A NONLINEAR ABR FLOW CONTROL WITH FEED-FORWARD COMPENSATION FOR ATM NETWORKS

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Abstract: In this paper the problem of flow control in fast, connection oriented communication networks supporting traffic generated by multiple sources is considered. The network is modelled as a dynamic system with different delay times. A nonlinear strategy governing the behaviour of the sources is proposed. The strategy combines Smith principle and feed-forward compensation with the conventional relay type controller. The strategy guarantees no cell loss and full bottleneck link utilisation in the controlled network. Furthermore, the feed-forward compensation helps to achieve better quality of service in the controlled network.

Keywords: Congestion control, ATM networks, time delay systems, Smith principle.

1. INTRODUCTION

The asynchronous transfer mode (ATM) technology plays the crucial role in the design and implementation of broadband integrated services digital networks (B-ISDN). This technology is well suited for video, voice and data transmission through the high speed telecommunication networks. The ATM networks are connection oriented, i.e. a virtual circuit (VC) is established between each source and destination for the connection lifetime. After setting up a VC, data is sent in relatively short, fixed size packets, usually called cells. Each data cell is 53 bytes long and consists of 48 bytes of transmitted information and a 5 byte long header. The small fixed cell size reduces delay variation which could be particularly harmful for multimedia traffic.

In order to properly serve diverse needs of different users the ATM Forum defines five service categories. Constant bit rate (CBR) service category provides the bandwidth which is always available to its user. This category is used by real time service. Typical examples are television, telephone, etc. Variable bit rate (VBR) is designed for both real and non-real time applications. An example of such real time application is video conferencing, and multimedia email is an example of non-real time VBR service. Available bit rate (ABR) is a service category whose rate depends on the available bandwidth. Users should adjust their flow rates according to the feedback information received from the network. Electronic mail is an example of this service category. Unspecified bit rate (UBR) category is used to send data on the first in first out (FIFO) basis, using the capacity not consumed by other services. No initial commitment is made to a UBR source and no feedback concerning congestion is provided. This type of service can be used for background file transfer. Guaranteed frame rate (GFR) is a service intended for non-real time applications with little rate requirements. No feedback control protocol is applied in this service category. An example of this service is frame relay interworking.

As stated above ABR is the only service category using feedback information to control source flow rate. Therefore, ABR control is particularly important for congestion avoidance and full resource utilisation. This problem, i.e. the ABR flow control in multi-source ATM networks is considered further in the paper.

The difficulty of the ABR flow control is mainly caused by long propagation delays in the network. If congestion occurs at a specific node, information about this condition must be conveyed to all the sources transmitting data cells through the node. Transferring this information involves feedback propagation delays. After this information has been received by the particular source, it can be used to adjust the flow rate of this source. However, the adjusted flow rate will start to affect the congested node only after forward propagation delay.

ABR flow rate control has recently been studied by several researchers (Izmailov, 1995; Chong, *et al.* 1998; Mascolo, 1999; Lengliz and Kamoun, 2000; Mascolo, 2000; Imer, *et al.* 2001; Gómez-Stern, *et al.*, 2002; Jagannathan and Talluri, 2002; Laberteaux, *et al.*, 2002; Quet, *et al.*, 2002; Bartoszewicz and Karbowanczyk, 2003; Mascolo, 2003; Bartoszewicz and Molik, 2004). A valuable survey of earlier congestion control mechanisms is given by Jain (1996). Furthermore, Izmailov (1995) considered a single connection controlled by a linear regulator whose output signal is generated according to the several states of the buffer measured at different time instants. Asymptotic stability, nonoscillatory system behaviour and locally optimal rate of convergence have been proved. Chong, *et. al*. (1998) proposed and thoroughly studied the performance of a simple queue length based flow control algorithm with dynamic queue threshold adjustment. Lengliz and Kamoun (2000) introduced a proportional plus derivative controller which is computationally efficient and can be easily implemented in ATM networks. Imer *et. al*. (2001) gave a brief, excellent tutorial exposition of the ABR control problem and presented new stochastic and deterministic control algorithms. Another interesting approach to the problem of flow rate control in communication networks has been proposed by Quet, *et al*. In the recent paper (Quet, *et al*., 2002) the authors considered a single bottleneck multi-source ATM network and applied minimisation of an H-infinity norm to the design of a flow rate controller. The proposed controller guarantees stability robustness to uncertain and time-varying propagation delays in various channels. Adaptive control strategies for ABR flow regulation have been proposed by Laberteaux and Rohrs (2002). Their strategies reduce convergence time and improve queue length management. Also a neural network controller for ABR service in ATM networks has recently been proposed. Jagannathan and Talluri (2002) showed that their neural network controller can guarantee stability of the closed loop system and the desired quality of service (QoS).

