A DISCRETE-TIME PERFORMANCE MODEL FOR CONGESTON CONTROL MECHANISM USING QUEUE THRESHOLDS WITH QOS CONSTRAINTS

LIN GUAN, MIKE E WOODWARD, IRFAN U AWAN

Department of Computing
School of Informatics, University of Bradford,
Bradford, West Yorkshire, UK, BD7 1DP
E-mail: {L.Guan, M.E.Woodward, I.U.Awan}@Bradford.ac.uk

Abstract: This paper presents a new analytical framework for the congestion control of Internet traffic using a queue threshold scheme. This framework includes two discrete-time analytical models for the performance evaluation of a threshold based congestion control mechanism and compares performance measurements through typical numerical results. To satisfy the low delay along with high throughput, model-I incorporates one threshold to make the arrival process step reduce from arrival rate α_1 directly to α_2 once the number of packets in the system has reached the threshold value L_1. The source operates normally, otherwise. Model-II incorporates two thresholds to make the arrival rate linearly reduce from α_1 to α_2 with system contents when the number of packets in the system is between two thresholds L_1 and L_2. The source operates normally with arrival rate α_1 before threshold L_1, and with arrival rate α_2 after the threshold L_2. In both performance models, the mean packet delay W, probability of packet loss P_L and throughput S have been found as functions of the thresholds and maximum drop probability. The performance comparison results for the two models have also been made through typical numerical results. The results clearly demonstrate how different load settings can provide different tradeoffs between throughput, loss probability and delay to suit different service requirements.

Keywords: Queueing Theory, Markov Chain, Queue Thresholds, Congestion Control

1. INTRODUCTION

With the enormous growth in the Internet traffic, the control of congestion has become one of the most critical issues in present networks to accommodate the increasingly diverse range of services and types of traffic [Atsumi et al. 1993]. It is also a major challenge to the researchers in the field of performance modelling. Congestion control to enable different types of Internet traffic to satisfy specified Quality of Service (QoS) constraints is becoming significantly important. Many systems in network environments require the queue to be monitored for impending congestion before it happens [Li et al. 1998].

The traditional technique for managing router queue lengths is only to set a maximum length for each queue, usually equal to the buffer capacity, and then accept packets until queue becomes full. The subsequent arrivals will be blocked until some space become available in the queue as a result of some departures. This technique is known as "tail drop", since the packet that arrived most recently (i.e., the one on the tail of the queue) is dropped when the queue is full. This method has been used for several years in the Internet, but it has two important drawbacks 'Lock-Out' and 'Full Queues' [Braden et al.1998]. In order to solve the problems, some active queue management (AQM) mechanisms have been proposed and implemented to manage the queue lengths, reduce end-to-end latency, reduce packet dropping, and avoid lock-out phenomena so that the control of congestion can be achieved by the use of appropriate buffer management schemes. These mechanisms include random early detection (RED) [Floyd and Jacobson 1993], random early marking (REM) [Lapsley and Low 1999; Athuraliya et al. 2000], a virtual queue based scheme where the virtual queue is adaptive [Gibbens and Kelly 1999; Kunniyur and Srikant 2000, 2001] and a proportional integral controller mechanism [Hoolot et al. 2000], among others. Of these schemes to implement AQM, the RED mechanism is the one recommended by the Internet Society in [Braden et al.1998]. Quote: "Unless a developer has reasons to provide another equivalent mechanism we recommend that RED be used". This mechanism has the potential to over-come some of the problems discovered in drop tail mechanisms which are specific to the Internet traffic, such as synchronization of TCP flows and correlation of the drop events (multiple packets dropped in sequence) within a TCP flow and it is therefore this mechanism that we will focus on in this paper.

RED drops arriving packets probabilistically depending on setting thresholds in the queue and this paper uses the principle and looks at this in a simplified way where we set up two discrete-time performance models. Model-I incorporates one threshold with arrival rate step reduction and another model includes two thresholds with arrival rate linear reduction, respectively. Model-II can also be potentially used as a model for RED.

The remainder of the paper is organised as follows: In Section 2, we introduce two discrete-time performance models for congestion control mechanism using queue thresholds, and present analytical expressions for various performance measures. Section 3 presents the performance comparison results of two models through typical numerical results. It also includes a detailed performance study of model-II. Conclusions and future work are followed in Section 4.

