TIME – VARYING SLIDING MODE FLOW CONTROL STRATEGY FOR CONNECTION – ORIENTED COMMUNICATION NETWORKS

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Abstract: In this paper a new sliding mode flow control strategy for the connection-oriented communication networks is proposed. The networks are modelled as discrete time systems with the available bandwidth acting as disturbance. The strategy employs a time-varying sliding surface, which helps reduce the initial flow rate magnitude. The proposed controller is designed in such a way that the closed-loop system stability and finite time error convergence are ensured. We demonstrate that the designed controller guarantees no bottleneck link buffer overflow and full utilization of its available bandwidth. Furthermore, transmission rates generated by the controller are always upper bounded and non-negative.

Keywords: discrete time sliding mode control, flow control, connection-oriented communication networks, time-delay systems, time-varying sliding surface design

1. INTRODUCTION

High-speed connection-oriented communication networks may allow various kinds of applications to run under a uniform infrastructure. In these networks the sequence of application data units are transmitted by a source and reach their destination via a path of intermediate switches. On each switch a server schedules and forwards data units along the path from their source to their destination in the network. The difficulty of the flow control is mainly caused by long propagation delays in the network. If congestion occurs at a specific switch, information about these circumstances must be conveyed to all the sources transmitting data units through the switch. This information is used to adjust source rates and may affect the congested switch after the round trip propagation delay.

Flow control in connection-oriented communication networks has recently become an exciting research field and valuable results have been reported in many papers (Bartoszewicz, 2006; Chong *et al.*, 1998; Imer *et al.*, 2001; Jagannathan and Talluri, 2002; Laberteaux *et al.*, 2002; Lengliz and Kamoun, 2000; Mascolo, 2000). Their authors proposed 'on-off' (Bartoszewicz, 2006; Chong *et al.*, 1998), classical PD (Lengliz and Kamoun, 2000), stochastic (Imer *et al.*, 2001), adaptive (Laberteaux *et al.*, 2002) and neural network based (Jagannathan and Talluri, 2002) controllers. Due to the significant propagation delays several researchers also applied the Smith predictors (Bartoszewicz, 2006; Mascolo, 2000) for the flow control in such networks.

On the other hand, it is well known that sliding mode control is an attractive and efficient strategy which offers robustness and good dynamic performance of the controlled systems (Utkin, 1977; DeCarlo *et al.*, 1988; Slotine and Li, 1991). Therefore, in this paper we attempt to apply discrete time sliding mode approach (Bartoszewicz, 1998; Furuta, 1990; Gao *et al.*, 1995) to the flow control in a single virtual circuit of a connection-oriented communication network. We consider a general model of a connection oriented network which provides feedback mechanism. An example of such networks is ABR service in ATM standard. In order to avoid excessive values of the initial flow rate the proposed control algorithm employs a time-varying sliding surface (Bartoszewicz, 1996; Bartoszewicz and Nowacka, 2005). Initially, the surface passes through the point determined by the system initial conditions in the error state space. Afterwards, the surface moves uniformly to the origin of the space, stops after reaching the origin at the predetermined time instant k_0T and then remains fixed. The parameters of the surface are determined so that the closed-loop system is stabilized and the error convergence to zero in finite time is guaranteed. When the designed sliding mode controller is applied no data loss and full link bandwidth utilization are ensured. The conditions for these features satisfaction are formulated and explicitly proved. Moreover, the transmission rates generated by the proposed controller are nonnegative and bounded. These properties will allow direct implementation of the proposed strategy in a network environment.

The remainder of the paper is organized as follows. The model of the network used throughout the paper is introduced in Section 2. The proposed time-varying sliding mode flow controller design and the system performance when the control strategy is applied are presented in Section 3. In the same section a lemma and two theorems that state conditions for satisfaction of the important properties of the controlled network are proved. Section 4 comprises a simulation example, and finally, Section 5 presents conclusions of the paper.

