ERPCAを用いたレート制御方式の性能評価
— EFCIスイッチの定常状態解析 —

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あらまし レート制御方式は、その実現の容易性などから ATM 網において有効な輻輳制御方式であるとされている．その実現方式の 1 つとして EPRCA (Enhanced Proportional Rate Control Algorithm) が ATM フォーラムにおいて提案されている．本稿は、ERPCA で提案されている EFCI スイッチを対象とし、その性能を解析的に評価する．まず、EPRCA の解析モデルを提案し、流体一次近似法を用いて性能指標を導出する．性能指標としては、スイッチにおける最大待ち行列長およびスループットを用いる．さらに、数値例によって、伝播遅延時間やコネクション数が EPRCA の性能に与える影響を明らかにする．

和文キーワード ATM 網、レート制御方式、ERPCA、EFCI スイッチ、定常状態解析

Performance of Rate-Based Control Method Using ERPCA
– Steady State Analysis of EFCI Switch –

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Abstract Rate-based congestion control is effective and still simple for traffic management in ATM networks. As one of practical realization schemes, Enhanced Proportional Rate Control Algorithm (EPRCA) is recently proposed in ATM Forum. The main purpose of this paper is to analyze the performance of EFCI switch, which is an essential one suggested in EPRCA. First, we provide an analytic model for EPRCA with homogeneous traffic sources and a single bottleneck ATM link. Then, we obtain performance measures in terms of the maximum queue length at the switch and its throughput by utilizing the first order fluid approximation method. We provide suggestive equations for parameter tunings of EPRCA and show some numerical examples.

英文 key words ATM Network, Rate-Based Congestion Control, EPRCA, EFCI Switch, Steady State Analysis

1 Introduction

Two congestion control strategies have been proposed in ATM networks; an open-loop control and a closed-loop control [1]. In the former approach, each source end station (SES) negotiates its traffic parameters, such as peak rate and burst length, with the network at its connection setup. Therefore, there is a possibility that a connection may be rejected when the network is short of resources. On the other hand, once the connection is admitted, its agreed quality of service (QOS) is satisfied unless SES violates its negotiated parameters. This sort of congestion control methods would be suitable for CBR (constant bit rate) and VBR (variable bit rate) services, e.g., for voice and motion video.

However, the open-loop control becomes insufficient for data communications because each connection never emits cells exceeding its negotiated parameters even when there is unused capacity in the network. Furthermore, the data traffic is not likely to have a capability to predict their own bandwidth requirements at connection setup time. Those are reasons why the closed-loop rate control is promising for ABR (Available Bit Rate) service, which is mainly suitable for data communications in ATM networks, similarly to the existing packet switched networks [2]. Among several algorithms to implement such a control mechanism, a rate-based congestion control scheme is considered to be effective as a means of controlling connections' flows and fully utilizing network bandwidth [3]. The function of the rate-based control mechanism is that the cell transmission rate at SES is controlled by feedback information from the network. If some of the switches in the network becomes congested, SES receives congestion indication from the network and then decreases its cell transmission rate to avoid cell overflow at the congested switch. When congestion is relieved, the transmission rate is again increased to utilize network resources.

In ATM networks, such a mechanism can be realized as follows. First, each SES is informed of congestion from the network by using a congestion indicator (CI) bit in RM (Resource Management) cells, which are returned from destination end system (DES) or the congested switch (if it has such an ability). Next, a simplest solution to detect network congestion is to use the threshold values of queue length at the switch buffer. To establish the effective rate–based control, however, it is not an easy task to determine control parameters such as the threshold values.

In this paper, we evaluate the rate-based control scheme, which has been adopted as a standard traffic management mechanism by ATM Forum. While a lot of simulation studies have been contributed by researchers to ATM Forum, our main purpose in the current paper is to give analytic results for the standard mechanism. Regarding the analytic approaches for rate-based control schemes, Blot et al. showed the dynamical behavior by utilizing first-order fluid approximations in [4]. In their model, the switch is assumed to recognize congestion when an arrival rate of cells exceeds its service rate, i.e., the link bandwidth. On the other hand, we deal with a more realistic situation in which congestion of the switch is detected by its queue length, i.e., the number of cells queued at the switch buffer. The same model has been treated in [1] and analyzed using a similar analytic technique. In their paper, however, the method for notifying congestion from the switch to SES is not explicitly modelled. That is, the rate is increased linearly and decreased exponentially, and the time interval to update the increase/decrease rate is assumed to be fixed. However, this scheme has recently been found to be of problem in some situations [5].