2. PERFORMANCE ANALYSIS OF THE PROPOSED MODELS

In this section, we introduce two proposed system models in discrete-time settings and present the analytical framework to be used in the remainder of the paper. In both discrete-time queueing systems, we will assume that a departure always takes place before an arrival in any unit time (slot). Arrivals form an independent Bernoulli process, with $a_n \in \{0,1\}$, n=1,2,3,…., and there is a finite waiting room of M packets, including any in service. The queueing discipline is first-come first-served. [Woodward 1993]

2.1 Model-I: Threshold Based Step Reduction of Arrival Rate

Model-I incorporates one threshold to make the arrival process step reduce from arrival rate α_1 directly to α_2 once the number of packets in the system has been reached to the threshold value L_1. The source operates normally, otherwise. This can be considered as implicit feedback from the queue to the arrival process. In addition, this can alternatively be viewed as the source continuing to send at rate α_1 but with arriving packets dropped with probability $1-\alpha_2/\alpha_1$. (c.f. Figure 1)

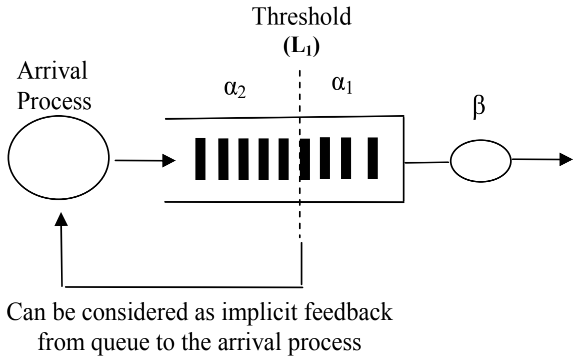


FIGURE 1. Single Buffer with One Threshold L_1

Let the probability of an arrival in a slot be α_1 before the number of packets in the system reaches the threshold L_1, the probability of an arrival in a slot be reduced to α_2 after L_1 and the probability of a departure in a slot be β. We assume that the queueing system is in equilibrium. The state transition diagram is shown in Figure 2, and the queue length process is a Markov chain with a finite state space $\{0, 1, \ldots, M(M=L_1+J)\}$.

We assume that $\alpha_1 \neq \beta$, $\alpha_2 \neq \beta$ $(\alpha_1>\alpha_2)$ and the balance equations of the discrete-time finite queue with one threshold (L_1) can be expressed as follows:

$$\pi_0 = \pi_0(1-\alpha_1) + \pi_1[\beta(1-\alpha_1)] \quad (1)$$

$$\pi_1 = \pi_0\alpha_1 + \pi_1[\alpha_1\beta + (1-\alpha_1)(1-\beta)] + \pi_2[\beta(1-\alpha_1)] \quad (2)$$

In general

$$\pi_i = \pi_{i-1}[\alpha_1(1-\beta)] + \pi_i[\alpha_1\beta + (1-\alpha_1)(1-\beta)] + \pi_{i+1}[\beta(1-\alpha_1)] \quad i = 2, 4,\ldots, L_1-2 \quad (3)$$

$$\pi_{L_1-1} = \pi_{L_1-2}[\alpha_1(1-\beta)] + \pi_{L_1-1}[\alpha_1\beta + (1-\alpha_1)(1-\beta)] + \pi_{L_1}[\beta(1-\alpha_2)] \quad (4)$$

$$\pi_{L_1} = \pi_{L_1-1}[\alpha_1(1-\beta)] + \pi_{L_1}[\alpha_2\beta + (1-\alpha_2)(1-\beta)] + \pi_{L_1+1}[\beta(1-\alpha_2)] \quad (5)$$

In general

$$\pi_i = \pi_{i-1}[\alpha_2(1-\beta)] + \pi_i[\alpha_2\beta + (1-\alpha_2)(1-\beta)] + \pi_{i+1}[\beta(1-\alpha_2)] \quad i = L_1+1,\ldots, L_1+J-1 \quad (6)$$

$$\pi_i = \pi_{i-1}[\alpha_2(1-\beta)] + \pi_i[\alpha_2 + (1-\alpha_2)(1-\beta)] + \pi_{i+1}[\beta(1-\alpha_2)]\ )] \quad i = L_1+J\ (M=L_1+J) \quad (7)$$

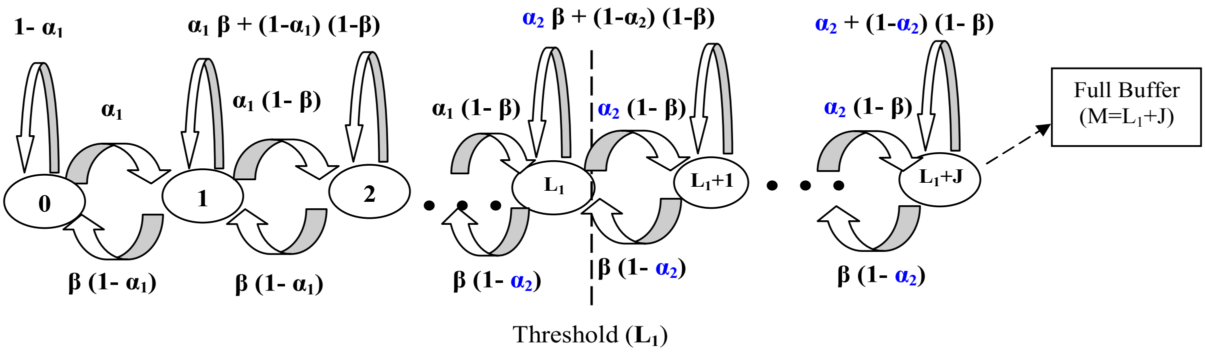


FIGURE 2. State Transition Diagram for Discrete-Time Finite Queue with Threshold L_1

