 and 14, one can find that although congestion propagation among routers can still be observed, periodicity in Fig. 14 is less obvious than in Fig. 3.

Although results are not included in this paper due to space limitation, we found that the spectral density of queue length and TCP flow's transmission rate in Figs. 14 and 15 do not have a large peak.

From these observations, we conclude that although the periodicity of congestion propagation becomes less obvious by setting the queue management mechanism of a router to RED, congestion propagation does not disappear.

4.4 Effect of TCP Protocol Version

Finally, we investigate the effect of TCP protocol version on congestion propagation.

There are several TCP protocol versions, and each of which adopts a different congestion control mechanism. TCP protocol versions may affect congestion propagation.

When TCP NewReno and TCP Reno were used instead of TCP Tahoe, evolutions of the queue length of a router and TCP flow's transmission rate are almost identical to the results with TCP Tahoe (see Figs. 16 through 19).

Evolutions of the queue length of a router and TCP flow's transmission rates are shown in Figs. 20 and 21. In these figures, TCP Vegas [14] was used instead of TCP Tahoe.

Figure 20 indicates that congestion propagation almost disappear in the case of TCP Vegas. Also, one can find that the periodicity of TCP flow's transmission rate in Fig. 21 cannot be observed.

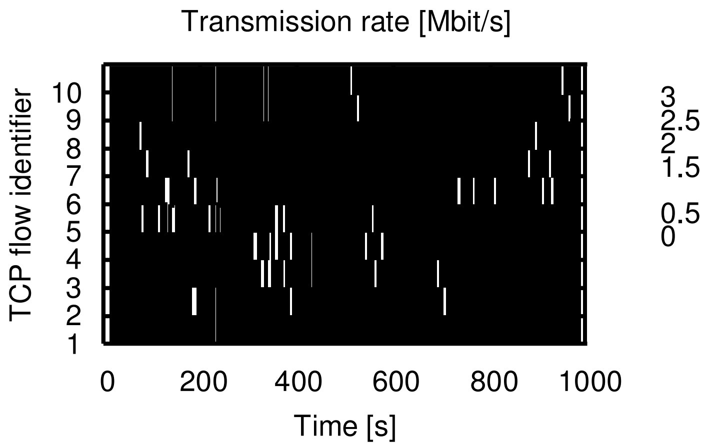

Figure 9: Evolution of TCP flow's transmission rate (B = 1 [Mbit/s])

From these observations, we conclude that changing the TCP protocol version to TCP Vegas diminishes congestion propagation.

5 Conclusion and Future Work

In this paper, we have revealed a cause of congestion propagation among routers in the ring network. We have performed simulation experiments while changing several network parameters and system parameters. Consequently, we have found: (1) speed of congestion propagation among routers is affected by the link bandwidth and the propagation delay of links, and (2) periodicity of congestion propagation among routers becomes less obvious as randomness of network traffic increases. Our findings are confirmed by spectral analysis.

As future work, we need to clarify other cause of congestion propagation among routers. Also, it is necessary to quantitatively evaluate the effect of congestion propagation among routers on TCP flow's end-to-end performance. Investigation of congestion propagation among routers in more general network topology is also important.

Acknowledgments

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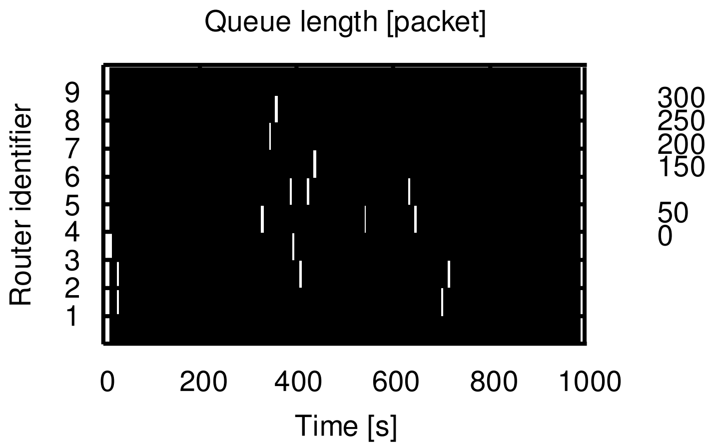

Figure 10: Evolution of queue length of routers with TCP traffic randomness (B = 10 [Mbit/s])

References

[1] W.E. Leland, M.S. Taqqu, W. Willinger, and D.V. Wilson, "On the self-similar nature of Ethernet traffic (extended version)," IEEE /ACM Transactions on Networking, vol.2, no.1, pp.1–15, Feb. 1994.