Due to the significant propagation delays which are critical for the closed loop performance, several researchers applied the Smith principle to control ABR flow in communication networks (Mascolo, 1999; Mascolo, 2000; Gómez-Stern, *et al*., 2002; Bartoszewicz and Karbowanczyk, 2003; Mascolo, 2003; Bartoszewicz and Molik, 2004). Mascolo (1999) considered the single connection congestion control problem in a general packet switching network. He used the deterministic fluid model approximation of packet flow and applied transfer functions to describe the network dynamics. The designed continuous time controller was applied to the ABR traffic control in ATM network and compared with ERICA standard. Furthermore, Mascolo showed that Transmission Control Protocol / Internet Protocol (TCP/IP) implements a Smith predictor to control network congestion. In the next paper (Mascolo, 2000) the same author applied the Smith principle to the network supporting multiple ABR connections with different propagation delays. The proposed control algorithm guarantees no cell loss, full and fair network utilisation, and ensures exponential convergence of queue levels to stationary values without oscillations or overshoots. Gomez-Stern, *et al*. (2002) further studied the ABR flow control using Smith principle. They proposed a continuous time proportional-integral (PI) controller which helps to reduce the average queue level and its sensitivity to the available bandwidth. Saturation issues in the system were handled using anti-wind up techniques. On the other hand, in the papers (Bartoszewicz and Karbowanczyk, 2003; Bartoszewicz and Molik, 2004) linear, discrete-time flow control strategies for the ABR service in ATM networks have been proposed. The strategies combine Smith principle with the discrete time proportional controllers. In the recent paper by Mascolo (2003) the idea of feed-forward compensation of time varying bandwidth effect has been introduced.

In this paper the ABR flow control in ATM networks is considered. Our approach is similar to that introduced in the papers (Mascolo, 1999; Mascolo, 2000; Gómez-Stern, *et al*., 2002; Bartoszewicz and Karbowanczyk, 2003; Bartoszewicz and Molik, 2004), however as opposed to those papers we propose a nonlinear control strategy with feed-forward compensation. The strategy combines Smith principle with the conventional relay type (i.e. continuous with respect to time and discontinuous with respect to its output signal) controller. The strategy guarantees full bottleneck node link utilisation and no cell loss in the network. Furthermore, if the proposed strategy is applied, then the steady-state bottleneck queue length does not depend on the available bandwidth. This property implies favourable quality of service in the controlled network. Since transmission rates generated by the proposed strategy are nonnegative and limited, it can be directly implemented in the network environment.

The remainder of this paper is organised as follows. The model of the network used throughout the paper is introduced in section 2. Then the nonlinear ABR flow control algorithm and the properties of the system are presented in section 3. Finally, Section 4 comprises conclusions of the paper.