Solving these equations recursively, and involving $\gamma_1=\frac{\alpha_1(1-\beta)}{\beta(1-\alpha_1)}$, $\gamma_2=\frac{\alpha_2(1-\beta)}{\beta(1-\alpha_2)}$, after the equilibrium probability can be expressed in terms of π_0, we use the normalising equations $\sum_{i=0}^{L_1+J}\pi_i = 1$, thus π_0 can be obtained as follows:

$$\pi_0 = \frac{(1-\beta)(1-\gamma_1)(1-\gamma_2)(1-\alpha_2)}{(1-\alpha_2)(1-\gamma_2)(1-\gamma_1^{L_1}-\beta(1-\gamma_1))+\gamma_1^{L_1}(1-\gamma_1)(1-\alpha_1)(1-\gamma_2^{J+1})} \tag{8}$$

The idea is to find the generating function of the queue length process for this finite queue which is given by

$$P(z) = \sum_{i=0}^{L_1+J}\pi_i z^i \tag{9}$$

Multiplying π_i by z^i, and summing them together we can find $P(z)$. To find the mean waiting time via Little's law, we must first evaluate the mean queue length which can be obtained from the generating function by taking the first derivative of $P(z)$ evaluated at $z=1$, thus the mean queue length for this finite queue with a threshold L_1 as follows:

$$P^{(1)}(1) = \frac{\pi_0}{(1-\beta)}\left[\frac{\gamma_1+\gamma_1^{L_1+1}(L_1(\gamma_1-1)-\gamma_1)}{(1-\gamma_1)^2} + \frac{\gamma_1^{L_1+1}(1-\alpha_1)[\gamma_2+L_1(1-\gamma_2)-\gamma_2^{J+1}(1+J(1-\gamma_2))]}{(1-\alpha_2)(1-\gamma_2)^2}\right] \tag{10}$$

The mean throughput of this finite queue given by the fraction of time the server is busy:

$$S = (1-\pi_0)\times\beta \tag{11}$$

The delay can be obtained from Little's law for this finite capacity queue as:

$$W = \frac{P^{(1)}(1)}{S} \tag{12}$$

Another very important performance measure is the probability of packet loss given by:

$$P_L = \frac{(\alpha_1-\alpha_2)\gamma_1^{L_1}(1-\alpha_1)(1-\gamma_2^{J+1})}{\alpha_1(1-\beta)(1-\alpha_2)(1-\gamma_2)}\pi_0 \tag{13}$$

where π_0 is in the equation (8).

2.2 Model-II: Threshold based Linear Reduction of Arrival Rate

Model II incorporates two thresholds to make the arrival rate reduce linearly between them. (c.f. Figure 3)

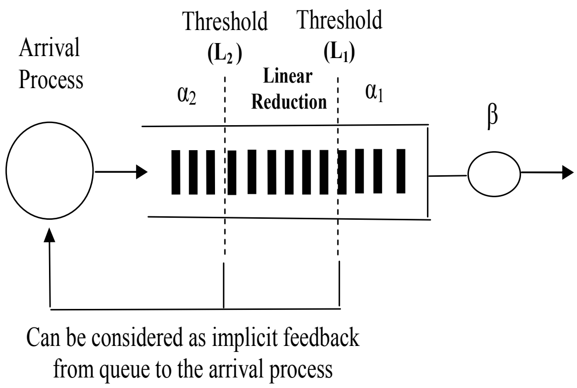


FIGURE 3. Single Buffer with Two Thresholds (L_1 and L_2)

Let the probability of an arrival in a slot be α_1 before the number of packets in the system reaches the first threshold L_1, the probability of an arrival in a slot be reduced to α_2 after the number of packets in the system reaches the second threshold L_2, and the probability of a departure in a slot be β. When the number of packets in the system is between the first threshold and the second threshold, the arrival rate (probability) will be linearly reduced with some probability which is the function of α_1, α_2 and the two thresholds. So the dropping probability increases linearly from 0 to the maximum $1-\alpha_2/\alpha_1$. This can be considered as implicit feedback from queue to the arrival process in that dropping packets reduces the effective arrival rate into the queue from α_1 to $\alpha_1-\alpha_2$ with a linear reduction. We assume that the queueing system is in equilibrium. The state transition diagram is shown in Figure 4, and the queue length process is a Markov chain with a finite state space $\{0, 1, \ldots, L_2+N\ (L_2+N=M)\}$.