2. NETWORK MODEL

In this paper we consider the connection-oriented communication network which consists of a single data source, intermediate nodes and destination, all interconnected via bi-directional links. Furthermore, it is assumed that there is only one bottleneck node in the network. The source sends data (as determined by the controller at the bottleneck node) and control units. The control units are processed by the nodes on a priority basis, i.e. they are not queued but sent to the next node without delay. These units carry information about the network state. After reaching their destination, they are immediately sent back to the source, along the same path they arrived. The information carried by the control units is used to adjust the amount of data transmitted by the source at each control period. The round trip time RTT of the control units in the virtual circuit can be expressed as the sum of forward and backward propagation delays denoted as T_F and T_B, respectively

$$RTT = T_F + T_B \tag{1}$$

The block diagram of the flow control system considered in this paper is shown in Figure 1.

Further in the paper, T represents the discretisation period, $y(kT)$ denotes the bottleneck queue length at

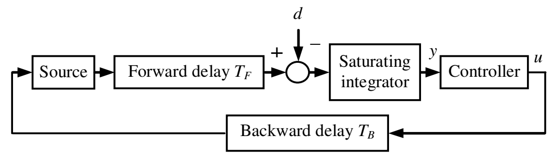

Fig. 1. Network model.

time instants kT, $k = 0, 1, 2, \ldots$, and $y_d > 0$ is the demand value of $y(kT)$. It is assumed that before setting up the connection, the bottleneck buffer is empty, i.e. $y(kT < 0) = 0$. Moreover, in this paper we assume that the round trip time is a multiple of the discretisation period, i.e. $RTT = m_{RTT}\, T$, where m_{RTT} is a positive integer.

The amount of data to be sent is generated by the controller placed at the bottleneck node. The controller output at time kT is denoted as $u(kT)$. This amount of data will be sent by the source after backward delay T_B and will arrive at the bottleneck node T_F later. Consequently, the bottleneck buffer for any time $kT \le RTT$ remains empty. It is assumed that before setting up the connection $u(kT < 0) = 0$. The amount of data which may leave the bottleneck buffer at time kT is modelled as an *a priori* unknown bounded function of time $d(kT)$, for $k = 0, 1, 2, \ldots$. The maximum value of $d(kT)$ is denoted by $d_{\max}$ and $h(kT)$ represents the amount of data actually leaving the bottleneck node at time kT. Consequently

$$\underset{k\geq 0}{\forall} \quad 0 \le h(kT) \le d(kT) \le d_{\max} \tag{2}$$

Initially, the bottleneck buffer is empty, i.e. $y(kT = 0) = 0$. Then, for any $k \ge 1$, the queue length can be expressed as follows

$$\begin{aligned} y(kT) &= \sum_{j=0}^{k-1} u(jT - RTT) - \sum_{j=0}^{k-1} h(jT) = \\ &= \sum_{j=0}^{k-m_{RTT}-1} u(jT) - \sum_{j=0}^{k-1} h(jT) \end{aligned} \tag{3}$$

3. PROPOSED CONTROL STRATEGY

Further in the paper, the problem of congestion control in the described network is considered. A chattering free discrete time sliding mode controller with a moving sliding plane is designed so that the flow rate is bounded as required and fast, finite time error convergence to zero is achieved. Moreover, several important properties of the proposed control strategy are formulated and proved.

3.1 Sliding Mode Controller.

In this subsection a discrete time sliding mode congestion controller for the considered network is designed. For this purpose, first a discrete time state space model of the controlled system is formulated. Then, a time-varying sliding hyperplane is introduced and its parameters are determined in such a way that the closed-loop system is stable and the error converges to zero in finite time.

Let us consider the following discrete time model of the network

$$\begin{aligned} \boldsymbol{x}\left[(k+1)T\right] &= \boldsymbol{A}\boldsymbol{x}(kT) + \boldsymbol{b}u(kT) + \boldsymbol{p}h(kT) \\ y(kT) &= \boldsymbol{q}^{\mathrm{T}}\boldsymbol{x}(kT) \end{aligned} \tag{4}$$

where $\boldsymbol{x}(kT) = [x_1(kT)\ \ x_2(kT)\ \ \ldots\ x_n(kT)]^{\mathrm{T}}$ is the state vector with $x_1(kT) = y(kT)$, $\boldsymbol{A}$ is $n \times n$ state matrix, $\boldsymbol{b}$, $\boldsymbol{p}$ and $\boldsymbol{q}$ are $n \times 1$ vectors