2. NETWORK MODEL

The network considered in this paper consists of data sources, nodes and destinations – all of them interconnected via bi-directional links. Each node of the network (i.e. switch) maintains one queue per output port. When a new data cell arrives at an input port of the node, it is directed to the appropriate output buffer, stored and forwarded to the next node on the first in first out (FIFO) basis. Similarly as in the papers (Chong, *et al.*, 1998; Lengliz and Kamoun, 2000; Mascolo, 2000; Gómez-Stern, *et al.*, 2002; Jagannathan and Talluri, 2002; Laberteaux, *et al.*, 2002; Quet, *et al.*, 2002; Bartoszewicz and Molik, 2004) the case of a single bottleneck link shared by n sources is considered. Our purpose is to design the ABR flow controller, to be implemented at the node, which will assure full bottleneck link utilisation, no buffer overflow and reduced sensitivity of the steady state queue length with respect to the available bandwidth.

The rate of cell outflow from the bottleneck buffer depends on the available bandwidth modelled as an a'priori unknown, bounded function of time $d(t)$ where

$$0 \le d(t) \le d_{max} \tag{1}$$

This is motivated by the fact that the ABR service dynamically uses the bandwidth temporarily left not consumed by rt-VBR and nrt-VBR which typically support unpredictable traffic.

The sources send data cells (at the rate determined by the controller) and resource management (RM) cells. The RM cells are processed by the nodes on the priority basis, i.e. they are not queued but sent to the next node without delay. These cells carry information about the network conditions. After reaching the destination they are immediately sent back to the source, along the same path they arrived. The information carried by the RM cells is used to adjust the source rates.

Further in this paper t denotes time and RTT_j represents the round trip time of the j-th (j = 1, 2, ..., n) virtual circuit contributing to the bottleneck queue under control. This time is equal to the sum of forward and backward propagation delays denoted as T_{fj} and T_{bj} respectively

$$RTT_j = T_{fj} + T_{bj} \tag{2}$$

Furthermore, $x(t)$ denotes the bottleneck queue length at time t, and x_d the demand value of $x(t)$. The virtual connections are numbered in such a way that

$$RTT_1 \le RTT_2 \le .... \le RTT_{n-1} \le RTT_n \tag{3}$$

Before setting up the connection, the bottleneck buffer is empty, i.e.

$$x(t<0) = 0 \tag{4}$$

On the other hand for $t \ge 0$

$$x(t) = \sum_{j=1}^{n} \int_0^t a_j\left(\tau - T_{fj}\right) d\tau - \int_0^t h(\tau) d\tau \tag{5}$$

where $a_j(t)$ is the j-th source rate at time t, and $h(t)$ represents the bandwidth which is actually consumed by the bottleneck link at time t. It is assumed that for any $j = 1, 2, ... , n$ $a_j(t<0) = 0$. Furthermore, if the queue length at the bottleneck link $x(t)$ is greater than zero, then the entire available bandwidth is consumed $h(t) = d(t)$. Otherwise, i.e. when $x(t) = 0$, then $h(t)$ is determined by the rate of data arrival at the node. In this case the available bandwidth may not be fully utilised. Consequently, for any time t

$$0 \le h(t) \le d(t) \le d_{max} \tag{6}$$

The block diagram of the flow control system considered in this paper is shown in Figure 1. The total source rate $\tilde{a}(t)$ is generated by the controller implemented at the switch, and equally allocated between all the sources contributing to the bottleneck queue. Thus the j-th source rate

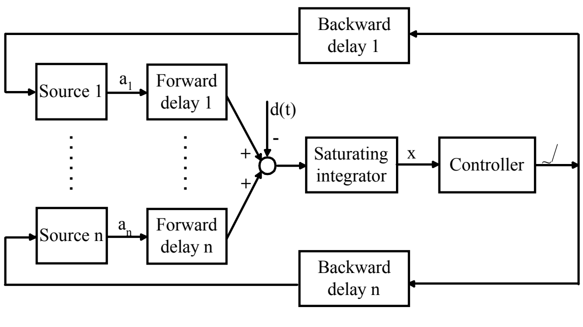

Fig. 1. Network model

$$a_j(t) = \frac{1}{n}\tilde{a}\left(t - T_{bj}\right) \tag{7}$$

The source rate should be determined in such a way that the bottleneck buffer overflow is avoided and the node has always enough data to send. The first condition implies that data cells are not lost and there is no need for their retransmission, while the latter one assures full bottleneck link utilisation which is highly desirable for economic reasons. In the next section a nonlinear controller which ensures that the two conditions are satisfied is proposed. Furthermore, the controller reduces the effect of the available bandwidth change on the steady state queue length.