[2] M.E. Crovella and A. Bestavros, "Self-similarity in World Wide Web traffic: Evidence and possible causes," IEEE /ACM Transactions on Networking, vol.5, no.6, pp.835–846, May 1997.

[3] A. Veras and M. Boda, "The chaotic nature of TCP congestion control," Proceedings of IEEE INFOCOM, pp.1715–1723, March 2000.

[4] D.E. Newman, N.D. Sizemore, V.E. Lynch, and B.A. Carreras, "Growth and propagation of disturbances in a communication network model," Proceedings of the 35th Hawaii International Conference on System Sciences (HICSS-35), pp.867–874, Jan. 2002.

[5] K. Fukuda, H. Takayasu, and M. Takayasu, "Spatial and temporal behavior of congestion in Internet traffic," Fractals, vol.7, no.1, pp.23–31, March 1999.

[6] J. Steger, P. Vaderna, and G. Vattay, "On the propagation of congestion waves in the Internet," Physica A, vol.359, pp.784–792, Jan. 2006.

[7] J.W. Cooley and J. Tukey, "An algorithm for the machine calculation of complex fourier series," Mathematics of Computation, vol.19, pp.297–301, April 1965.

[8] "The network simulator – ns2." available at `http://www.isi.edu/nsnam/ns/`.

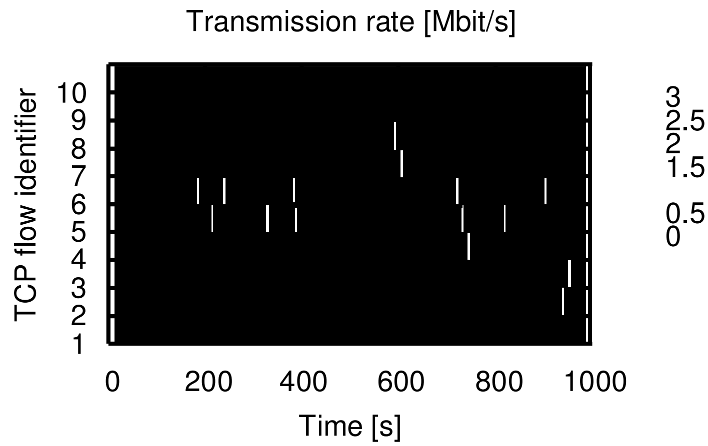

Figure 11: Evolution of TCP flow's transmission rate with TCP traffic randomness (B = 10 [Mbit/s])

[9] S. Floyd and V. Jacobson, "On traffic phase effects in packet-switched gateways," Internetworking: Research and Experience, vol.3, no.3, pp.115–156, Sept. 1992.

[10] S. Floyd and V. Jacobson, "Random early detection gateways for congestion avoidance," IEEE /ACM Transactions on Networking, vol.1, no.4, pp.397–413, Aug. 1993.

[11] S. Floyd, "Recommendations on using the gentle variant of RED," May 2000. Also available as `http://www.aciri.org/floyd/red/gentle.html`.

[12] J. Aweya, M. Ouellette, and D.Y. Montuno, "A control theoretic approach to active queue management," Computer Networks, vol.36, pp.203–235, July 2001.

[13] S. Athuraliya, V.H. Li, S.H. Low, and Q. Yin, "REM: Active queue management," IEEE Network, vol.15, no.3, pp.48–53, May/June 2001.

[14] L.S. Brakmo and L.L. Peterson, "TCP Vegas: End to end congestion avoidance on a global Internet," IEEE journal on Selected Areas in Communications, vol.13, no.8, pp.1465–1480, Oct. 1995.