Hence, an improved rate control algorithm called Enhanced Proportional Rate Control Algorithm (EPRCA) is recently proposed in [6], which is adopted by ATM Forum as a standard draft for the rate-based congestion control mechanism for ATM networks. In [6], they suggested three types of switches, EFCI bit setting switch (EFCI), Binary Enhanced Switch (BES), and Explicit Down Switch (EDS), which have different processing capabilities against congestion. The main purpose of this paper is to give analytic results for the latest EPRCA with EFCI switch. For other switches, we will report analytical results in the proceeding papers.

2 Analytic Model

We first describe a basic feature of EPRCA, which is based on a positive feedback mechanism. SES periodically sends an RM cell every N_{RM} data cells to check the congestion status of the network. The RM cell received at DES is returned to SES along the backward path if congestion does not occur in the network. The switch can notify its congestion occurrence to DES by marking an EFCI bit in the header of data cells. As presented in [1], the basic operation of the rate–based congestion control is that SES normally increases its allowable cell transmission rate, which is called ACR (Allowed Cell Rate), while it is decreased when the network falls into congestion. However, a notable feature of EPRCA is that SES always decreases ACR until SES receives the RM cell from DES. It can increase the rate only when the RM cell is received. If the RM cell is discarded at DES due to congestion indication, it results in that SES continues to decrease ACR. This control mechanism accomplishes a fast rate reduction at SES even if RM cells are lost at the switch due to congestion.

In EPRCA, three types of switch architectures are suggested in the form of pseudo codes with different functionalities [6]. The first one is an EFCI bit setting switch (EFCI), which is just same as the original PRCA [7] described in the above, and can be expected as a least expensive one. Since, in the EFCI switch, the congestion can be notified to DES by marking an EFCI bit in data cells, forward RM cells are not necessary. However, if at least one BES/EDS switch exists on the link, the forward RM cells should be sent by SES. From an analytical point of view, however, it is not a problem whether forward RM cells are explicitly sent by SES or not, and both cases of the EFCI switches can be treated in a unified manner as shown in the next section.

In this paper, an analytic model for EFCI switch is provided for a rather simple network model which consists of homogeneous traffic sources and a single bottleneck ATM link (Fig. 1). The number N_{VC} of VC's share it. We assume that these VC's behave identically, that is, all VC's have identical parameters, ICR, PCR, AIR and MDF (for these parameters, see [6]). The service rate of the switch,

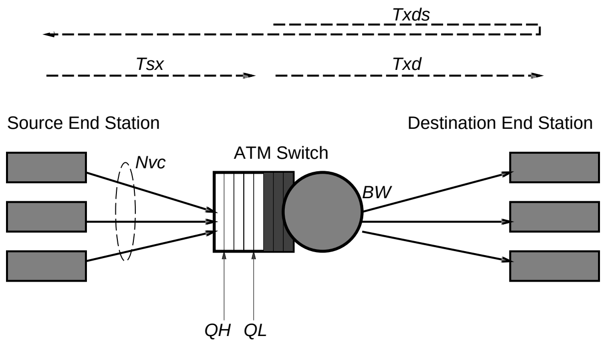

Figure 1: Analytic Model.

i.e., the bandwidth of the bottleneck link, is denoted by BW in cells/msec. Propagation delays from SES's to the switch and from the switch to DES's are represented by τ_{sx} and τ_{xd}, respectively. Propagation delays τ_{sx} and τ_{xd} may differ according to the network configuration (e.g., LAN, MAN, or WAN and the location of UNI). We define $\tau = 2(\tau_{sx} + \tau_{xd})$ as a round-trip propagation delay between SES and DES.We further introduce $\tau_{xds} = 2\tau_{xd} + \tau_{sx}$ which is a propagation delay of the congestion indication from the switch to SES via DES.