$$\boldsymbol{A}=\begin{bmatrix} 1 & 1 & 0 & \ldots & 0 \\ 0 & 0 & 1 & \ldots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \ldots & 1 \\ 0 & 0 & 0 & \ldots & 0 \end{bmatrix} \quad \boldsymbol{b}=\begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix} \quad \boldsymbol{p}=\begin{bmatrix} -1 \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix} \quad \boldsymbol{q}=\begin{bmatrix} 1 \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix} \tag{5}$$

and $n = m_{RTT} + 1$. Alternatively, the state space equation can be written as follows

$$\begin{cases} x_1\left[(k+1)T\right] = x_1(kT) + x_2(kT) - h(kT) \\ x_2\left[(k+1)T\right] = x_3(kT) \\ x_3\left[(k+1)T\right] = x_4(kT) \\ \quad\vdots \\ x_{n-1}\left[(k+1)T\right] = x_n(kT) \\ x_n\left[(k+1)T\right] = u(kT) \end{cases} \tag{6}$$

In this model the available bandwidth $h(kT)$ is represented as unmatched disturbance. The desired state of the system is denoted by $\boldsymbol{x}_d = [x_{d1}\ \ x_{d2}\ \ldots\ x_{dn}]^{\mathrm{T}}$. It can be noticed from (6) that all components x_{di} of vector $\boldsymbol{x}_d$ for $i = 2, \ldots, n$ are equal to zero when $h(kT) = 0$. Let us denote the first state variable x_{d1} representing the demand queue length by y_d.

For the sliding mode controller design purpose we neglect the effect of disturbance $h(kT)$. In order to avoid excessive control signal magnitude we introduce a time-varying sliding hyperplane. At first, the plane adapts itself to the initial conditions of the system, afterwards it moves towards the origin of the error state space, stops moving after a predetermined time k_0T and then remains fixed. Consequently, we propose a sliding hyperplane described for any $k \geq 0$ by the following equation

$$s(kT) = \boldsymbol{c}^{\mathrm{T}}\boldsymbol{e}(kT) + f(kT) = 0 \tag{7}$$

where $\boldsymbol{c}^{\mathrm{T}} = [c_1\ \ c_2\ \ldots\ c_n]$ is such a vector that $\boldsymbol{c}^{\mathrm{T}}\boldsymbol{b} \neq 0$, and $f(kT)$ is an *a priori* known function satisfying the following conditions:

- $f(0) = -\boldsymbol{c}^{\mathrm{T}}\boldsymbol{e}(0)$ so that, initially, the system representative point belongs to the sliding hyperplane (7);
- $f(kT)$ is strictly monotonic in the interval $[0; k_0]$;
- $f(kT) = 0$ for any $k \geq k_0$.

One possible definition of $f(kT)$ is

$$f(kT) = \frac{k-k_0}{k_0}\boldsymbol{c}^{\mathrm{T}}\boldsymbol{e}(0) \quad \text{for} \quad k = 0, 1, \ldots, k_0 \tag{8}$$

Further in the paper, the closed-loop system error is denoted as $\boldsymbol{e}(kT) = \boldsymbol{x}_d - \boldsymbol{x}(kT)$. Hence, substituting (4) into equation $\boldsymbol{c}^{\mathrm{T}}\boldsymbol{e}[(k+1)T] + f[(k+1)T] = 0$ the following feedback control law can be derived

$$u(kT) = \left(\boldsymbol{c}^{\mathrm{T}}\boldsymbol{b}\right)^{-1}\left\{\boldsymbol{c}^{\mathrm{T}}\left[\boldsymbol{x}_d - \boldsymbol{A}\boldsymbol{x}(kT)\right] + f\left[(k+1)T\right]\right\} \tag{9}$$

When this control signal is applied, the closed-loop system state matrix has the following form $\boldsymbol{A}_c = \left[\boldsymbol{I}_n - \boldsymbol{b}\left(\boldsymbol{c}^{\mathrm{T}}\boldsymbol{b}\right)^{-1}\boldsymbol{c}^{\mathrm{T}}\right]\boldsymbol{A}$. Then the characteristic polynomial of $\boldsymbol{A}_c$ can be found as follows

$$\begin{aligned} \det\left(z\boldsymbol{I}_n - \boldsymbol{A}_c\right) = z^n + \frac{c_{n-1}-c_n}{c_n}z^{n-1} + \frac{c_{n-2}-c_{n-1}}{c_n}z^{n-2} + \\ + \ldots + \frac{c_1-c_2}{c_n}z \end{aligned} \tag{10}$$