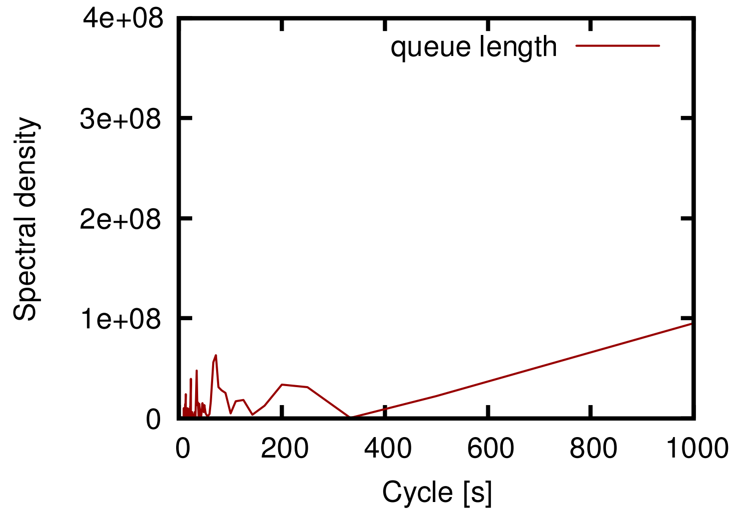

Figure 12: Spectral density of queue length of a router with TCP traffic randomness (B = 10 [Mbit/s])

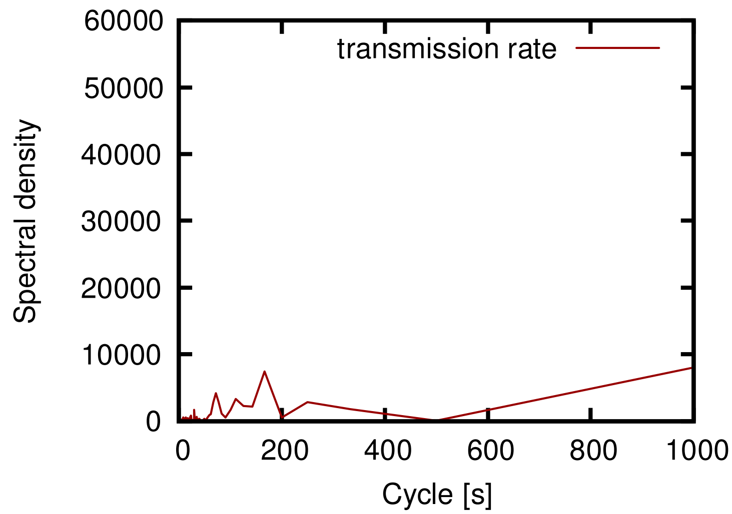

Figure 13: Spectral density of transmission rate of a TCP flow with TCP traffic randomness (B = 10 [Mbit/s])

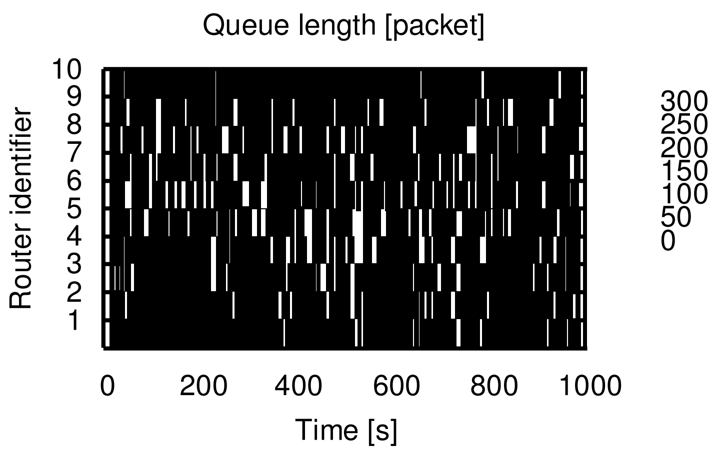

Figure 14: Evolution of queue length of routers (case of RED router) (B = 10 [Mbit/s])