The congestion is detected by threshold values of queue length at the switch buffer. The EFCI switch has high and low threshold values denoted as Q_H and Q_L, respectively. When the queue length at the switch exceeds Q_H, the switch detects congestion and marks the EFCI bit in the header of data cells. When the queue length goes under Q_L, it is regarded that the congestion terminates. SES determines the rate increase/decrease by RM cells in the EPRCA algorithm. Since the receiving rate for RM cells is influenced by the congestion status of the switch, we require another analytical treatment different from the one presented in [1]. More precisely, the rate control is performed by RM cells returned from DES in EPRCA. Therefore, if the switch is congested, the returned rate of RM cells is bounded by $BW/(N_{VC}\,N_{RM})$. On the other hand, the rate is identical to its transmission rate when the switch is not congested.

We introduce $ACR(t)$ and $Q(t)$ which represent ACR for each SES and the queue length at the switch observed at time t. In the following sections, we will analyze evolutions of $ACR(t)$ and $Q(t)$ in steady state assuming that (1) the switch has infinite capacity of the buffer, and that (2) SES always has cells to transmit. Therefore, $ACR(t)$ is equivalent to the actual cell transmission rate. Last, we note that initial transient analyses of those switches will be reported in the future.

3 Dynamical Behavior of EFCI Switch

In this section, we focus on the EFCI switch to analyze a dynamical behavior of the allowed cell rate $ACR(t)$ and the queue length $Q(t)$ in steady state. In what follows, RM cells for forward direction is not considered. Then, the model is equivalent to the original PRCA [7]. However, in our analysis, forward RM cells can be easily taken into account by replacing BW with BW' where BW' is defined as

$$BW' = BW \frac{N_{RM}}{N_{RM} + 1}. \qquad (1)$$

3.1 Determination of $ACR(t)$

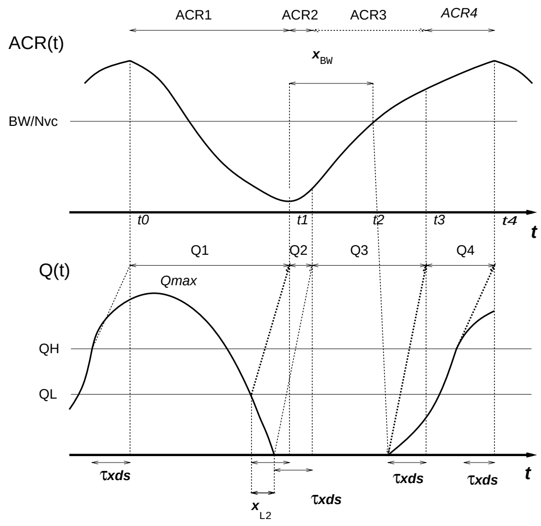

Figure 2: Pictorial View of $ACR(t)$ and $Q(t)$ in EFCI Switch.

Figure 2 shows a pictorial view of $ACR(t)$ and $Q(t)$ which have a periodicity in steady state. Let us set a starting point of one cycle at time when the congestion indication is received by SES. In the EFCI switch, it takes τ_{xds} to reach the congestion indication at SES after the queue length at the switch buffer reaches Q_H. We divide one cycle into four phases following behaviors of $ACR(t)$ and $Q(t)$ as in Fig. 2. For simplicity of presentation, we introduce $ACR_i(t)$ and $Q_i(t)$ as

$$\begin{aligned} ACR_i(t) &= ACR(t - t_{i-1}), \quad 0 \le t < t_i, \\ Q_i(t) &= Q(t - t_{i-1}), \quad 0 \le t < t_i, \end{aligned}$$

where t_i is defined as the time when phase i terminates. Further, the length of phase i is represented by

$$t_{i-1,i} = t_i - t_{i-1}.$$

We note here that more rigorous treatment is required for representing system behaviors dependent on system parameters as will be presented in the next subsection. For a meanwhile, however, we assume that the system behaves like Fig. 2.

$ACR_i(t)$ ($1 \le i \le 4$) is determined as follows.