which leads to the condition $c_n \neq 0$. Asymptotic stability of the discrete time system is ensured if and only if all its eigenvalues are located inside the unit circle. Moreover, in order to ensure the closed-loop system error convergence to zero in finite time, the characteristic polynomial (10) has to satisfy

$$\det\left(z\boldsymbol{I}_n - \boldsymbol{A}_c\right) = z^n \tag{11}$$

Comparing coefficients on the right-hand sides of (10) and (11), the following form of vector $\boldsymbol{c}$ is obtained $\boldsymbol{c}^{\mathrm{T}} = \begin{bmatrix}1 & 1 & 1 & \ldots & 1\end{bmatrix}c_n$. Substituting this vector $\boldsymbol{c}$ and matrices given in (5) into (9) the following state feedback control can be derived

$$u(kT) = y_d - \sum_{i=1}^{n} x_i(kT) + \frac{1}{c_n} f\left[(k+1)T\right] \tag{12}$$

Alternatively, from (6), one can get the state variables x_i ($i = 2, 3, \ldots, n$) expressed in terms of the control signal generated by the controller at the previous $n - 1$ samples

$$x_i(kT) = u\left[(k-n+i-1)T\right] \quad \text{for} \quad i = 2, 3, \ldots, n \tag{13}$$

Substituting these expressions into (12) and putting $x_1(kT) = y(kT)$, we obtain

$$u(kT) =$$
$$= y_d - y(kT) - \sum_{j=1}^{m_{RTT}} u\left[(k-j)T\right] + \frac{1}{c_n} f\left[(k+1)T\right] =$$
$$= y_d - y(kT) - \sum_{j=k-m_{RTT}}^{k-1} u(jT) + \frac{1}{c_n} f\left[(k+1)T\right] \quad (14)$$

which represents a dynamic sliding mode controller. This completes the design of the flow control algorithm which guarantees the closed-loop system stability and the finite time error convergence to zero in the considered network.

3.2 Properties of the Controlled Network.

In the previous subsection the time-varying sliding hyperplane has been designed in order to ensure the system stability and the finite time error convergence. It has been shown that for any integer $k \geq 0$ the amount of data to be sent should be generated according to formula (14). Hence

$$u(0) = y_d + \frac{1}{c_n} f(T) \quad (15)$$

Further in this paper, a lemma and two theorems which state crucial properties of the controlled system will be presented. The lemma formulates a relation between the control signal $u(kT)$ and the consumed bandwidth. Afterwards, the first theorem gives the conditions that must be satisfied to eliminate the risk of data loss as a consequence of exceeding the bottleneck node buffer capacity, and the latter one provides a condition for full bottleneck link bandwidth utilization.

Lemma If the proposed sliding mode flow controller is applied, then for any integer $k \geq 1$ the following relation holds

$$u(kT) = h\left[(k-1)T\right] + \frac{1}{c_n}\left\{f\left[(k+1)T\right] - f(kT)\right\} \quad (16)$$

Proof: Using equation (3), relation (14) can be rewritten as follows

$$u(kT) = y_d - y(kT) - \sum_{j=k-m_{RTT}}^{k-1} u(jT) + \frac{1}{c_n} f\left[(k+1)T\right] =$$
$$= y_d - \sum_{j=0}^{k-m_{RTT}-1} u(jT) + \sum_{j=0}^{k-1} h(jT) - \sum_{j=k-m_{RTT}}^{k-1} u(jT) +$$
$$+ \frac{1}{c_n} f\left[(k+1)T\right] =$$
$$= y_d - \sum_{j=0}^{k-1} u(jT) + \sum_{j=0}^{k-1} h(jT) + \frac{1}{c_n} f\left[(k+1)T\right] \quad (17)$$