3. PROPOSED CONTROLLER

In this section we propose the following control algorithm. The j-th source rate is determined by equation (7). For any time $t \geq 0$, the total source rate signal $\tilde{a}(t)$ in this equation is generated by the controller (placed at the bottleneck node) according to the following formula

$$\tilde{a}(t) = \frac{1}{2}a_{max} + \frac{1}{2}a_{max} \cdot sgn\Big[x_d - x(t) + \\ - \sum_{j=1}^{n}\frac{1}{n}\int_{t-RTT_j}^{t}\tilde{a}(\tau)d\tau + \beta\sum_{j=1}^{n}\frac{RTT_j}{n}\cdot h(t)\Big] \tag{8}$$

where a_{max} is such a positive constant that

$$a_{max} > d_{max} \tag{9}$$

and β is a non-negative constant smaller than or equal to one. Furthermore, the signum function in equation (8) is defined as $sgn(x \leq 0) = -1$ and $sgn(x > 0) = 1$. It is assumed that for any time $t < 0$, the total source rate signal $\tilde{a}(t) = 0$. Notice that when the proposed strategy is applied the j-th source does not send any data for the time smaller than T_{bj}, i.e.

$$\forall j \;\; \forall t < T_{bj}, \;\; a_j(t) = 0 \tag{10}$$

Consequently, for any time smaller than or equal to RTT_1 the queue length $x(t) = 0$.

The strategy proposed in this section combines a generalised continuous time Smith predictor with the nonlinear on-off controller with feed-forward compensation. The signum function in equation (8) introduces the relay action, the sum $\sum_{j=1}^{n}\frac{1}{n}\int_{t-RTT_j}^{t}\tilde{a}(\tau)d\tau$ is responsible for the Smith prediction and the term $\beta\sum_{j=1}^{n}\frac{RTT_j}{n}\cdot h(t)$ represents the feed-forward compensation. The effect of this compensation on the system performance can be tuned by the appropriate choice of the constant β. When $\beta = 1$ the effect has its full strength, and it becomes smaller when β decreases to zero.

In the sequel two theorems presenting important properties of the proposed control strategy are introduced.

<u>*Theorem 1*</u>
If the proposed strategy is applied, then the bottleneck link queue length can always be upper bounded by an arbitrary positive constant q_{max}, i.e.

$$x(t) \leq q_{max} = x_d + \beta \cdot d_{max} \cdot \frac{1}{n}\sum_{j=1}^{n}RTT_j \tag{11}$$

<u>*Proof*</u>
As it has already been mentioned, for any time smaller than or equal to RTT_1 the queue length $x(t) = 0$. Therefore, in order to prove the theorem, it is necessary to show that the queue length will not exceed $q_{max} = x_d + \beta \cdot d_{max} \cdot \frac{1}{n}\sum_{j=1}^{n}RTT_j$ at any time t greater than RTT_1. Let

$$\varphi(t) = x(t) + \sum_{j=1}^{n}\frac{1}{n}\int_{t-RTT_j}^{t}\tilde{a}(\tau)d\tau \tag{12}$$

This function represents the sum of the three terms: the number of cells currently stored in the bottleneck buffer; the number of ‘in flight’ cells, i.e. those cells which have already been sent by the sources but not arrived at the bottleneck node yet; and the number of those cells which will inevitably be sent by the sources (this is because the controller already sent out the command to do so to all the sources).

