Abstract—In this paper, a novel integral sliding mode control strategy is designed for rate-based flow control problem in asynchronous transfer mode (ATM) networks. The control scheme, which includes a predictor, guarantees stability robustness to multiple time-delays in different channels and changeful available bit-rate (ABR) bandwidth. It also achieves two expectant goals, i.e. it ensures exponential convergence of queue length to the desired steady-state value and satisfies a weighted fairness condition. The algorithm exhibits good performance and most importantly, has a solid theoretical foundation. Simulation results show that the control system is rapid, robust and adaptive.

I. INTRODUCTION

CONGESTION in computer networks is the main reason for reduced performance and poor QoS. Therefore, congestion control of computer networks received a growing attention in control community recently, ATM in particular which is a key technology for integrating broadband integrated services (B-ISDN) in heterogeneous networks where data, video and voice sources transmit information. To support multimedia traffic, the ATM Forum[1] has defined five service classes of which ABR is the ideal one that responds to network congestion by means of a feedback control mechanism in order to improve network utilization. The ATM forum decided to use a closed-loop rate-based congestion control scheme as the standard for the ABR service, which may be classified into two schemes: 1) Binary feedback scheme. 2) Explicit rate (ER) scheme.

Our focus in this paper is on the explicit rate feedback framework. Over the years, many congestion control algorithms have been proposed on control theoretic principles in this framework. In [2], an analytic method for the design of a congestion controller is proposed. This algorithm, however, requires a complex online tuning of control parameters to ensure stability and to damp oscillations under different network conditions. In [3], based on the work in [2], the authors design a dual PD controller, where the control parameters can be designed to ensure the stability of the control loop in a control-theoretic sense, over a wide range of traffic patterns and propagation delays. In [4], a control scheme based on a smith predictor with a proportional controller inside is presented. Although it can lower the average queue level, the scheme is sensitive to the round-trip delays between the source and the switches on the connection path. So if the propagation delays change, the system may be unstable. In [5], an H-infinite controller is designed. The controller can guarantee robustness against multiple time-delays and bring the queue length at the bottleneck node to the desired value and also satisfy a weighted fairness condition. But unfortunately, the validity of the controller depends on the estimate of delays. In [6], [7] and [8], in contrast to the methods above, the authors model the ATM networks in the form of state space equation. Especially in [7] and [8], the authors give the proof that the stability of the congestion control system with a single source is equivalent to the stability of the one with multiple sources for congestion control systems with linear controller, however, the methods depend on the network model terribly. Because the traditional control methods are model-based, the intelligent control methods, such as fuzzy logic have emerged as viable techniques for dealing with complicated characteristics and environmental changes that cannot be described by an exact mathematical process. In [9], a fuzzy immune-PID (FI-PID) controller is proposed, simulation results show that the control system is adaptive and robust to the changeful ABR bandwidth. However it bases on the assumption that all the time-delays are equal to the maximum time-delay. To briefly summarize, the challenging aspects in ABR flow control as far as controller design in this framework is concerned, are the existence of multiple time-delays in the data flow and the changeful ABR bandwidth due to the variation of high priority variable bit rate (VBR) traffic.

In this paper, an integral sliding mode controller (ISM C) is introduced, which can overcome the adverse effect by the multiple propagation delays and keep stable robustness with respect to uncertainties of ABR bandwidth. The proposed sliding surface includes a predictor which consists of not only the current state but also the past control input during the period of delay[10]. The predictor is applied to compensate for the input delay, then the ISM technique is used to minimize the effects of the changeful ABR bandwidth. We construct this controller on a solid analytical basis and simulation results show that our algorithm indeed achieves another two goals for a variety of networks scenarios: 1 tracking, which is to keep the queue size close to a certain desired size. By choosing this level sufficiently larger than zero and sufficiently smaller than the buffer size, nonlinear effects may also be avoided and the outgoing flow rate may be kept close.
to the full capacity (thus achieving the maximum utilization of the network). 2 weighted\ fairness, which means allocating different percentages of the available capacity to different sources. Thus, weighted fairness may be used as a pricing tool.

