On the Impact of Time Scales on Feedback Based Rate Control *

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Abstract

Since delay tolerable, the ABR applications can be allocated the remaining resources after CBR (Constant Bit Rate) and VBR (Variable Bit Rate) applications have been accommodated. To avoid excessive losses, the transmission rates of the ABR applications should be modulated by the amount of remaining resources. That is, the ABR rates should be controlled through a feedback based rate control mechanism. In this paper, a network link shared by remote ABR and VBR applications is considered and the impact of various system time scales on the effectiveness of the feedback based flow control scheme is investigated. These time scales are expressed in terms of the network transmission speed, the minimum tolerable ABR rate and the rate of change of the VBR source rate. While the negative impact of a decreased network time scale on the effectiveness of this control scheme is well known, the impact of the ABR and VBR time scales has not been investigated in the past. It turns out that for a given network time scale, the induced cell losses can be significantly reduced for increased ABR and/or VBR time scales and thus, the latter time scales should be taken into consideration when evaluating the effectiveness of an adaptive feedback based rate control mechanism.

1 Introduction

As indicated by the ATM Forum, the ABR service class allows non-real time, delay tolerant traffic sources to share the available bandwidth not utilized by the VBR and CBR service classes. Due to the fluctuations in the bandwidth usage of VBR/CBR sources, the ABR source rates should be controlled through a feedback based rate control mechanism.

When the ABR source receives the feedback generated by the receiving end or a network node, it adjusts its rate to the current available bandwidth according to the traffic control policy in effect [1], [2], [3]. Several traffic control policies have been proposed for the rate based flow control such as the Explicit Forward Congestion Indication (EFCI) [4], Backward Explicit Congestion Notification (BECN) [5], Proportional Rate Control Algorithm (PRCA) [6], Explicit Rate Feedback (ERF) [7] and Enhanced Proportional Rate Control Algorithm (EPRCA) [8].

Under the feedback based rate control policy used in this paper, a feedback carrying information about the available bandwidth is transmitted to the ABR source, every time that the available bandwidth for the ABR source changes. If the propagation delay between the ABR source and the network access node is non-negligible, then the ABR source will transmit at a rate based on the most recent level of available bandwidth until it receives the feedback. For example, if the propagation delay between the ABR source and the network access node is T_d and the available bandwidth changes at time t, the ABR source will learn about the change in bandwidth availability at time $t + T_d$. The adjusted rate from the ABR source will reach the network access node at time $t + 2T_d$, assuming that the backward and forward propagation delays are equal. Therefore, for a roundtrip propagation delay of $2T_d$ a bandwidth mismatch will occur. During a bandwidth mismatch the capacity of the link will either be exceeded (overutilization) or will be used inefficiently (underutilization). Since ABR cell losses occur during overutilization periods of bandwidth mismatch cycles and the magnitude of bandwidth mismatch is proportional to the propagation delay, the effectiveness of a rate based flow control scheme decreases with increased propagation delay. The impact of increased propagation delay on the flow control schemes has been studied in the past [9], [10], [11], [12]. Besides the physical distance other system parameters namely the network, ABR and VBR time scales impact considerably on the effectiveness of the flow control schemes. In this paper, the impact of these system parameters on the effectiveness of the feedback based flow control is studied.

The network time scale is defined as the transmission time of a cell and it decreases as the network speed increases. Therefore, decreased network time scale corresponds to increased propagation delay. The VBR time scale is defined to be a measure of the rate of change of the VBR source rate and the ABR time scale is defined as the minimum distance among consecutive blocks of consecutive cells generated by the ABR source.

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The remainder of the paper is organized as follows. In section 2, the system considered in order to evaluate the impact of time scales is described. In section 3, a suitable Markov Chain for the system is formulated. Some numerical results are presented in section 4 and the paper ends with some conclusions presented in section 5.

2 Description of the System

In order to simplify the analysis and facilitate the understanding of the impact of the various time scales, a system with one VBR source and one ABR source is considered where each of these sources can deliver at most one cell per slot. The propagation delay between the ABR source and the network access node is assumed to be non-negligible. The ABR source rates are calculated at the network access node by using the current VBR source rate. The calculated transmission rates are fed back to the ABR source when a VBR source rate change occurs. Thus, the network access node is supposed to be able to detect a change in the VBR source rate. This may be possible through an explicit indication the VBR source carries by certain cells or an estimation mechanism implemented at the network access node.