As shown in Figure 4, the arrival rate is α_1 in part I and α_2 in part III, which are all independent. However in part II (between two thresholds), the arrival rate depends on the state, that means each arrival rate is different with each state and will be linearly reduced by dropping packets. We assume that $\alpha_1 \neq \beta$, $\alpha_2 \neq \beta$ ($\alpha_1>\alpha_2$) and the final state L_2+N ($L_2+N=M$) is the full buffer situation.

To find the equilibrium probability, first the transition probabilities of arrivals and departures from state L_1 to state L_2-1 can be defined as:

$$\lambda_k = \alpha_k(1-\beta)$$
$$\mu_k = \beta(1-\alpha_k),\ L_1 \le k \le L_2-1 \qquad (14)$$

where

$$\alpha_k = \alpha_1 - (k - L_1 + 1)\frac{\alpha_1-\alpha_2}{L_2-L_1+1},\ L_1 \le k \le L_2-1 \qquad (15)$$

and the transition probabilities of arrivals and departures in part I and III can also be defined as:

$$\lambda_0 = \alpha_1,\ \lambda_1 = \alpha_1(1-\beta),\ \mu_1 = \beta(1-\alpha_1)$$
$$\lambda_2 = \alpha_2(1-\beta),\ \mu_2 = \beta(1-\alpha_2) \qquad (16)$$

Similarly with model I, after solving the balance equations of the discrete-time finite queue with two thresholds L_1 and L_2 ($L_2>L_1$) recursively, and involving $\rho_1 = \frac{\lambda_1}{\mu_1}$ and $\rho_2 = \frac{\lambda_2}{\mu_2}$, the equilibrium probability π_i can be expressed in terms of π_0, then we use the normalising equations $\sum_{i=0}^{L_2+N} \pi_i = 1$, thus π_0 can be obtained as follows:

$$\pi_0 = \left[\frac{\lambda_1(1-\rho_1)+\lambda_0\left(\rho_1-\rho_1^{L_1}\right)}{\lambda_1(1-\rho_1)} + \lambda_0\rho_1^{L_1}\sum_{i=L_1}^{L_2-1}\prod_{k=L_1}^{i-1}\left(\frac{\lambda_k}{\mu_k}\right)\frac{1}{\mu_i} + \frac{\lambda_0\rho_1^{L_1}\left(1-\rho_2^{N+1}\right)}{1-\rho_2}\prod_{k=L_1}^{L_2-1}\left(\frac{\lambda_k}{\mu_k}\right)\frac{1}{\mu_2}\right]^{-1} \qquad (17)$$

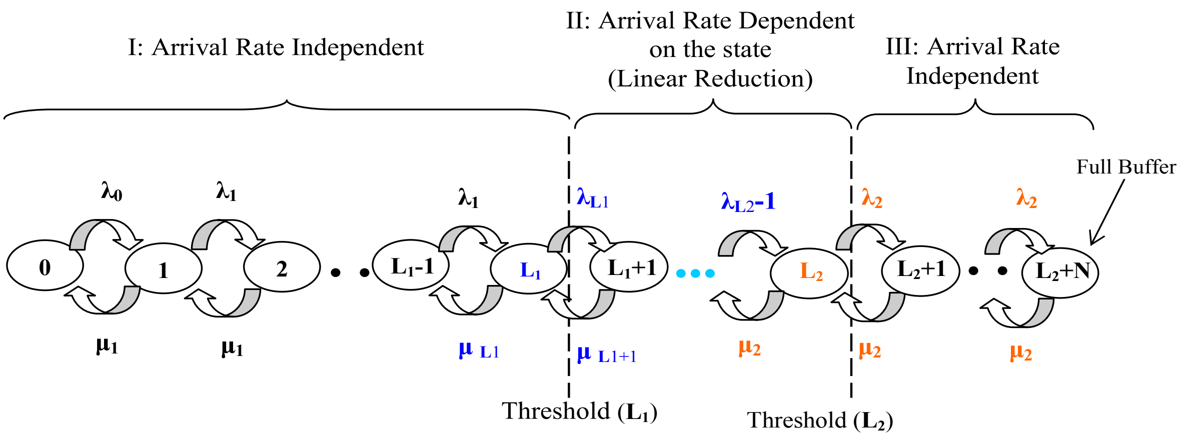


FIGURE 4. State Transition Diagram for the Discrete-Time Finite Queue with two Thresholds (L_1 and L_2)