Phase 1: $ACR_1(t)$
At time $t = 0$, Phase 1 starts with an initial value $ACR_1(0)$ by receiving the congestion indication. During this phase, the next cell emission time is determined as an inverse of the current $ACR_1(t)$, and the new rate is determined by subtracting ADR (= $ACR_1(0)/MD$) from $ACR_1(t)$. A differential equation for $ACR_1(t)$ is then obtained as

$$\frac{dACR_1(t)}{dt} = -\frac{ACR_1(0)}{MD} ACR_1(t),$$

which gives

$$ACR_1(t) = ACR_1(0) e^{-\frac{ACR_1(0)}{MD} t}.$$

Note that we do not take into account MCR (Minimum Sustained ACR) in the above equation, i.e., $MCR = 0$ is assumed.

Phase 2: $ACR_2(t)$

During this period, SES receives RM cells at a constant rate since the switch is fully utilized, i.e., $0 < Q(t - \tau_{xds})$. By letting the interarrival time of RM cells be x, we have

$$\frac{1}{x} = \frac{BW}{N_{VC}\, N_{RM}}.$$

Actually, ACR is increased only when the RM cell is received, and otherwise decreased continuously like Phase 1. However, we consider the values of ACR at the time when ACR is increased. Then, we derive an envelop of ACR in Phase 2 as follows;

$$\begin{aligned}\frac{dACR_2(t)}{dt} &= -\frac{ACR_2(t)ADR + N_{RM}(ADR + AIR)}{x} \\ &= -\frac{ACR_2(t)^2}{MD} + \frac{BW}{MD\, N_{VC}}ACR_2(t) + \frac{BW}{N_{VC}}AIR.\end{aligned}$$

By solving this equation for $ACR_2(t)$, we obtain

$$ACR_2(t) = \frac{a_1 e^{-a_1 t} + a_2 r e^{-a_2 t}}{c_1(e^{-a_1 t} + r e^{-a_2 t})}, \qquad (2)$$

where a_1 and a_2 are roots of the equation

$$a^2 + c_2 a + c_1 c_3 = 0,$$

and c_1, c_2 and c_3 are given by

$$c_1 = -\frac{1}{MD}; \quad c_2 = \frac{BW}{MD\, N_{VC}}; \quad c_3 = \frac{BW\, AIR}{N_{VC}}.$$

The initial transmission rate $ACR_2(0)$ determines r as

$$r = \frac{a_1 - c_1\, ACR_2(0)}{c_1\, ACR_2(0) - a_2}.$$

Phase 3: $ACR_3(t)$

This phase continues until τ_{xds} after when the queue length at the switch becomes 0. During this phase, the RM cell arrives at SES depending on its own rate $ACR_3(t-\tau)$. By letting the interarrival time of two RM cells be x, a differential equation for $ACR_3(t)$ should satisfy the following equation;

$$\begin{aligned}&\frac{dACR_3(t)}{dt} = \frac{N_{RM}\, AIR}{x} \\ &+\frac{1}{x}\left\{N_{RM}\frac{ACR_3(t)}{MD} + ACR_3(t)\{1 - e^{-\frac{ACR_3(t)}{MD}x}\}\right\}.\end{aligned}$$

However, it is difficult to solve the above equation, and we approximately use the following equation by neglecting the second term.

$$\frac{dACR_3(t)}{dt} = \frac{N_{RM}\, AIR}{x}.$$

Recalling that ACR is decreased during not receiving RM cells, the inter-arrival times of two successive RM cells, x, satisfies the following equation.

$$\int_0^x ACR_3(t-\tau)e^{-\frac{ACR_3(t-\tau)}{MD}y}dy = N_{RM}.$$

This leads to

$$x = \frac{MD \log(\frac{MD}{MD - N_{RM}})}{ACR_3(t-\tau)}.$$

Finally, $ACR_3(t)$ is solved as;

$$ACR_3(t) \cong ACR_3(0)e^{\beta t},$$

where β is given as a root of the equation

$$\beta = \frac{N_{RM}\, AIR}{MD\, \log(\frac{MD}{MD - N_{RM}})}e^{-\tau\beta}.$$

Phase 4: $ACR_4(t)$

Since the receiving rate of RM cells at SES is just same as in the case of Phase 2, $ACR_4(t)$ is given in an equivalent form to Eq.(2).