We will prove that relation (16) is true for any integer $k \geq 1$ using the principle of mathematical induction. First, let us check whether the relation holds for $k = 1$. From (15) and (17) it follows immediately that

$$u(T) = y_d - u(0) + h(0) + \frac{1}{c_n} f(2T) =$$
$$= y_d - y_d - \frac{1}{c_n} f(T) + h(0) + \frac{1}{c_n} f(2T) = \quad (18)$$
$$= h(0) + \frac{1}{c_n}\left[f(2T) - f(T)\right]$$

which shows that (16) is indeed true for $k = 1$. Now, let us assume that (16) holds for each $k = 1, 2, \ldots, m$, where m is a positive integer. Then, using this assumption, it can be found from (17) that

$$u\left[(m+1)T\right] =$$
$$= y_d - \sum_{j=0}^{m} u(jT) + \sum_{j=0}^{m} h(jT) + \frac{1}{c_n} f\left[(m+2)T\right] =$$
$$= y_d - u(0) - \sum_{j=1}^{m} u(jT) + \sum_{j=0}^{m} h(jT) + \frac{1}{c_n} f\left[(m+2)T\right] =$$
$$= -\frac{1}{c_n} f(T) - \sum_{j=1}^{m} h\left[(j-1)T\right] + \sum_{j=0}^{m} h(jT) +$$
$$- \frac{1}{c_n} \sum_{j=1}^{m} \left\{f\left[(j+1)T\right] - f(jT)\right\} + \frac{1}{c_n} f\left[(m+2)T\right] =$$
$$= h(mT) + \frac{1}{c_n}\left\{f\left[(m+2)T\right] - f\left[(m+1)T\right]\right\} \quad (19)$$

which proves relation (16) for $k = m + 1$. Finally, taking into account (18) and (19) one can conclude that relation (16) actually holds for any positive integer k. This ends the proof of the lemma.

Remark 1 Since $f(kT) = 0$ for $k \geq k_0$, then relation (16) can be rewritten as $u(kT) = h[(k-1)T]$.

Remark 2 From the definition of function f and the above considerations one can easily notice that the following relations hold

- $f(0) = -\boldsymbol{c}^{\mathrm{T}}\boldsymbol{e}(0) = -c_n y_d$
- c_n and $f(kT)$ have opposite signs; consequently

$$\forall_{k \geq 0} \quad -y_d \leq \frac{1}{c_n} f(kT) \leq 0 \quad (20)$$

- $$\forall_{k \geq 0} \quad 0 \leq \frac{1}{c_n}\left\{f\left[(k+1)T\right] - f(kT)\right\} \leq y_d \quad (21)$$

Relations (2), (15), (20), (21) and the lemma show that the designed discrete time sliding mode controller determines data transmission rate which is nonnegative and upper bounded at any time instant $kT \geq 0$, i.e.

$$\forall_{k \geq 0} \quad 0 \leq u(kT) \leq d_{\max} + y_d \quad (22)$$

In the sequel, two theorems which state favourable properties of the proposed flow control scheme are proved.

Theorem 1 If the proposed strategy is applied, then the queue length is always upper bounded by its demand value, i.e.

$$\underset{k\geq 0}{\forall} \quad y(kT) \leq y_d \tag{23}$$

Proof: Since the bottleneck buffer for any time $kT \leq RTT$ remains empty, then one has that the queue length $y(kT \leq RTT) = 0$. Therefore, in order to prove the theorem, it is only necessary to show that inequality (23) is satisfied for any integer $k \geq m_{RTT} + 1$.

Recall that the queue length for $kT > RTT$ is determined by (3). Since it follows from (2) that the consumed bandwidth is always nonnegative, then using the lemma, equation (3) can be rewritten as follows

$$\begin{aligned}
y(kT) &= u(0) + \sum_{j=1}^{k-m_{RTT}-1} u(jT) - \sum_{j=0}^{k-1} h(jT) = \\
&= y_d + \frac{1}{c_n} f(T) + \\
&\quad + \sum_{j=1}^{k-m_{RTT}-1} \left\{ h[(j-1)T] + \frac{1}{c_n} \{ f[(j+1)T] - f(jT) \} \right\} + \\
&\quad - \sum_{j=0}^{k-1} h(jT) = \\
&= y_d + \frac{1}{c_n} f(T) + \sum_{j=1}^{k-m_{RTT}-1} h[(j-1)T] - \sum_{j=0}^{k-1} h(jT) + \\
&\quad + \frac{1}{c_n} \sum_{j=1}^{k-m_{RTT}-1} \{ f[(j+1)T] - f(jT) \} = \\
&= y_d - \sum_{j=k-m_{RTT}-1}^{k-1} h(jT) + \frac{1}{c_n} f[(k-m_{RTT})T] \leq y_d
\end{aligned} \tag{24}$$

which shows that the bottleneck buffer queue length is actually upper bounded by its demand value y_d for any $k \geq 0$. This completes the proof of Theorem 1.