II. THE NETWORK MODEL

In ATM networks, the best-effort traffic class, in particular the ABR service, may be guaranteed a minimum cell data (MCR) and a peak cell rate (PCR) with very little a priori. The guaranteed-service traffic referred to as either (constant bit rate) CBR or VBR gets a higher scheduling priority compared with ABR traffic. In other words, at a given node, when both ABR traffic and CBR/VBR traffic are backlogged (i.e., having packets that they are waiting to send), the packets from the guaranteed-service traffic are processed first, and the best effort traffic is served only if there is some bandwidth left by the CBR/VBR traffic. So if the rates of each ABR source are not adjusted in time, congestion may be caused in ATM networks. In order to solve this problem, a buffer is used in the switch node where the cells can be stored temporarily. Associated with each buffer there is an explicit rate (ER) computation engine that determines the explicit rate for each user. A congestion control scheme is required to efficiently allocate the unused bandwidth of link to the ABR traffic in order to improve network utilization and avoid congestion of the buffer. The ATM networks with one bottleneck and n ABR sources is depicted by Fig.1.

Fig. 1. Block diagram of ATM networks.

For the ith ABR source, a Resource Management (RM) cell is sent once every Nrm cells which can be used by switches to convey feedback. The RM cells contain some special fields including the MCR field, PCR field and the (ER) field which denotes the rate that the switch can support. The RM cells travel to the destination and return to the source in the same path. Each node encountered by the RM cell, stamps the computed value for the input rate on the RM cell only if this value results to be less than the rate already stored. The node that has the smallest ER value is called bottleneck node. The RM cells will return source from bottleneck node after a delay \( \tau^b \), where \( \tau^b \) denotes the backward propagation delay.

On receiving the backward RM cell, the source adjusts its transmission rate according to the ER value. The effect of the new rate becomes apparent at the switch under consideration after another delay \( \tau^f \), where \( \tau^f \) denotes the forward propagation delay. The sum of propagation delay in the forward and the backward path represents the round-trip propagation delay, denoted by \( \tau = \tau^b + \tau^f \). From Fig.1 the dynamics of the queue is described as

\[
\dot{q}(t) = \sum_{i=1}^{n} u'_i(t) - d(t) \tag{1}
\]

where \( q(t) \) is the queue length at time \( t \), \( u'_i(t) \) is the rate of data received at the bottleneck node from the ith source node, \( n \) denotes the number of ABR sources, \( d(t) = D - \omega(t) \) is the capacity of the outgoing flow rate from the bottleneck node, here \( D \) is the capacity of the link which is a known constant usually, \( \omega(t) \) is the bandwidth of VBR+CBR and \( |\omega(t)| < \beta \). Here we assume that the ABR source adjusts its transmission rate to the ER value computed at time \( t - \tau^b \), i.e. \( u'_i(t) = u_i(t - \tau^b) \). By using the relation \( e(t) = q_d(t) - q(t) \), (1) can be rewritten as

\[
\dot{e}(t) = -\sum_{i=1}^{n} u_i(t - \tau_i) + d(t) \tag{2}
\]

where the round-trip delay \( \tau_i \) is assumed to satisfy \( 0 \leq \tau_i < h \).

III. THE CONTROL LAW

Sliding mode control is a robust technique well known for its ability to withstand external disturbance and model uncertainties, so it is very suitable for compensating the changeful ABR bandwidth \( d(t) \). Reference [11] proposes a new sliding mode design concept, namely integral sliding mode which gets the focus of many researchers recently due to its excellent characteristics. An integral term is included in the sliding manifold which guarantees that the system trajectories will start in the manifold from the first time instant\([11,12,13]\).

The basic idea of ISM is to define the control law as the sum of a continuous nominal control and a discontinuous control. The nominal control is responsible for the performance of the nominal system, i.e., without perturbations, and the discontinuous control is used to reject the perturbations (ABR bandwidth). So the controller proposed is designed in the form

\[
u_i(t) = u_{i0}(t) + u_{i1}(t) \tag{3}
\]
where \( u_{i0}(t) \) is the nominal control and \( u_{i1}(t) \) is the discontinuous control. Substitute (3) into (2) we get

\[
\dot{e}(t) = -\sum_{i=1}^{n} u_{i0}(t - \tau_i) - \sum_{i=1}^{n} u_{i1}(t - \tau_i) + d(t)
\]  