3.2 Evolution of $ACR(t)$ and $Q(t)$

In this subsection, we investigate the evolution of $ACR(t)$ and $Q(t)$. For this purpose, we should determine the initial values $ACR_i(0)$ and the length of each phase $t_{i,i+1}$. For given initial rates of $ACR_1(t)$ and $Q_1(t)$, $Q_1(t)$ is obtained as;

$$\begin{aligned}Q_1(t) &= Q_1(\tau_{xds}) \\ &\quad + \int_{x=\tau_{xds}}^{t}(N_{VC}\, ACR_1(x - \tau_{sx}) - BW)dx\end{aligned} \qquad (3)$$

The length of Phase 1, $t_{12}(= t_1)$ is given as

$$t_{12} = x_{L1} + \tau_{xds},$$

where x_{L1} is obtained by solving the equation $Q_1(x_{L1}) = Q_L$. In what follows, we will use convention $x_{L1} = Q_1^{-1}(Q_L)$ for brevity.

For Phase 2 and later phases, we need a careful treatment. First, let us introduce x_{L2} as

$$x_{L2} = Q_2^{-1}(0) - Q_2^{-1}(Q_L).$$

That is, x_{L2} is the time for the queue length to become 0 after it goes below Q_L. Further,

$$x_{BW} = ACR_2^{-1}(\frac{BW}{N_{VC}}) - t_1,$$

which defines the time when the aggregate ACR reaches BW. We must consider the following four cases depending on x_{L2}, x_{BW} and τ_{sx} (see Fig. 2 which corresponds to Case 1 in the below).

Case 1: $x_{L2} \le \tau$, $x_{L2} < x_{BW} + \tau_{sx}$
Case 2: $x_{L2} \le \tau$, $x_{L2} \ge x_{BW} + \tau_{sx}$
Case 3: $x_{L2} > \tau$, $x_{L2} < x_{BW} + \tau_{sx}$
Case 4: $x_{L2} > \tau$, $x_{L2} \ge x_{BW} + \tau_{sx}$

Due to lack of space, only Cases 1 and 4 are explained in the below. In Case 1, we have

$$\begin{aligned}t_2 &= t_1 + x_{L2} \\ Q(t) &= 0, \quad t_2 + \tau_{sx} < t \le t_3 + \tau_{sx}.\end{aligned}$$

In the above equation, t_3 is given by

$$t_3 = t_2 + x'_{BW} + \tau,$$

where x'_{BW} is the time when the aggregate ACR reaches BW, i.e.,

$$x'_{BW} = ACR_3^{-1}(\frac{BW}{N_{VC}}) - t_2.$$

Further, we have the following equation.

$$Q(t) = \begin{cases} 0, \quad t_2 + \tau_{sx} < t \leq t_2 + \tau_{sx} + x'_{BW} \\ \displaystyle\int_{t_2+\tau_{sx}+x'_{BW}}^{t} (N_{VC}\, ACR_3(x - \tau_{sx}) - BW)dx, \\ \quad t_2 + \tau_{sx} + x'_{BW} < t \leq t_3 + \tau_{sx} \end{cases}$$

Finally, we have the equations for phase 4 as

$$\begin{aligned} t_4 &= t_3 + t_{H4} + \tau_{xds} \\ Q(t) &= \int_{t_3+\tau_{sx}}^{t} (N_{VC}\, ACR_4(x - \tau_{sx}) - BW dx, \\ & \quad (t_3 + \tau_{sx} < t \leq t_4 + \tau_{sx}), \end{aligned}$$

where $t_{H4} = Q_4^{-1}(Q_H)$.

In Case 4, the queue length never reaches 0, that is, under-utilization does not occur. Thus, neither $ACR_2(t)$ nor $ACR_3(t)$ appear. We have

$$t_4 = Q_4^{-1}(Q_H) + \tau_{xds}.$$

$Q_4(t)$ is then obtained from eq.(3).

By setting

$$\begin{aligned} ACR_1(0) &= ACR_4(t_4), \\ Q_1(0) &= Q_4(t_4 + \tau_{xds}), \end{aligned}$$

and iteratively calculating the above equations, we can obtain the dynamical behavior of the EPRCA algorithm by the EFCI switch in steady state.

4 Parameter Tuning

In this subsection, two suggestive results are presented for parameter tuning; a maximum queue length in steady state and a condition that a link is never under-utilized. The former is important to determine the buffer size of the switch with cell-loss free. The latter condition is necessary to obtain high throughput.