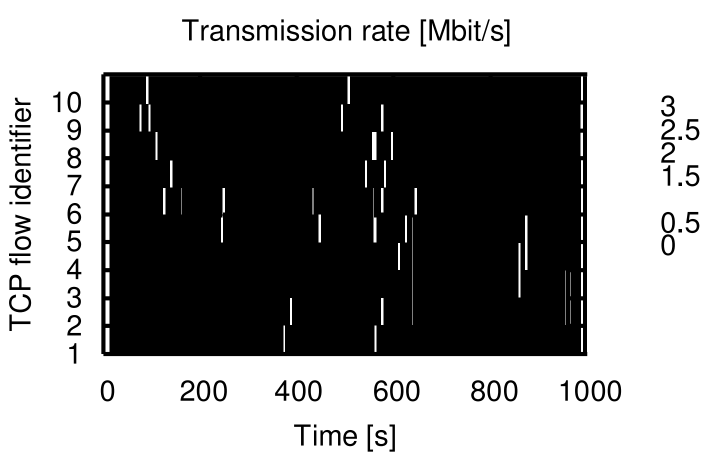

Figure 15: Evolution of TCP flow's transmission rate (case of RED router) (B = 10 [Mbit/s])

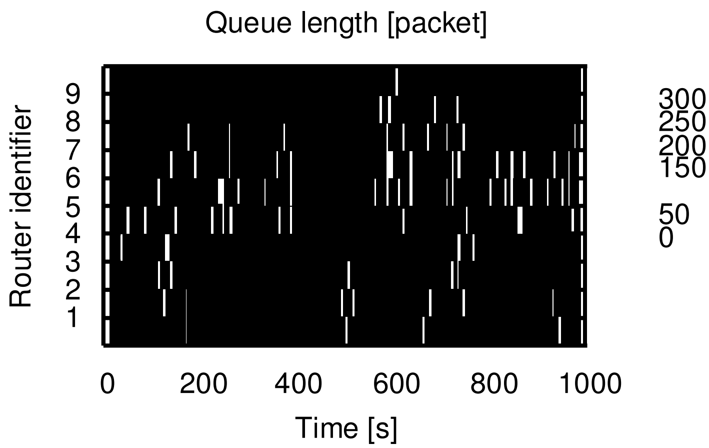

Figure 16: Evolution of queue length of routers (case of TCP NewReno)

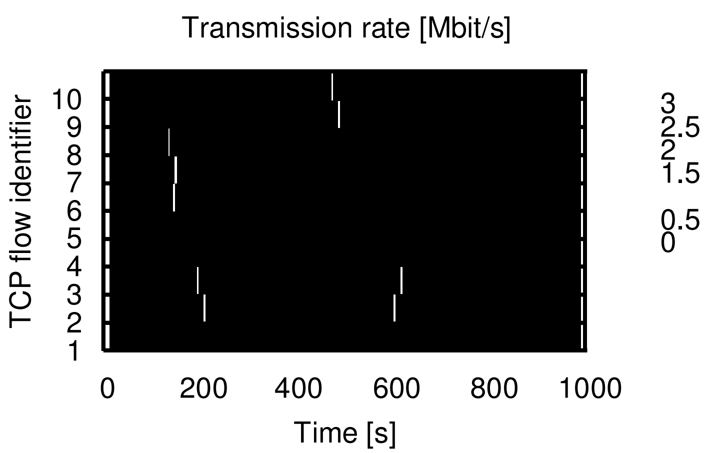

Figure 17: Evolution of TCP flow’s transmission rate (case of TCP NewReno)

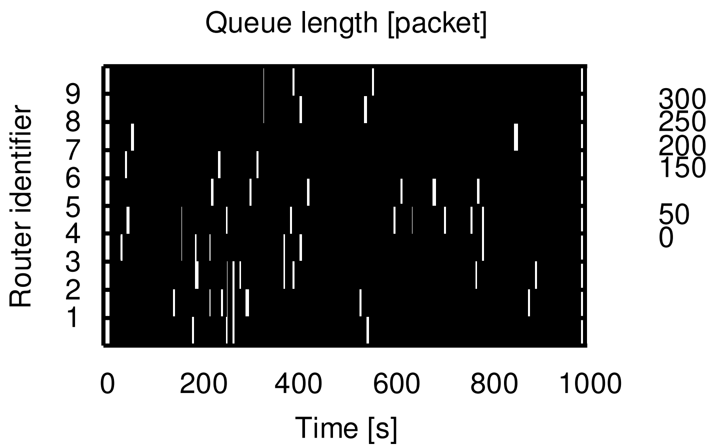

Figure 18: Evolution of queue length of routers (case of TCP Reno)