(4)

Because it is very difficult to design the sliding mode controller with input delays, a sliding mode predictor is used to obtain the free-delay discontinuous control input \( u_{i1}(t) \), which is in the form as follows

\[
\bar{e}(t) = e(t) - \sum_{i=1}^{n} \int_{0}^{\tau_i} u_{i1}(t + \theta) d\theta
\]  

(5)

Differentiating equation (5) and substituting for \( \dot{e}(t) \) from (4) gives

\[
\dot{\bar{e}}(t) = -\sum_{i=1}^{n} u_{i0}(t - \tau_i) - \sum_{i=1}^{n} u_{i1}(t - \tau_i) + d(t)
\]  

(6)

Firstly, let us design the feedback nominal controller to stabilize the following nominal system

\[
\dot{\bar{e}}(t) = -\sum_{i=1}^{n} u_{i0}(t - \tau_i)
\]  

(7)

Design the nominal controller in the form

\[
u_{i0}(t) = k \bar{e}(t)
\]  

(8)

where \( k \) is the gain of controller.

The following lemmas will be used to prove Theorem 1.

**Lemma 1.** For any \( z, y \in \mathbb{R}^{n} \) and any positive definite matrix \( X \in \mathbb{R}^{n \times n} \),

\[-2z^T y \leq z^T X^{-1} z + y^T X y
\]  

(9)

**Lemma 2.** Let \( a(t) \leq b(t) \), then the following inequality is satisfied

\[
\left\| \int_{a}^{b} f(s) ds \right\|^2 \leq (b - a) \left\| f(s) \right\|^2 ds
\]  

(10)

**Theorem 1.** For a given \( \varepsilon > 0 \), if there exists \( k \) satisfying the following inequality, then nominal system (7) is exponentially stable.

\[-(2kn - k^2n^2 - k^2n \sum_{j=1}^{n} \tau_j^2) < -\varepsilon
\]  

(11)

**Proof:** By adopting the relation \( \bar{e}(t - \tau_i) = \bar{e}(t) - \int_{t-\tau_i}^{t} \dot{\bar{e}}(s) ds \) and equation (7), we have

\[
\dot{\bar{e}}(t) = -kn\bar{e}(t) - k^2 \sum_{i=1}^{n} \int_{t-\tau_i}^{t} \bar{e}(s - \tau_i) ds
\]  

(12)

Let \( v_0(t) = \frac{1}{2} \bar{e}^2(t) \), taking the derivative of \( v_0 \) and using (12) we get

\[
\dot{v}_0 = -kn\bar{e}^2 - k^2 \sum_{i=1}^{n} \int_{t-\tau_i}^{t} \bar{e}(s - \tau_i) ds
\]  

(13)

By lemma 1 and lemma 2, we can get the following inequality

\[
\dot{v}_0 \leq -kn\bar{e}^2 + \frac{k}{2} \sum_{i=1}^{n} \left( \bar{e}^2 + \int_{t-\tau_i}^{t} \bar{e}(s - \tau_i) ds \right)^2
\]  

\[
\leq -kn\bar{e}^2 + \frac{k}{2} n^2 \bar{e}^2 + \frac{k}{2} \left( \sum_{i=1}^{n} \int_{t-\tau_i}^{t} \bar{e}(s) ds \right)^2
\]  

(14)

Let \( v_1(t) = \frac{1}{2} k \sum_{i=1}^{n} \int_{t-be}^{t} \bar{e}(s) ds d\theta \), taking the derivative of \( v_1 \) gives

\[
\dot{v}_1 = \frac{1}{2} k^2 \sum_{i=1}^{n} \sum_{j=1}^{n} \tau_j \bar{e}^2 - \frac{1}{2} k^2 \sum_{i=1}^{n} \int_{t-\tau_i}^{t} \bar{e}^2(s) ds
\]  

(15)

Chose the Lyapunov-Krasovskii functional candidate as

\[V(t) = v_0(t) + v_1(t)\]  

(16)

By condition (11), we get \( \dot{V} \leq -\frac{1}{2} \bar{e}^2 \). Because of

\[-\frac{1}{2} \bar{e}^2 \leq -\varepsilon(1 - \frac{v_0}{V}) \]  

for any \( \bar{e}(t) \neq 0 \), there must exist \( \gamma > 0 \) satisfying \( \dot{V} \leq -\varepsilon \gamma \). Then we get

\[V < c \cdot \exp(-\gamma t)\]  

which implies \( |\bar{e}(t)| < \sqrt{2c \cdot \exp(-\gamma t)} \), where \( c \) is a constant, that completes the proof.