Another desirable property of the analyzed sliding mode flow control system is full bottleneck link bandwidth utilization. If the queue length $y[(k + 1)T]$ is greater than zero, then the link bandwidth $d(kT)$ is fully used. The next theorem gives the condition guarantying that the queue length is strictly positive.

Theorem 2 If the proposed flow controller is applied and the demand queue length satisfies the following inequality

$$y_d > (m_{RTT} + 1) d_{\max} \tag{25}$$

then for any integer $k \geq m_{RTT} + k_0 + 1$ the queue length in the bottleneck buffer is always strictly positive.

Proof: Notice that by definition function $f(kT) = 0$ for any $k \geq m_{RTT} + k_0 + 1$. Moreover, from (2) one has that the consumed bandwidth is always upper bounded, i.e. for any integer $k \geq 0$ inequality $h(kT) \leq d_{\max}$ holds. In consequence, from relations (24) and (25) one obtains that for $k \geq m_{RTT} + k_0 + 1$

$$y(kT) = y_d - \sum_{j=k-m_{RTT}-1}^{k-1} h(jT) \geq y_d - (m_{RTT} + 1) d_{\max} > 0 \tag{26}$$

In other words, if condition (25) is satisfied then at any time instant $kT \geq RTT + (k_0 + 1)T$ there are always data units in the bottleneck buffer and the available bandwidth is fully used. This conclusion ends the proof of Theorem 2.

4. SIMULATION EXAMPLE

In order to verify the properties of the sliding mode flow control strategy proposed in this paper computer simulations of network (4) are performed. The discretisation period T is selected as 1 ms. The round trip time RTT in the virtual circuit is assumed to be 10 ms. Consequently, $m_{RTT} = 10$ and $n = 11$. The forward and backward propagation delays are 2 ms and 8 ms, respectively. The maximum available bandwidth of the bottleneck link $d_{\max} = 4$ Mb per second. Function $f(kT)$ is defined by formula (8) with k_0 equal to 5 and 20. The bandwidth which is actually available for the connection is shown in Figure 2. According to Theorem 2, the demand value of the queue length required to assure full link bandwidth utilization in the analyzed network must be at least equal to 0.044 Mb. Consequently, $y_d = 0.0502$ Mb, which is a multiple of the ATM cell length, is chosen. The transmission rate generated by the controller and the queue length evolution for $k_0 = 5$ and $k_0 = 20$ are shown in Figures 3 and 4, respectively.

It can be clearly seen from the figures that the transmission rate is always nonnegative and upper bounded. Furthermore, increasing k_0 significantly reduces the initial flow rate magnitude. Moreover, the queue length actually never exceeds its demand value which implies no data loss in the bottleneck node and no need for data retransmission. Furthermore, for any time greater than $(k_0 + 11)$ ms the queue length is positive, which implies full utilization of the available bandwidth.

5. CONCLUSION

A new discrete time sliding mode flow control strategy for a single virtual circuit in connection-oriented communication networks has been presented. The strategy which employs a time-varying sliding hyperplane is designed so that the closed-loop system stability and finite-time error convergence are ensured. Furthermore, conditions for full bottleneck node link utilization and no cell loss in the controlled network are derived. As a result, the need for cell retransmission is eliminated and the maximum throughput is achieved. The flow rate generated by the proposed strategy is always nonnegative and bounded which is important for the real network implementation. Further research on adapting the control strategy proposed in this paper for multi-source networks is currently being performed by the authors.

REFERENCES

Bartoszewicz, A. (2006). Nonlinear flow control strategies for connection-oriented communication networks. *IEE Proceedings on Control Theory and Applications*, Vol. **153**, No.1, pp. 21–28.

Bartoszewicz, A. (1998). Discrete time quasi-sliding mode control strategies. *IEEE Transactions on Industrial Electronics*, Vol. **45**, No.4, pp. 633–637.

Bartoszewicz, A. (1996). Time-varying sliding modes for second-order systems. *IEE Proceedings on Control Theory and Applications*, Vol. **143**, No.5, pp. 455–462.