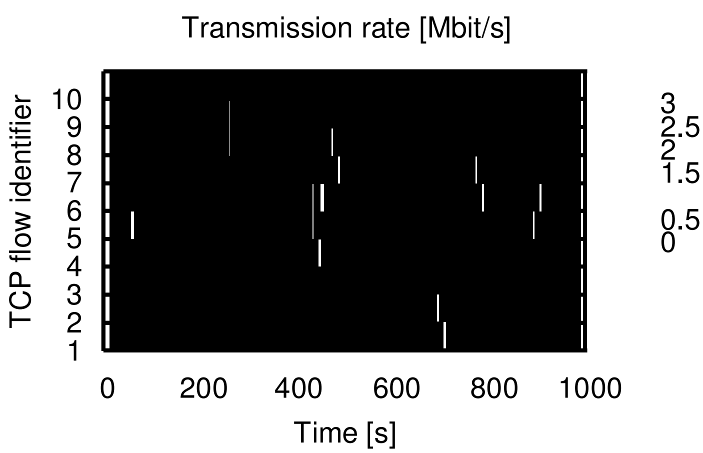

Figure 19: Evolution of TCP flow's transmission rate (case of TCP Reno)

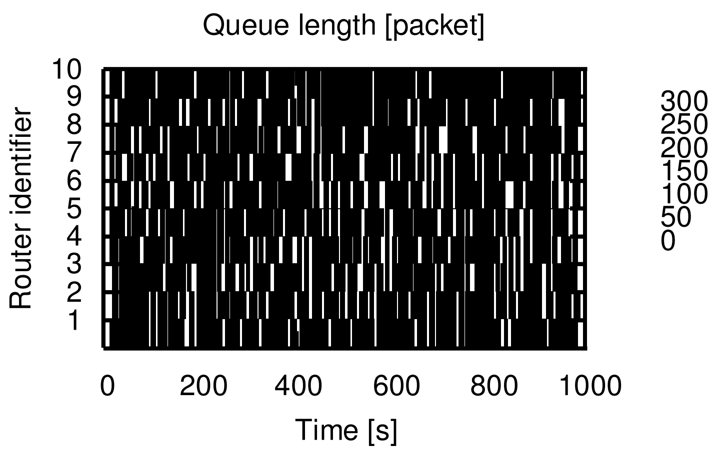

Figure 20: Evolution of queue length of routers (case of TCP Vegas)

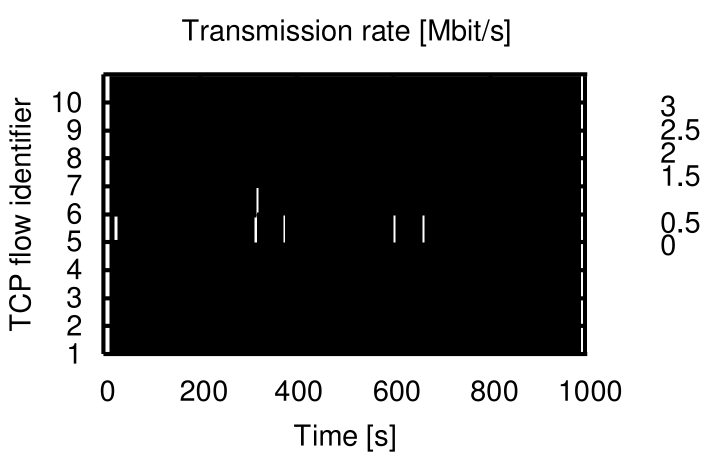

Figure 21: Evolution of TCP flow's transmission rate (case of TCP Vegas)