4.1 Maximum Queue Length

To obtain a maximum queue length, we first obtain a maximum value of $ACR_4(t)$ by letting $t \to \infty$.

$$\begin{aligned} \lim_{t\to\infty} ACR_4(t) &= \left. \frac{a_1 e^{(a_2-a_1)t} + a_2 r}{c_1(e^{(a_2-a_1)t} + r)} \right|_{t\to\infty} \\ &= \frac{BW + \sqrt{BW^2 + 4N_{VC}\, MD\, BW\, AIR}}{2N_{VC}}. \end{aligned} \quad (4)$$

We should note here that $ACR_4(t)$ may terminate before reaching its maximum value dependent on system parameters. Nevertheless, it is important because we can obtain an upper bound of the maximum queue length from this equation as follows. Suppose now that SES receives congestion indication at time $t = 0$, and its ACR equals its maximum value, i.e., $ACR_1(0) = ACR_4(\infty)$. $Q_1(t)$ starts at time $t = \tau_{sx}$ with the initial value

$$\begin{aligned} Q(\tau_{sx}) &= Q_H + \int_0^{\tau_{xds}+\tau_{sx}} (N_{VC}\, ACR_4(\infty) - BW)dt \\ &= Q_H + (N_{VC}\, ACR_4(\infty) - BW)\tau. \end{aligned}$$

The queue length begins to decrease when the aggregate cell arrival rate at the switch is below the bandwidth BW at time t_{max}, which is given by

$$N_{VC}\, ACR_4(\infty) e^{-\frac{ACR_4(\infty)}{MD} t_{max}} = BW,$$

i.e.,

$$t_{max} = \frac{MD}{ACR_4(\infty)} \log \frac{N_{VC}\, ACR_4(\infty)}{BW}.$$

Then, using eq.(3), we have

$$\begin{aligned} Q_{max} &= Q_1(t_{max}) \\ &= Q_H + (N_{VC}\, ACR_4(\infty) - BW)\tau \\ & \quad + N_{VC} MD(1 - \frac{BW}{N_{VC}}) \\ & \quad - \frac{BW\, MD}{ACR_4(\infty)} \log \frac{N_{VC}\, ACR_4(\infty)}{BW}. \end{aligned}$$

where $ACR_4(\infty)$ has been given in eq.(4). From the above equation, we can observe that the number of VC's has a serious impact on the maximum queue length especially when the propagation delay between SES and DES is large.

4.2 Conditions of Avoiding Under-Utilization

As previously noted, a fully link usage is accomplished by fulfilling the following conditions, which corresponds to Case 4 in the previous subsection.

$$\begin{aligned} x_{L2} &> \tau, \\ x_{BW} + \tau_{sx} &< x_{L2}. \end{aligned}$$

5 Numerical Examples

In this subsection, we provide numerical examples for the EFCI switch. Threshold values Q_H and Q_L are identically set to 500, and the bandwidth of bottleneck link is set to 353.208 cells/msec assuming 150Mbps ATM link. For other control parameters, the values suggested in [6] are used throughout this paper unless other values are specified explicitly. Equation (1) is used for BW.

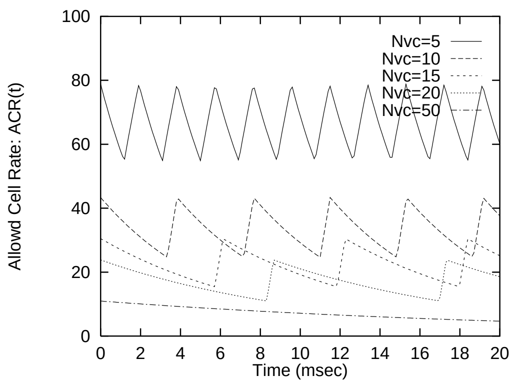

Figure 3: Effect of N_{VC} on $ACR(t)$ in EFCI Switch (τ = 0.02msec).