Bartoszewicz, A. and A. Nowacka (2005). Switching plane design for the sliding mode control of systems with elastic input constraints. *Proceedings of Institution of Mechanical Engineers, Part I, Journal of Systems & Control Engineering*, Vol. **219**, No.6, pp. 393–403.

Chong, S., R. Nagarajan and Y. Wang (1998). First-order rate-based flow control with dynamic queue threshold for high-speed wide-area ATM networks. *Computer Networks and ISDN Systems*, Vol. **29**, pp. 2201–2212.

DeCarlo, R.S., S. Żak and G. Mathews (1988). Variable structure control of nonlinear multivariable systems: a tutorial. *Proceedings of IEEE*, Vol. **76**, No.3, pp. 212–232.

Furuta, K. (1990). Sliding mode control of a discrete system. *Systems & Control Letters*, Vol. **14**, pp. 145–152.

Gao, W., Y. Wang and A. Homaifa (1995). Discrete-time variable structure control systems. *IEEE Transactions on Industrial Electronics*, Vol. **42**, pp. 117–122.

Imer, O., S. Compans, T. Basar and R. Srikant (2001). Available bit rate congestion control in ATM networks. *IEEE Control Systems Magazine*, pp. 38–56.

Jagannathan, S. and J. Talluri (2002). Predictive congestion control of ATM networks: multiple sources/single buffer scenario. *Automatica*, Vol. **38**, pp. 815–820.

Laberteaux, K., Ch. Rohrs and P. Antsaklis (2002). A practical controller for explicit rate congestion control. *IEEE Transactions on Automatic Control*, Vol. **47**, pp. 960–978.

Lengliz, I. and F. Kamoun (2000). A rate-based flow control method for ABR service in ATM networks. *Computer Networks*, Vol. **34**, pp. 129–138.

Mascolo, S. (2000). Smith's principle for congestion control in high-speed data networks. *IEEE Transactions on Automatic Control*, Vol. **45**, pp. 358–364.

Slotine, J.J. and W. Li (1991). *Applied Nonlinear Control*. Prentice-Hall International Editions.

Utkin, V. (1977). Variable structure systems with sliding modes. *IEEE Transactions on Automatic Control*, Vol. **22**, pp. 212–222.

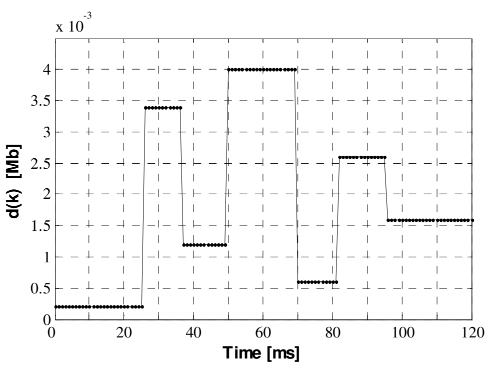

Fig. 2. Available bandwidth.

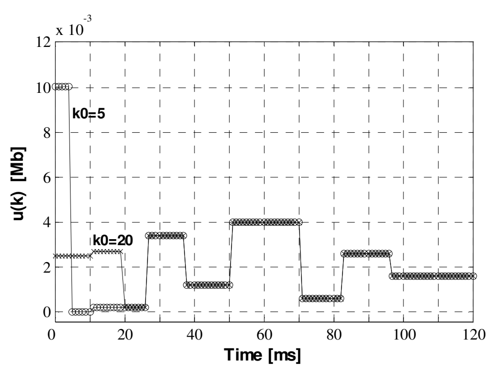

Fig. 3. Amount of data generated by the controller.

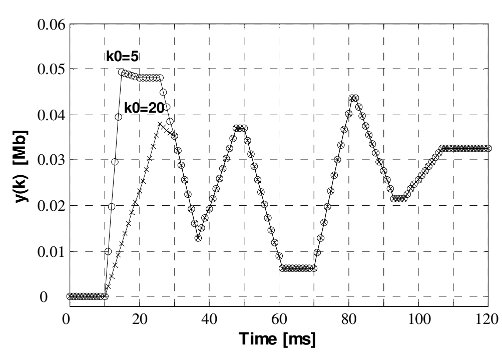

Fig. 4. Queue length.