Also from (11), we can get the value of \( k \), which can keep the closed-loop nominal system (7) stable.

Next let us design the integral sliding mode controller to compensate the changeful bandwidth of ABR and stabilize the closed-loop system. Now define an integral sliding mode surface as follows

\[s(t) = s_0(\bar{e}(t)) + z(t)
\]  

(17)

where \( s_0(\bar{e}(t)) \) and \( z(t) \) are both auxiliary variables which will be defined below

\[s_0(\bar{e}(t)) = \alpha \bar{e}(t)
\]  

(18)

where \( \alpha \) is a positive constant. Taking the derivative of (18) results in

\[\dot{s}(t) = \dot{z}(t) + \alpha(-\sum_{i=1}^{n} u_{i0}(t - \tau_i) - \sum_{i=1}^{n} u_{i1}(t) + d(t))
\]  

(19)

Select the auxiliary variable \( z(t) \) as the solution to the differential equation
\[
\dot{z}(t) = \alpha \sum_{i=1}^{n} u_{io}(t - \tau_i)
\]
(20)

with the initial conditions \( z(\theta) = -s_0(\bar{c}(\theta)) \) for \( \theta \in [-h, 0] \). So the equation for \( \dot{s}(t) \) becomes
\[
\dot{s}(t) = \alpha(-\sum_{i=1}^{n} u_{ri}(t) + d(t))
\]
(21)

Finally, to realize a sliding mode dynamics, let us design the discontinuous controller
\[
u_{ri}(t) = \hat{\lambda}_i (D + \beta \text{sign}(s(t)))
\]
(22)

where the fairness weight of ABR sources \( \hat{\lambda}_i (\hat{\lambda}_i \geq 0) \) is such that \( \sum_{i=1}^{n} \hat{\lambda}_i = 1 \), and if the weights must be distributed equally among the sources, we take \( \hat{\lambda}_i = \frac{1}{n} \).

Substitute (8) and (22) into (3), the ABR rate controller using sliding surface (17) can be designed as
\[
u_{ri}(t) = k\bar{c}(t) + \hat{\lambda}_i (D + \beta \text{sign}(s(t)))
\]
(23)

The following facts reveal the nice property of the proposed control law.

**Fact 1**: The controller (23) can maintain the sliding mode.

**Proof**: Substituting (23) and \( \dot{z}(t) = \alpha \sum_{i=1}^{n} u_{io}(t - \tau_i) \) into (19) gives
\[
\dot{s}(t) = \alpha(-\beta \text{sign}(s(t)) - \omega(t))
\]
(24)

Choose a Lyapunov function as \( V(s(t)) = 0.5s^2(t) \), differentiating \( V \) and using (24) yields
\[
\dot{V} = \alpha s(-\beta \text{sign}(s(t)) - \omega(t))
\]
(25)

According to \( |\omega(t)| < \beta \) and \( \alpha > 0 \), we get \( \dot{V} < 0 \), that completes the proof.

**Fact 2**: In sliding mode, the integral sliding mode controller (23) completely compensates the effect of variation of ABR bandwidth from the beginning of the process and the closed-loop dynamics becomes
\[
\ddot{\bar{c}}_{\text{eq}}(t) = -\sum_{i=1}^{n} u_{io}(t - \tau_i)
\]
(26)

where \( u_{io}(t) \) is the nominal controller which can ensure the nominal system stable.

**Proof**: In the sliding mode \( \bar{c}(t) = \bar{c}_{\text{eq}}(t) \) and \( \dot{s}(t) = 0 \), then from (21) we have
\[
\sum_{i=1}^{n} u_{i,\text{eq}}(t) = d(t)
\]
(27)

Substituting the previous equation into (6), one obtains (26) which ends the proof.