Similarly with model I, by using the generating function of the queue length process for this finite queue, $p(z) = \sum_{i=0}^{L_2+N} \pi_i z^i$, and taking the first derivative of $P(z)$ evaluated at $z=1$, the mean queue length for this finite queue with two thresholds L_1 and L_2 can be obtained as follows:

$$P^{(1)}(1)=\pi_0\left[\frac{\lambda_0\rho_1\left(1-\rho_1^{L_1}-\rho_1^{L_1-1}L_1(1-\rho_1)\right)}{\lambda_1(1-\rho_1)^2}+\lambda_0\rho_1^{L_1-1}\sum_{i=L_1}^{L_2-1}\prod_{k=L_1}^{i-1}\left(\frac{\lambda_k}{\mu_k}\right)\frac{i}{\mu_i}\right]+\pi_0\left[\lambda_0\rho_1^{L_1}\prod_{k=L_1}^{L_2-1}\left(\frac{\lambda_k}{\mu_k}\right)\frac{1}{\mu_2}\left(\frac{L_2\left(1-\rho_2-\rho_2^{N+1}+\rho_2^{N+2}\right)+\rho_2\left(1-\rho_2^N-N\rho_2^N(1-\rho_2)\right)}{(1-\rho_2)^2}\right)\right] \quad (18)$$

The delay can be obtained using Little's law for this finite capacity queue as:

$$W=\frac{\pi_0}{S}\left[\frac{\lambda_0\rho_1\left(1-\rho_1^{L_1}-\rho_1^{L_1-1}L_1(1-\rho_1)\right)}{\lambda_1(1-\rho_1)^2}+\lambda_0\rho_1^{L_1-1}\sum_{i=L_1}^{L_2-1}\prod_{k=L_1}^{i-1}\left(\frac{\lambda_k}{\mu_k}\right)\frac{i}{\mu_i}\right]+\frac{\pi_0}{S}\left[\lambda_0\rho_1^{L_1}\prod_{k=L_1}^{L_2-1}\left(\frac{\lambda_k}{\mu_k}\right)\frac{1}{\mu_2}\left(\frac{L_2\left(1-\rho_2-\rho_2^{N+1}+\rho_2^{N+2}\right)+\rho_2\left(1-\rho_2^N-N\rho_2^N(1-\rho_2)\right)}{(1-\rho_2)^2}\right)\right] \quad (19)$$

where S is the mean throughput of this queue given by the fraction of time the server is busy:

$$S=(1-\pi_0)\times\beta \quad (20)$$

π_0 can be found in the equation (17).

Another important performance measure is the probability of packet loss given by the following expression:

$$P_L=\frac{1}{\alpha_1}\lambda_0\rho_1^{L_1-1}\pi_0\frac{\alpha_1-\alpha_2}{L_2-L_1+1}\sum_{i=L_1}^{L_2-1}\prod_{k=L_1}^{i-1}\left(\frac{\lambda_k}{\mu_k}\right)\frac{i-L_1+1}{\mu_i}+\left(\lambda_0\rho_1^{L_1-1}\prod_{k=L_1}^{L_2-1}\left(\frac{\lambda_k}{\mu_k}\right)\frac{1}{\mu_2}\pi_0\left(\frac{1-\rho_2^N}{1-\rho_2}\left(1-\frac{\alpha_2}{\alpha_1}\right)+\rho_2^N\left(1-\beta\frac{\alpha_2}{\alpha_1}\right)\right)\right) \quad (21)$$

3. NUMERICAL RESULTS

This section presents numerical results based on the two proposed models. Performance measurements comparison between two models is shown in the first part, and the further detailed performance study of model-II is included in the second part.

3.1 Numerical Performance Results Comparison

Since in both analytical performance models, the mean packet delay W, probability of packet loss P_L and throughput S have been expressed as functions of the thresholds and maximum drop probability, this section presents the comparison results for both performance measurement parameters through graphical results. (c.f. Figures 6-8)

Model-I is called 'Step Reduction' since it incorporates one threshold to make the arrival process step reduce from arrival rate α_1 directly to α_2 once the number of packets in the system has been reached to the threshold value L_1. The source operates normally, otherwise. Model-II is called 'Linear Reduction' since it incorporates two thresholds to make the arrival rate linearly reduce from α_1 to α_2 with system contents when the number of packets in the system is between two thresholds L_1 and L_2. The source operates normally with arrival rate α_1 before threshold L_1, and with arrival rate α_2 after the threshold L_2. (c.f. Figure 5)

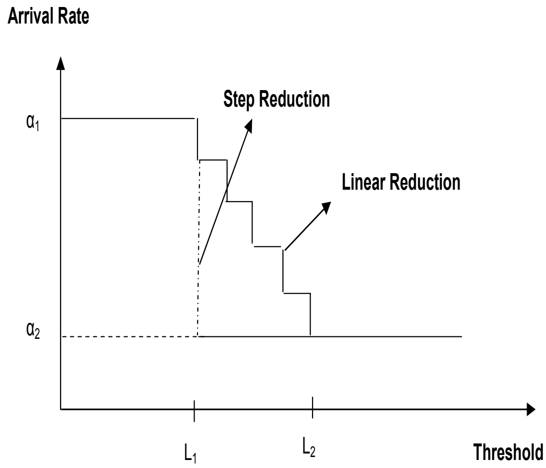


FIGURE 5. Step Reduction and Linear Reduction

Figures 6-8 present numerical results comparison between step and linear reduction of arrival rate by setting normalised throughput, normalised delay and probability of packets loss against same range of load (α_2) respectively. The performance advantages of using two thresholds with linear reduction of arrival rate compared to schemes which use only a single threshold with step reduction of arrival rate have been clearly demonstrated in Figure 6 and 8, where the linear reduction can always give a higher throughput anda lower packet loss probability for the same load. However, in Figure 7, step reduction gives the lower delay against the same load compared with linear reduction.