The network access node is assumed to have a finite buffer of capacity C for the temporary storage of the ABR and VBR cells and the cell departures are assumed to occur before cell arrivals occurring over the same slot.

2.1 The ABR Traffic Source

As indicated previously, the ABR source rate is calculated based on the current VBR source rate. If the current VBR source rate is equal to r_v, then the maximum allowable ABR source rate will be equal to $1-r_v-\epsilon$. Here, ϵ is an arbitrarily small positive number to ensure that the maximum system load is below 1 (stability condition). It is assumed that the ABR source can always transmit with its maximum allowable rate (heavy traffic assumption). With this assumption, the worst case performance for the ABR source will be derived.

In order to satisfy its maximum allowable rate, the ABR source can transmit one cell per T_k slots where $T_k = \lceil \frac{1}{1-r_v-\epsilon} \rceil$. In this paper, T_k will be referred to as the *fundamental ABR subframe*. Note that, the same rate can also be achieved, if the ABR source transmits a batch with B_k cells per subframe of length $B_k T_k$ (*B_k-order subframe*).

The ABR time scale is the length of a B_k-order subframe ($B_k T_k$). Although the ABR time scale will be different under different order subframe transmission schemes, the same rate will be maintained. Figure 1 shows examples of transmission employing fundamental or higher-order subframes. Note that, for a given subframe, the ABR cells are transmitted only for the first B_k slots. In the rest of the paper, a fixed batch size (B_k) will be chosen for all possible ABR source rates and subframes. Thus, a static ABR time scale approach will be considered.

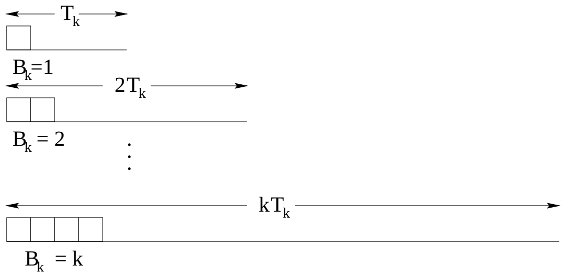

Figure 1: The ABR traffic subframes for a transmission rate of $1/T_k$

2.2 The VBR Traffic Source

Although the activity level of the VBR traffic source is not controllable and can change in principle at any slot, a change in the rate requires some time period to be manifested. In this paper, it will be assumed that such changes occur only at subframe boundaries for analysis tractability.

Let $\{S_k\}_{k\geq 1}$ denote a 2-state underlying Markov chain with state space $\overline{S} = \{0,1\}$. $\{S_k\}_{k\geq 1}$ will be used to describe the VBR source activity. Let $r_v(s_k)$ denote the rate of the VBR source at the k^{th} subframe, $s_k \in S$. Without loss of generality, it is assumed that $r_v(1) > r_v(0)$. The VBR cell arrival process is modeled as a Markov Modulated Bernoulli process. The probability of transmitting 1(0) cell in a slot of the k^{th} subframe is $r_v(s_k)(1-r_v(s_k))$.

Let $p_s(s_k)$ denote the probability that S_k changes at the end of the k^{th} subframe at the beginning of which it was in state s_k. $p_s(s_k)$ will reflect the average time over which VBR applications maintain a constant rate (or VBR time scale). If $p_s(0) = p_s(1) = p_s$, then the VBR time scale will be equal to $1/p_s$; otherwise, two time scales may be defined.

3 Analysis of the System

In order to determine the arrival process at the network access node over the k^{th} subframe, the network access node needs to know the current VBR source rate ($r_v(s_k)$) and whether the current ABR rate is based on the most recent feedback sent by the node or not (that is, whether the feedback's impact is not pending or pending, respectively). Therefore, let J_k be an indicator function which assumes the value of 1, if the impact of a feedback carrying a VBR source rate change is pending. If the impact of the feedback is not pending, J_k is equal to 0. The fundamental ABR subframe (thus, the ABR source rate) will be completely determined by (S_k, J_k) and it is given by $T_k = \lceil \frac{1}{1-r_v(s_k \oplus j_k)-\epsilon} \rceil$ where $\oplus$ denotes the modulo 2 addition.