**IV. SIMULATION RESULTS**

In this section, computer simulations are carried out to confirm the validity of the proposed algorithm. For comparison purposes, the performance of the proposed ISMC is compared with the fuzzy immune-PID algorithm introduced in [9]. The simulation model is depicted by Fig2.

![Fig. 2. Single bottleneck link simulation model.](image)

It has one switch with 128 cell buffers, five ABR sources which are persistent (with infinite backlog) and one group of VBR sources consisting of four VBR sources. The buffer set point \( q_d = 50 \) cells. All links have a capacity of 365 cells/ms (155Mb/s). Nonlinearities of the system are also taken into account in these simulations: the queue length and all the rates must be non-negative, and the queue size cannot exceed 128 packets. We choose the sliding surface as (17) with the initial condition \( q(\theta) = 0, z(\theta) = -5 \) for \( \theta \in [-0.1, 0] \).

The control law (23) is revised as follows under boundary layer modification which is commonly used to eliminate control chattering.

\[
u_{ri}(t) = \begin{cases} 
  k\bar{c}(t) + \hat{\lambda}_i (D + \beta \text{sign}(s(t))), & \text{if } |s(t)| \geq \varepsilon \\
  k\bar{c}(t) + \hat{\lambda}_i \left(D + \frac{\beta s(t)}{\varepsilon}\right), & \text{if } |s(t)| < \varepsilon
\end{cases}
\]
(28)

where \( \varepsilon = 0.1 \) and \( \beta = 250 \).

**A. Simulation in WAN**

Only five ABR sources here are considered. The round-trip delays (in ms), forward delays and fairness weights are shown in Table 1.

As obtained in Fig3, all ABR flow rates become stable quickly and the relative steady-state flow rates of sources are equal to the relative fairness weights of these sources, so the weighted fairness are guaranteed.

**Table I: The Simulation Parameters in WAN**

<table>
<thead>
<tr>
<th>i</th>
<th>( \tau_i (\text{ms}) )</th>
<th>( \tau_i' (\text{ms}) )</th>
<th>( \hat{\lambda}_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>10</td>
<td>0.2</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>20</td>
<td>0.1</td>
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<tr>
<td>3</td>
<td>50</td>
<td>10</td>
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<td>0.2</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>30</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Fig.4. shows the queue level of the buffer by virtue of the
FI-PID controller, the queue length converges to the desired point \( q_d = 50 \) cells after 650ms with a little overshoot and our controller converges to stable more quickly without any overshoot. So it is easy to get the conclusion that the controller in this paper can overcome the adverse effect caused by multiple propagation time delays in different channel and it makes the system more stable and rapid than FI-PID algorithm.

![Fig. 3. ABR source rate in WAN.](image)

![Fig. 4. Queue level of the buffer.](image)

**B. Simulation in WAN with VBR existing**

Next we consider the system as in simulation A, with the same delays, fairness weights and the controller parameters. But in this case, we add four MPEG sources with a peak rate of 35 cells/ms and average rate of 21 cells/ms. The MPEG sources have service priority over ABR sources. Note that the ABR sources are persistent (with infinite backlog).

From Fig. 5 the aggregate rate of four MPEG sources is about 73 cells/ms with high frequency fluctuation. From Fig. 6, it is obvious that the queue stays around the target value with less oscillations compared with the one utilizing the FI-PID technique.

Therefore it is concluded that the ISMC can reduce sensitivity to variational ABR bandwidth and can improve the performance of the ATM networks with VBR existing, which has good robustness.

![Fig. 5. VBR source rate in WAN.](image)

![Fig. 6. Queue level of the buffer with VBR existing](image)

**V. CONCLUSION**

In this paper, we have proposed a control-theoretic approach to the design of closed-loop rate-based flow control in ATM networks with multiple time-delays. The novel integral sliding mode controller is proposed to control ABR rate because of its nice properties to compensate disturbance caused by changing VBR bandwidth, which includes a sliding mode predictor to obtain the free delay control input. The exponential convergence of queue levels to the desired point and weight fairness are guaranteed by utilizing this controller. Finally, simulation results have been included to demonstrate the validity and superiority of the algorithm by comparison with fuzzy immune-PID algorithm.

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