It follows from equations (5) and (7), that for any $t \geq 0$ the queue length

$$x(t) = \sum_{j=1}^{n}\int_{0}^{t}\frac{1}{n}\tilde{a}\left(\tau - RTT_j\right)d\tau - \int_{0}^{t}h(\tau)d\tau = \\ = \sum_{j=1}^{n}\int_{0}^{t-RTT_j}\frac{1}{n}\tilde{a}(\tau)d\tau - \int_{0}^{t}h(\tau)d\tau \tag{13}$$

Consequently, the function $\varphi(t)$ can be expressed as

$$\varphi(t) = \sum_{j=1}^{n}\int_{0}^{t}\frac{1}{n}\tilde{a}(\tau)d\tau - \int_{0}^{t}h(\tau)d\tau = \\ = \int_{0}^{t}\tilde{a}(\tau)d\tau - \int_{0}^{t}h(\tau)d\tau \tag{14}$$

Taking into account relation (6) it can be easily concluded that this function increases only if $a(t) = a_{max}$. Together with equation (8) this implies that

$$\forall t \geq 0, \quad \varphi(t) \leq x_d + \beta \cdot d_{max} \frac{1}{n} \sum_{j=1}^{n} RTT_j \qquad (15)$$

On the other hand, since $\tilde{a}(t)$ is always non-negative, one concludes that

$$\begin{aligned} x(t) &= \varphi(t) - \sum_{j=1}^{n} \frac{1}{n} \int_{t-RTT_j}^{t} \tilde{a}(\tau) d\tau \leq \varphi(t) \leq \\ &\leq x_d + \beta \cdot d_{max} \frac{1}{n} \sum_{j=1}^{n} RTT_j = q_{max} \end{aligned} \qquad (16)$$

Since $x_d \in \mathbf{R}^+$ and $\beta \in [0, 1]$, the upper bound of the queue length q_{max} can be an arbitrarily selected positive number. This conclusion ends the proof.

Another desired property of a properly designed flow control system is full link utilisation. If the queue length is greater than zero, then the link bandwidth is fully used. The next theorem shows how the buffer capacity should be chosen in order to ensure the strictly positive queue length and as a consequence full bottleneck link bandwidth utilisation.

Theorem 2

If the demand value of the queue length x_d satisfies the following inequality

$$x_d > a_{max} \frac{1}{n} \sum_{j=1}^{n} RTT_j \qquad (17)$$

and the bottleneck link buffer capacity is greater than or equal to $q_{max} = x_d + \beta \cdot d_{max} \frac{1}{n} \sum_{j=1}^{n} RTT_j$, then for any $t > RTT_n$ the queue length is greater than zero.

Proof

At the initial time $t = 0$ the function $\varphi(t)$, defined by equation (12), equals zero. Afterwards, if $\varphi(t) < x_d$, then $\varphi(t)$ increases. This follows directly from relations (8), (9), (12), and (14). Equation (14) is satisfied because by assumption $q_{max} = x_d + \beta \cdot d_{max} \frac{1}{n} \sum_{j=1}^{n} RTT_j$ is big enough to ensure that no data is lost in the controlled system. Furthermore, it can be noticed that: for any $t < RTT_1$, the actually consumed bandwidth $h(t) = 0$, for any $t \in [RTT_1, RTT_2)$, $h(t) \leq a_{max}/n$, for any $t \in [RTT_2, RTT_3)$, $h(t) \leq 2a_{max}/n$, ..., for any $t \in [RTT_{n-1}, RTT_n)$, $h(t) \leq (n-1)a_{max}/n$. Consequently, it follows from relation (14) that if $\varphi(t) < x_d$, then: for any $t < RTT_1$, $\varphi(t)$ increases at the rate a_{max}, for any $t \in [RTT_1, RTT_2)$, $\varphi(t)$ increases at least at the rate $a_{max}(n-1)/n$, for any $t \in [RTT_2, RTT_3)$, $\varphi(t)$ increases at least at the rate $a_{max}(n-2)/n$, ..., for any $t \in [RTT_{n-1}, RTT_n)$, $\varphi(t)$ increases at least at the rate a_{max}/n, for any time $t > RTT_n$, $\varphi(t)$ increases at least at the rate equal to the difference between a_{max} and d_{max}. Consequently, if $\varphi(t) < x_d$, then