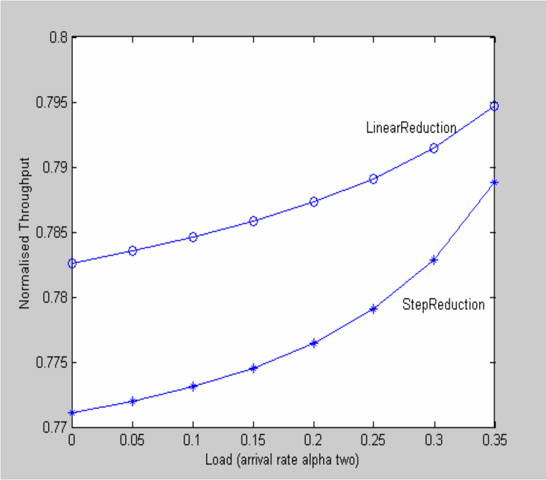


FIGURE 6. Comparison Results for Normalised Throughput

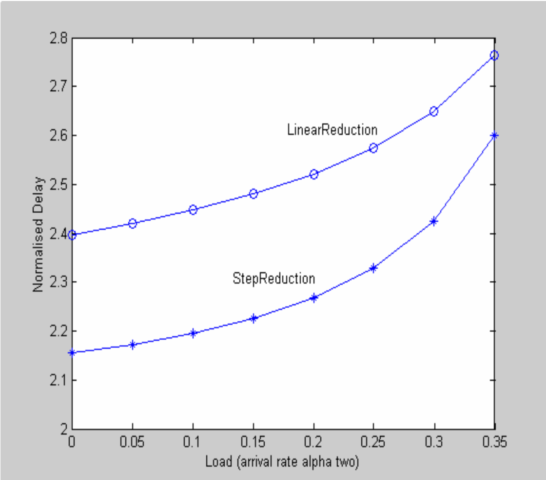


FIGURE 7. Comparison Results for Normalised Delay

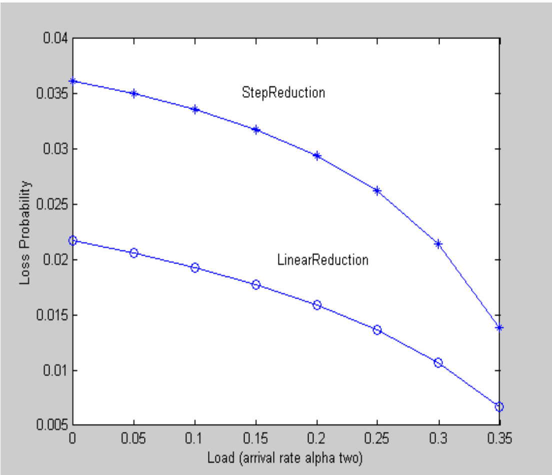


FIGURE 8. Comparison Results for Probability of Packets Loss

3.2 A Detailed Performance Study of Model-II

Using the expressions (19) and (21) for the delay and probability of packet loss respectively, the graphical results of delay and probability of packet loss against L_2-L_1 are shown in Figures 9-12.

- **α_1, α_2 fixed, L_2 is variable, results for different values of L_1 are compared**

Figure 9 indicates that the absolute value of mean delay is lower for the lower threshold settings, as expected. However, this figure also indicates that the change in mean delay depends only on the distance between the queue thresholds and is independent of the positions of the thresholds in the queue. Figure 10 shows that a lower probability of packet loss can be achieved by using a high setting for the threshold L_1 and a wide separation of the thresholds, with the probability of packet loss tending to converge to the same value for a very wide thresholds separation.