A Markov chain can be constructed to describe the evolution of the system under fixed and non-zero roundtrip propagation delays. Here, a simplifying assumption is made by assuming that the roundtrip propagation delay is random and geometrically distributed with mean $\frac{1}{p_f}$, measured in terms of subframes.

Although it is possible that more than one feedback be pending at any time, at most one pending feedback will be considered in order to simplify the analysis. This approximation holds true if $max_{s_k}\{p_s(s_k)\} \ll p_f$; that is, if the VBR source time scale is much larger than the propagation delay. This is expected to be the case in order for a feedback based rate control scheme to be reasonably effective.

With these assumptions, it is easy to establish that the stochastic process $\{S_k, J_k, Q_k\}$ embedded at subframe boundaries is a Markov chain with state space $\{(s_k, j_k, q_k) : 0 \leq s_k \leq 1, 0 \leq j_k \leq 1, 0 \leq q_k \leq C\}$. Here, Q_k is a random variable describing the buffer occupancy at the beginning of the k^{th} subframe.

Let $P(s_k j_k q_k; s_{k+1} j_{k+1} q_{k+1})$ be the transition probability that the Markov chain $\{S_k, J_k, Q_k\}$ moves from state (s_k, j_k, q_k) to state $(s_{k+1}, j_{k+1}, q_{k+1})$. It is clear that (s_{k+1}, j_{k+1}) is independent from the queue occupancy (q_k) and thus $P(s_k j_k q_k; s_{k+1} j_{k+1} q_{k+1})$ can be expressed as follows.

$$P(s_k j_k q_k; s_{k+1} j_{k+1} q_{k+1}) = P(s_k j_k; s_{k+1} j_{k+1}) P(q_{k+1}/s_k j_k q_k)$$

where $P(s_k j_k; s_{k+1} j_{k+1})$ is the probability of passing from (s_k, j_k) to (s_{k+1}, j_{k+1}) and $P(q_{k+1}/s_k j_k q_k)$ is the probability of being at queue occupancy q_{k+1} at the beginning of the next subframe given the current subframe parameters. The derivation of these probabilities are shown in detail in [12].

After the calculation of the transition probabilities, the steady state probability distribution $\Pi(s_k, j_k, q_k)$ can be derived by using the following matrix equations, $\Pi = \Pi P$ and $\sum_i \Pi_i = 1$ where P is the state transition matrix each of whose elements show the transition probabilities $P(s_k j_k q_k; s_{k+1} j_{k+1} q_{k+1})$.

In order to study the impact of the network and source time scales, the ABR cell loss probability will be derived since the only negotiated QoS parameter for the ABR service class is the Cell Loss Ratio (CLR). The ABR cell loss probability can be calculated using the average number of cells lost and arrived in a subframe at the beginning of which $\{S_k, J_k, Q_k\}_{k\geq 1}$ is in state (s_k, j_k, q_k) and taking the expectation over all possible states.

Let, LP denote the ABR cell loss probability, and let $\overline{L}(s_k, j_k, q_k)$ and $\overline{M}(s_k, j_k, q_k)$ denote the number of cells lost and arrived in a subframe at the beginning of which $\{S_k, J_k, Q_k\}_{k\geq 1}$ in state (s_k, j_k, q_k) respectively. Then,

$$LP = E\{\frac{\overline{L}(s_k, j_k, q_k)}{\overline{M}(s_k, j_k, q_k)}\}$$

Let $I(s_k, j_k, q_k; i)$ $(R(s_k, j_k, q_k; i))$ denote the number of cells lost (arrived) at the i^{th} slot of the k^{th} subframe in state (s_k, j_k, q_k); $1 \leq i \leq B_k T_k$. Clearly, $R(s_k, j_k, q_k; i)$ does not depend on the queue occupancy and is only a function of s_k, j_k and i. Thus,

$$R(s_k, j_k, q_k; i) = R(s_k, j_k; i) = \begin{cases} A(s_k) & \text{if } i > B_k \\ A(s_k) + 1 & \text{if } i \leq B_k \end{cases}$$

where $A(s_k)$ denotes the number of VBR cell arrivals in a slot when the current VBR state is s_k.