$$\varphi(t) \geq f(t) \qquad (18)$$

where $f(t)$ is defined as follows:

for $t \in [0, RTT_1]$ $f(t) = a_{max} t$;

for $t \in [RTT_1, RTT_2]$ $f(t) = a_{max} RTT_1 + a_{max}(t - RTT_1)(n-1)/n$;

for $t \in [RTT_2, RTT_3]$ $f(t) = a_{max} RTT_1 + a_{max}(RTT_2 - RTT_1)(n-1)/n + a_{max}(t - RTT_2)(n-2)/n$;

....

for $t > RTT_n$

$$f(t) = \frac{a_{max}}{n} \sum_{j=1}^{n} RTT_j + (a_{max} - d_{max})(t - RTT_n).$$

It follows from inequality (18) and the definition of function $f(t)$, that there exists a time instant $t_1 \leq RTT_n$, when $\varphi(t)$ becomes equal to $a_{max} \sum_{j=1}^{n} RTT_j / n$ and further rises. Moreover, relations (6), (8) and (14) imply, that $\varphi(t)$ always increases when $\varphi(t) < x_d$. Therefore, after becoming (immediately after the time instant $t_1 \leq RTT_n$) greater than $a_{max} \sum_{j=1}^{n} RTT_j / n$, the function $\varphi(t)$ will never decrease below this value. As a result

$$\forall t > RTT_n, \quad \varphi(t) > \frac{a_{max}}{n} \sum_{j=1}^{n} RTT_j \qquad (19)$$

On the other hand, from equation (12), one directly obtains

$$x(t) = \varphi(t) - \sum_{j=1}^{n} \frac{1}{n} \int_{t-RTT_j}^{t} \tilde{a}(\tau) d\tau \qquad (20)$$

Finally, relations (19) and (20) imply

$$\forall t > RTT_n, \quad x(t) > 0 \qquad (21)$$

This conclusion ends the proof.

Theorem 2 shows that using the strategy proposed in this paper one can always assure full link utilisation, provided the bottleneck node buffer capacity is greater than the product $a_{max} \sum_{j=1}^{n} RTT_j / n$. In fact this property can be achieved if the buffer capacity satisfies a weaker condition, i.e.

$$x_d > \frac{1}{n}\sum_{j=1}^{n} RTT_j \cdot d_{max} \quad (22)$$

However, in this case the queue length is not guaranteed to be strictly positive for any time t greater than RTT_n, but only after the elapse of some longer time since setting up the controlled connections.

Finally let us calculate the steady state value of the queue length, i.e. the queue length when the bandwidth available for the controlled connections $d(t) = d_{ss}$ is constant. From relation (8) we get

$$x_{ss} = x_d + (\beta - 1) d_{ss} \sum_{j=1}^{n} \frac{RTT_j}{n} \quad (23)$$

It can be seen from equation (23) that the feed-forward compensation, represented by the term $\beta \sum_{j=1}^{n} \frac{RTT_j}{n} \cdot h(t)$, reduces the effect of the available bandwidth change on the steady state queue length. Choosing $\beta = 1$ one ensures complete insensitivity of the steady state queue length with respect to the changing available bandwidth. This property helps to obtain better quality of service, i.e. smaller cell delay time variation in the considered system.

4. CONCLUSIONS

In this paper a new nonlinear flow control strategy for wide area high speed communication networks has been proposed. The strategy combines Smith predictor with the relay controller and feed-forward compensation. It has been proved that the proposed solution assures full bottleneck link utilisation and no cell loss in the controlled connections. Furthermore, the flow rates in the considered network are always nonnegative and bounded. Since the proposed strategy assures insensitivity of the steady-state queue length with respect to the available bandwidth, favourable quality of service is achieved.

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