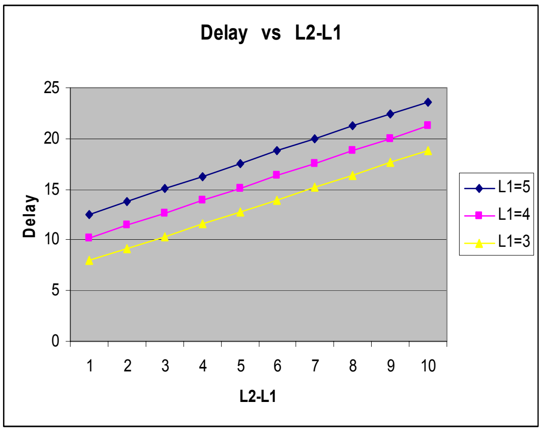


FIGURE 9. Delay vs L_2-L_1

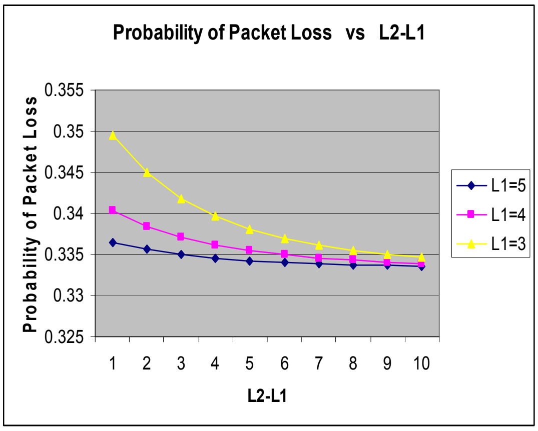


FIGURE 10. Probability of Packets Loss vs L_2-L_1

- **α_1, L_1 fixed, L_2 is variable, results for different values of α_2 are compared**

Varying the parameter α_2 is the equivalent of varying the maximum drop probability, which is $1-\alpha_2/\alpha_1$. Figure 11 shows that a higher value of maximum drop probability gives a lower delay for the same threshold separation L_2- L_1 whereas Figure 12 shows that a lower value of maximum drop probability gives a lower probability of packet loss for the same threshold separation. However, a lower probability of packet loss can be achieved by using a low maximum drop probability and a wide separation of the thresholds, although for a very wide threshold separation the probability of packet loss converges to the same value, irrespective of the maximum drop probability.

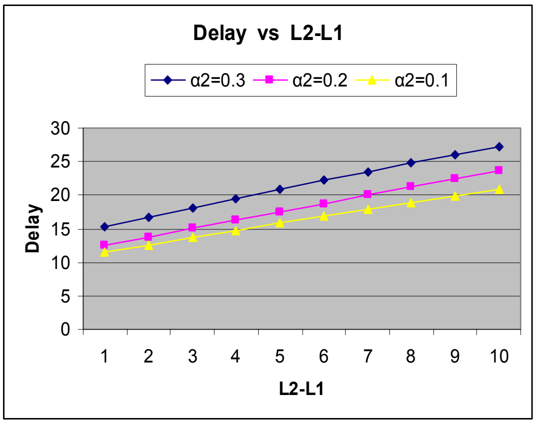


FIGURE 11. Delay vs L_2-L_1

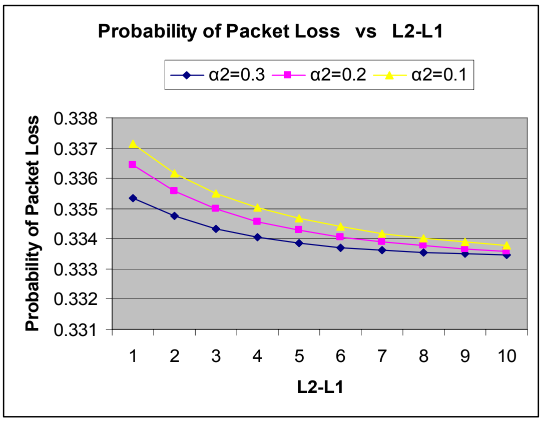


FIGURE 12. Probability of packets loss vs L_2-L_1

Taking the results of Figure 9-12 overall, these suggest that a lower delay for a specific packet loss probability can be obtained by using a high maximum drop probability, a low setting for the threshold L_1 and a narrow separation of the thresholds. A lower probability of packet loss can be achieved by using a low maximum drop probability, a high setting for the threshold L_1 and a wide separation of the thresholds. Settings of these parameters thus can be chosen to suit the type of service required. For example, real-time services require low delay whereas data services require low packet loss.

4. CONCLUSIONS AND FUTURE WORK

Two discrete-time analytical models for the performance evaluation of congestion control mechanism using queue thresholds have been developed and analysed in this paper. Comparison of performance measurements from both models have been clearly demonstrated through typical numerical results. Model-I incorporates one threshold to make the arrival process step reduce from arrival rate α_1 directly to α_2 once the number of packets in the system has been reached the threshold value L_1. In addition, this can alternatively be viewed as the source continuing to send at rate α_1 but with arriving packets dropped with probability $1-\alpha_2/\alpha_1$. In model-II, the operation with the queue length between the two thresholds can also be interpreted as either (i) the arrival rate (probability) will be linearly reduced with some probability which is the function of α_1, α_2 and the two thresholds or (ii) the original arrival rate of α_1, but the dropping probability increases linearly from 0 to the maximum $1-\alpha_2/\alpha_1$. This can be considered as implicit feedback from queue to the arrival process in that dropping packets reduces the effective arrival rate into the queue from α_1 to α_1- α_2 with a linear reduction. The performance model developed and analysed enables the best load settings and drop probability to be chosen to suit a given situation; that is, to give an appropriate trade-off among throughput, delay and packet loss probability.