The number of lost cells in a slot can be found by considering the number of arrivals in the slot, the buffer occupancy in the previous slot and the buffer capacity C. Therefore,

$$I(s_k, j_k, q_k; i) = \begin{cases} m & \text{if } R(s_k, j_k; i) = C + 1 - q_{k,i-1} + m \\ 0 & \text{otherwise} \end{cases}$$

where $q_{k,i-1}$ denotes the queue occupancy at the $i - 1^{th}$ slot of the k^{th} subframe.

Clearly, the number of cell arrivals over a subframe at the beginning of which the system Markov Process $\{S_k, J_k, Q_k\}_{k\geq 1}$ is in state (s_k, j_k, q_k) is the summation of $R(s_k, j_k; i)$ over all slots i. Thus, the average number of cell arrivals in a subframe at the beginning of which $\{S_k, J_k, Q_k\}_{k\geq 1}$ is in state (s_k, j_k, q_k) can be expressed as,

$$\begin{aligned} \overline{M}(s_k, j_k, q_k) &= \sum_{i=1}^{B_k T_k} E\{R(s_k, j_k; i)\} \\ &= B_k + B_k T_k r_v(s_k). \end{aligned}$$

The total number of cells lost over the entire subframe is equal to the summation of $I(s_k, j_k, q_k; i)$ for all i slots of the subframe. Thus, the following equation is obtained for $\overline{L}(s_k, j_k, q_k)$.

$$\overline{L}(s_k, j_k, q_k) = \sum_{i=1}^{B_k T_k} E\{I(s_k, j_k, q_k; i)\}$$

After some manipulations, $\overline{L}(s_k, j_k, q_k)$ can be shown to be equal to,

$$\begin{aligned} \overline{L}(s_k, j_k, q_k) &= \sum_{i=1}^{B_k} \sum_{l=0}^{C} \sum_{m=0}^{l-C+1} m P\{A(s_k) = C - l + m/q_k, s_k, j_k\} \\ &\times P\{q_{k,i-1} = l/q_{k,0} = q_k\} \end{aligned}$$

Combining $\overline{L}(s_k, j_k, q_k)$ and $\overline{M}(s_k, j_k, q_k)$ the ABR cell loss probability can be expressed as follows.

$$\begin{aligned} LP &= \sum_{s_k=0}^{1} \sum_{j_k=0}^{1} \sum_{q_k=0}^{C} \frac{\Pi(s_k, j_k, q_k)}{B_k + r_v(s_k) B_k T_k} \\ &\times \sum_{i=1}^{B_k} \sum_{l=0}^{C} \sum_{m=0}^{l-C+1} m P\{A(s_k) = C - l + m/q_k, s_k, j_k\} \\ &\times P\{q_{k,i-1} = l/q_{k,0} = q_k\} \end{aligned}$$

4 Numerical Results

In this section, some numerical results are presented to illustrate the impact of the network and source time scales on the performance of an ABR source which is located away from the network access node.

Figure 2 illustrates the ABR cell loss probability as a function of p_f for $p_s(0) = p_s(1) = p_s = 0.005, 0.001, 0.0005$ and

0.0001. For this plot, results are derived for VBR source rates $r_v(1) = 0.8$ and $r_v(0) = 0.4$ cells/slot and a buffer with capacity $C = 40$. As the propagation delay decreases (p_f increases), the amount of time that it takes for the ABR source to respond to the feedbacks generated at the network access node decreases. As a consequence, the amount of bandwidth mismatch (thus the overutilization periods) decreases, causing a decrease in the ABR cell loss probability. In addition to the propagation delay, the VBR time scale ($1/p_s$) also has a considerable effect on the ABR cell loss probability. When the VBR time scale decreases (p_s increases), VBR source rate changes occur more frequently. By this way, more bandwidth mismatch cycles are initiated resulting in more ABR cell losses. Note that $p_s \ll p_f$ in order for the assumption of no multiple pending feedbacks to be reasonably accurate.