Figures 3 and 4 show the effect of the number of VC's, N_{VC}, on $ACR(t)$ and $Q(t)$, respectively. Here, we choose the propagation delay $\tau_{sx} = \tau_{xd} = 0.005$ msec (2km between SES and DES) as a typical parameter for a LAN environment. In the figures, it is easily observed that as N_{VC} is

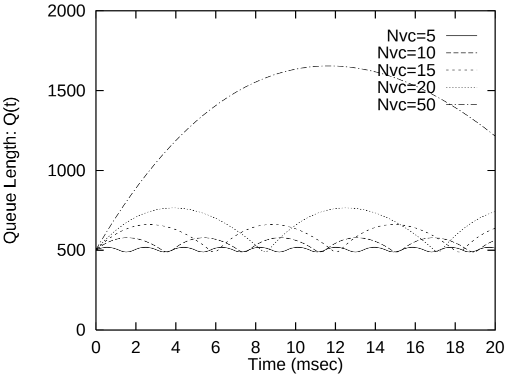

Figure 4: Effect of N_{VC} on $Q(t)$ in EFCI Switch (τ = 0.02msec).

increased, the maximum queue length becomes large and the cycle is lengthened. However, the maximum queue length can be limited to acceptable values when the propagation delay is small.

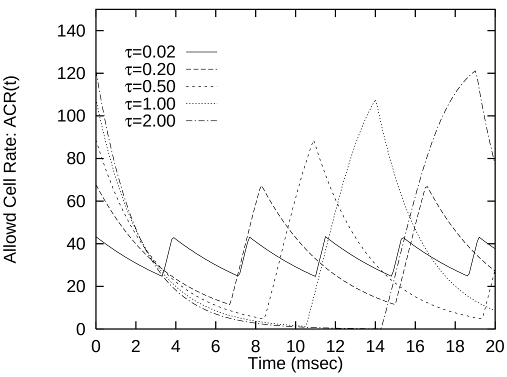

Figure 5: Effect of Propagation Delay on $ACR(t)$ in EFCI Switch (N_{VC} = 10).

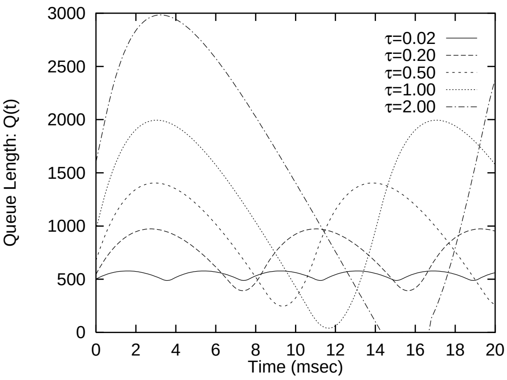

Figure 6: Effect of Propagation Delay on $Q(t)$ in EFCI Switch (N_{VC} = 10).

$ACR(t)$ and $Q(t)$ by different values of the propagation delays are compared in Figs. 5 and 6 for N_{VC} = 10. As can be observed in them, the larger τ causes slower congestion notification, and it results in increase of the maximum queue length. Further, the under-utilization appears when the propagation delays τ is beyond 2.0 msec (400km) in the figures. Therefore, we may conclude that the EFCI switch should be used in rather small networks from these numerical results.

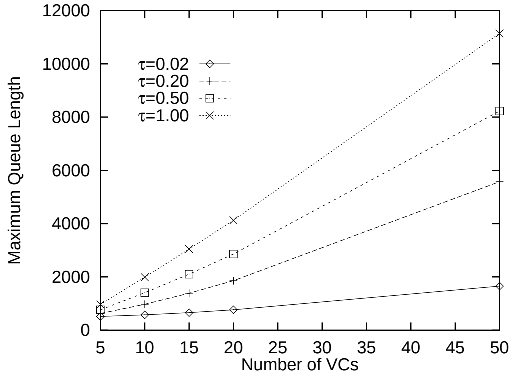

Figure 7: Effect of N_{VC} on Maximum Queue Length in EFCI Switch.

Another problem of the EFCI switch can be found by letting N_{VC} be large. As shown in Fig. 7, the maximum queue length grows as N_{VC} becomes large even with small values of propagation delays.

6 Conclusion

One problem of the rate-based congestion control exists in the initial transient state. When a number of SES's start cell transmission simultaneously, the queue length grows very large. We have finished its analysis and plan to report in the future.

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