In the future work, we aim to next generalize the results we have obtained to some extent by allowing for multiple arrivals in a slot which can be applied to any arrival process. Furthermore, we want to apply this model to Internet traffic e.g. a TCP/IP flow so that the technique of variable thresholds and blocking can be applied as a congestion control mechanism.

REFERENCES:

Atsumi, Y., E. Kondoh, O. Altintas, T. Yoshida, 1993. "A New Congestion Control Algorithm for Sack Tcp with RED Routers" Ultra-high speed Network & Computer Technology Labs. (UNCL), Japan.

Athuraliya, S., D. Lapsley and S. Low, 2000. "An Enhanced Random Early Marking Algorithm for Internet Flow Control ", INFOCOM'2000, Tel-Aviv, Israel, pp.1425-1434.

Braden, B. et al. 1998. "Recommendations on Queue Management and Congestion Avoidance in the Internet" IETF RFC 2309.

Floyd, S. and V. Jacobson, 1993. "Random Early Detection Gateways for Congestion Avoidance", IEEE/ACM Transaction on Networking, Vol 1, No 4, pp.397-413.

Gibbens, R. and F. Kelly, 1999. "Distributed Connection Acceptance Control for a Connectionless Network", Proceeding of the 16th Intl. Teletraffic Congress, Edinburgh, Scotland.

Hoolot, C., V. Misra, D.Towlsey and W.Gong, 2000. "On Designing Improved Controllers for AQM Routers Supporting TCP Flows", UMass CMPSCI Technical Report 00-42.

Kunniyur, S. and R. Srikant, 2000. "End-to-End Congestion Control: Utility Function, Random Losses and ECN Marks", Proceedings of INFOCOM'2000, Tel Aviv, Israel.

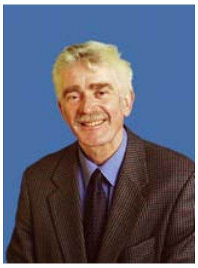
Kunniyur, S. and R. Srikant, 2001. "A Time-Scale Decomposition Approach to Adaptive ECN Marking", Proceeding of INFOCOM'2001, Alaska, Anchorage.

Li, Jian-Min, Indra Widjaja, Marcel F. Neuts. 1998. "Congestion Detection in ATM Network". *Performance Evaluation* 34, 147-168.

Lapsley, D. and S. Low, 1999. "Ransom Early Marking for Internet Congestion Control", Proceeding of GlobeCom'99, pp.1747-1752.

Woodward, M. E. 1993. *Communication and Computer Networks: Modelling with discrete- time queues*, Pentech Press, London, 1993.

BIOGRAPHIES



Mike E Woodward graduated with a first class honours degree in Electronic and Electrical Engineering from the University of Nottingham in 1967 and received a PhD degree from the same institution in 1971 for research into the decompostion of sequential logic systems. In 1970 he joined the staff of the Department of Electronic and Electrical Engineering at Loughborough University as a lecturer, being promoted to Senior Lecturer in 1980 and Reader in Stochastic Modelling in 1995. He remained at Loughborough unitil 1998 when he was appointed to the Chair in Telecommunications at the University of Bradford where he also became the Director of the Telecommunications Research Centre. He is currently the Head of the Department of Computing at the University of Bradford. His current research interests include queueing networks, telecommunications traffic modelling, quality of service routing and mobile communications systems and he is the author of two books and over one hundred research papers on the above and related topics. He currently holds two EPSRC grants and is supervisor to seven full time and six part time research students. Professor Woodward is a Fellow of the Institute of Mathematics and its Applications (FIMA) and is both a Chartered Mathematician (CMath) and a Chartered Engineer (CEng).

Irfan Awan received his PhD in 1997 with the thesis title: 'Performance Analysis of Queueing Network Models with Priorities and Blocking', from the University of Bradford, UK. He was a lecturer in the Department of Computer Science, BZ University Pakistan from 1990-1993 and an assistant professor in the faculty of Computer Science, GIK Institute Pakistan from 1997-1999. He spent two summer terms (1998 and 1999) in the Department of Computer Science at the University of Bradford and worked with the performance modelling and engineering research group. He is now a senior lecturer in the Department of Computing at the University of Bradford which he joined in 1999. Dr Awan's research has mainly focussed on developing cost effective analytical models for measuring the performance of complex queueing networks with finite capacities and priorities. He is a member of BCS and ILT.

Lin Guan received the B.Sc degree in computer science from Heilongjiang University, Heilongjiang, China, in 2001. She has studied in the department of computing of University of Bradford since 2000 to finish her first degree through the partnership scheme between two universities. She is currently a PhD student in University of Bradford. Her research interests focus on developing cost effective analytical models for the performance evaluation of congestion control algorithms with QoS constraints for Internet traffic and validate them using simulations.