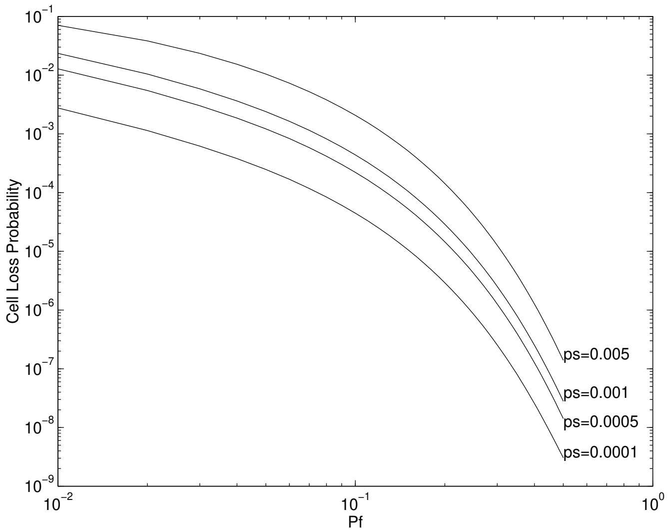

Figure 2: ABR cell loss probability vs. p_f for various p_s

Figures 3 and 4, illustrate the ABR cell loss probability as a function of batch size B_k for $C = 10, 15, 20, 25$ and 30. The distance between the ABR source and the network access node is assumed to be 20000 and 200 slots for Figure 3 and Figure 4 respectively. Since the VBR source rates are assumed to be $r_v(1) = 0.8$ and $r_v(0) = 0.4$, the fundamental subframe lengths are 2 and 6 slots. Thus, a B_k-order subframe (ABR time scale) has lengths of $2B_k$ and $6B_k$ slots. For a fixed value of C, it can be observed that, the ABR cell loss probability initially decreases as B_k (the ABR time scale) increases. This behavior is reversed when B_k exceeds a threshold. Thus, for a given C, there is an optimal B_k (or ABR time scale) that minimizes the induced ABR cell losses. The optimal B_k also depends on the propagation delay. For example, the optimal B_k for $C = 15$ is equal to 8 in Figure 3 while it is equal to 2 in Figure 4. This trend may be attributed to the decreasing positive impact of a large ABR time scale for a decreased propagation delay.

In addition to the network and source time scales, the VBR source rates also have considerable effects on the performance. Figure 5 shows the effects of the VBR source rates on the ABR cell loss probability. For a fair comparison, the mean VBR arrival rate is kept constant for the cases considered. The VBR source rates for the first case are $r_v(1) = 0.9$ and $r_v(0) = 0.3$ cells/slot, while for the second case $r_v(1) = 0.8$ and $r_v(0) = 0.4$ cells/slot. It can be clearly observed that the loss performance improves as the difference between the two rates decreases. For the case with $r_v(0) = 0.3$ and $r_v(1) = 0.9$, the fundamental subframe lengths are 2 and 11 slots. These subframe lengths correspond to ABR source rates of 0.5 and 0.091 respectively. Therefore, during a bandwidth mismatch initiated by a VBR source rate change, the total rate on the link can increase up to 1.4 causing potentially high losses. However, when VBR rates are $r_v(0) = 0.4$ and $r_v(1) = 0.8$, the corresponding ABR rates will be 0.5 and 0.167. During a bandwidth mismatch, the total rate on the link will be at most 1.3. Compared to 1.4, the overutilization in this case is decreased. Therefore, a decrease in the ABR loss probabilities occurs.

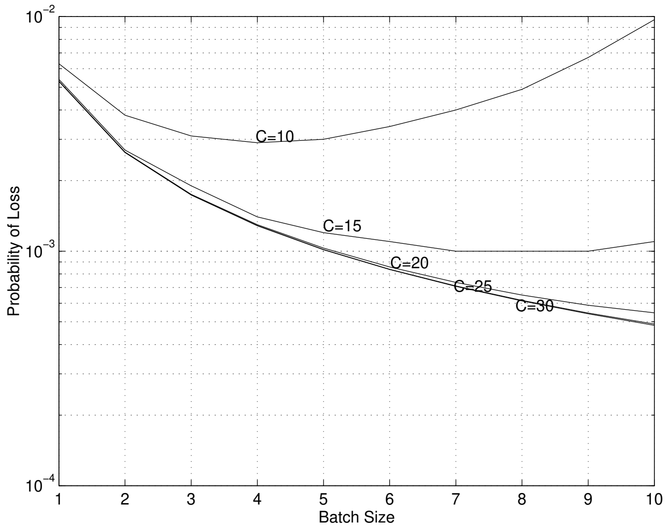

Figure 3: ABR cell loss probability vs. B_k for various values of C for an average distance of 20000 slots

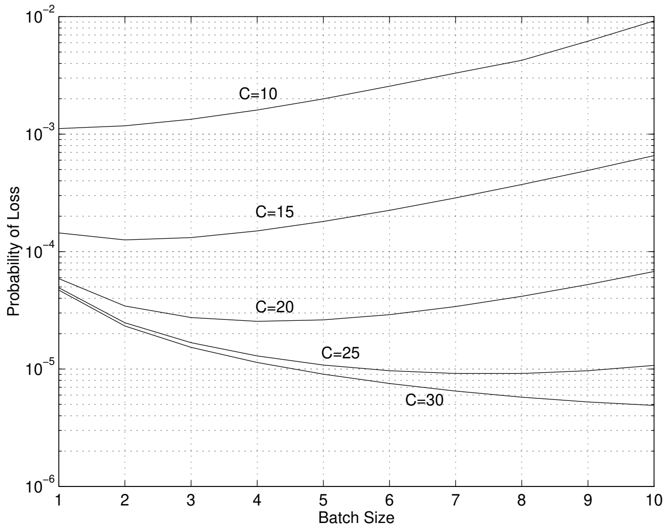

Figure 4: ABR cell loss probability vs. B_k for various values of C for an average distance of 200 slots

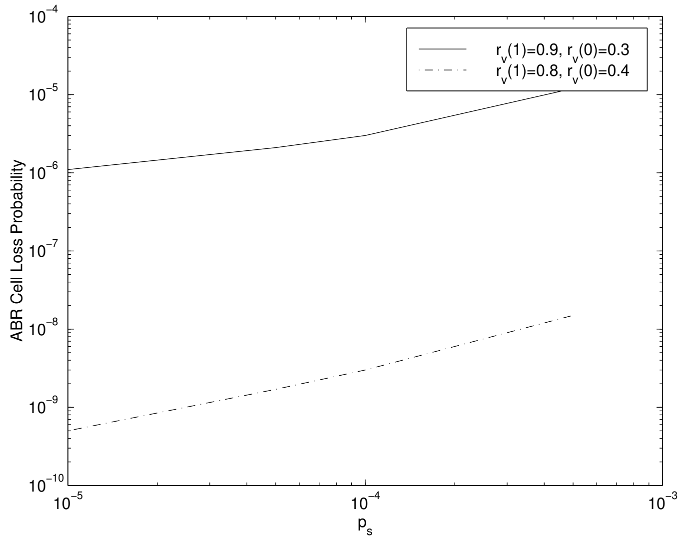

Figure 5: ABR cell loss probability vs. p_s for various VBR arrival rates

5 Conclusions

In this paper, the impact of network and source time scales on the performance of ABR applications is studied. The network time scale is defined as the transmission time of a cell. The VBR time scale is defined in terms of the rate of change of the VBR source rate. The ABR time scale is defined as the minimum distance between consecutive blocks of consecutive cells generated by the ABR source. In order to evaluate the impact of these time scales, a system with one ABR and one VBR source is considered.

While the impact of the network time scale has been considered in detail in the past, that of other relevant time scales has not been investigated. The main contribution of this paper is the study of the impact of the VBR and ABR time scales on feedback based flow control.

The increased VBR time scale has a positive impact on the ABR loss performance. This is due to the fact that, less frequent VBR rate changes (or bandwidth mismatch cycles) occur when the VBR time scale increases, resulting in reduced ABR cell losses. Increasing the ABR time scale (or the batch size B_k), initially decreases the loss probability. But, after the batch size exceeds a threshold, the situation is reversed. The optimal batch size -defined to be the one corresponding to this threshold- increases with the buffer capacity, as the capability of absorbing larger batches by the buffer increases with increased buffer space. For large propagation distances, the optimal batch size is large. As the propagation distance decreases, the optimal batch size decreases as well. This may be due to the reduced positive impact of the ABR time scale for decreased propagation delay.

The major conclusion of this work is that in addition to the network time scale, the ABR and VBR time scales may impact substantially a feedback based flow control as well. Thus the impact of *all system time scales* should be considered in order to accurately evaluate the effectiveness of a flow control algorithm.

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