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CONGESTION CONTROL IN CONNECTION-ORIENTED DATA TRANSMISSION NETWORKS

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In this paper formal, control-theoretic methods are applied to design an efficient congestion control algorithm for modern connection-oriented data transmission networks. The design is based on the principles of discrete-time sliding-mode control and linear-quadratic optimal control. The asymptotic stability of the closed-loop system with the designed controller implemented is demonstrated, and the conditions for achieving the maximum throughput in the networks are defined.

1. INTRODUCTION

In recent years, we have experienced a rapid evolution of networking services and an increase in long distance traffic intensity in telecommunication systems. In addition to fast and reliable information interchange, crucial e.g. for banking transactions, modern data transmission networks are expected to provide high-throughput, low-jitter end-to-end connectivity, which is important for multimedia transmission. Since such a large variety of networking applications cannot be satisfactorily served by the currently available connectionless technologies, the attention of the research community turns toward connection-oriented solutions [1]. In this kind of networks, a virtual circuit is created between the communicating entities before the actual exchange of data commences. Transferring the data along the established, fast-switched path, extends the possibilities for loss reduction, more efficient resource utilization, and Quality-of-Service (QoS) enhancements. However, all of these can only be achieved if the available resources are administered in a coordinated manner according to dynamically changing networking conditions. If the network load increases beyond the channel capacity, a congestion occurs, leading to packet discards and throughput degradation. If, on the other hand, the traffic intensity excessively drops, then only part of the available bandwidth at the intermediate links is used for the data transfer, and the revenue of telecommunication service providers decreases. Therefore, in order to combat the congestion and at the same time ensure high throughput in the network, it is imperative to implement appropriate flow control mechanisms which will guarantee stable and efficient network operation [2].

The summary of earlier flow control schemes can be found in [3]. Afterwards, various authors proposed the use of control engineering techniques [4, 5], a stochastic analysis [6], a game theory [7], and elements of artificial intelligence [8] to regulate the flow of data in communication networks. Since high throughput and robustness are of primary concern for handling a diversity of services and for fulfilling the traffic demand of the users, in this work a new algorithm based on the robust regulation technique – sliding mode control (SMC) [9] – is developed. The key part of the design of SM controllers is the selection of an appropriate sliding plane [10]. Here, the plane parameters are obtained from the linear-quadratic (LQ) optimization procedure [11]. In contrast to the typical approaches to the LQ problem [12], the optimization task for the considered system is solved analytically, which leads to a simple in-implementation and operationally efficient form of the control law. The conditions for eliminating the packet losses and entire bandwidth usage are specified. In consequence, the proposed algorithm ensures the maximum throughput in the network.

2. NETWORK MODEL

The connection-oriented network considered in this paper consists of data sources, intermediate nodes and destinations. The sources send data packets at the rate determined by the controller placed at a network node. The packets pass through a series of nodes operating in the store-and-forward mode without the traffic prioritization to be finally delivered to the destination. However, somewhere on the transmission path a node is encountered, whose output link cannot handle the incoming flow. Consequently, a congestion occurs, and the packets accumulate in the buffer allocated for that link. We assume that the sources are persistent, and the congestion control problem can be solved through an appropriate input rate adjustment only.

We deal with m data flows which pass through the bottleneck link. The feedback mechanism for the input rate regulation is provided by means of control units emitted periodically by each source. These special units travel along the same path as data packets. However, unlike data packets, they are not stored in the queues at the intermediate nodes. Instead, once they appear at the node input link and the feedback information is incorporated, they are immediately transferred at the appropriate output port. As soon as control units reach the destination, they are turned back to be retrieved at the origin, and to be used for the transfer speed adjustment round trip time after they have been generated.

The presented scenario is illustrated in Figure 1. The sources send packets at discrete time instants kT, where T is the discretization period and k = 0, 1, 2,..., in the amounts determined by the controller placed at the bottleneck node. After forward propagation delay T_{fp} packets from source p (p = 1, 2,..., m) reach the bottleneck node and are served according to bandwidth availability at the output link $d(kT)$. The remaining data accumulates in the buffer. The packet queue length in the buffer, which at time kT will be denoted as $y(kT)$, and its demand value y_d, are used to calculate the current amount of data $u(kT)$ to be sent by the sources. The mth share of the total amount, $u(kT)/m$, is recorded as the feedback information in every management unit passing through the node. Once the control units from source p appear at the end system, they are turned back to arrive at their origin with backward propagation delay T_{bp} after being processed by the congested node. Since the management units are not subject to the queuing delays, round trip time $RTT_p = T_{fp} + T_{bp} = n_pT$, where n_p is a positive integer, remains constant for the duration of the connection. Without the loss of generality we may order the flows in the following way

$$RTT_1 \le RTT_2 \le \ldots \le RTT_{m-1} \le RTT_m \tag{1}$$

Denoting the number of flows whose round trip time equals jT (j = 1, 2, …, n_m) by β_j we have $\sum_{j=1}^{n_m} \beta_j = m$, where some β_j may be equal to zero (including all β_j, for $j < n_1$).

The available bandwidth (the number of packets which may leave the bottleneck node at the kT instant) is modeled as an *a priori* unknown, bounded function of time $d(kT)$. If there are packets ready for the transmission in the buffer, then the bandwidth consumed by the sources $h(kT)$ (the number of packets actually leaving the node) will be equal to the available bandwidth. Otherwise, the output link is underutilized and the exploited bandwidth matches the data arrival rate at the node. Thus, we may write

$$0 \le h(kT) \le d(kT) \le d_{\max} \tag{2}$$

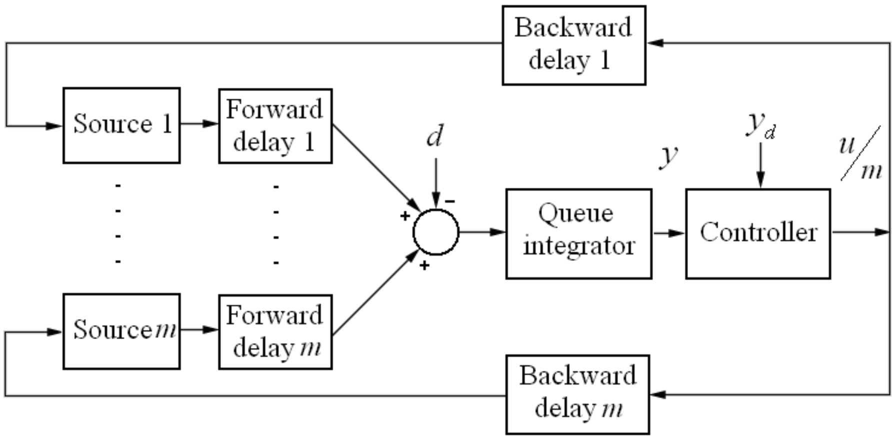

Fig. 1. Network model

The rate of change of the queue length depends on the amount of arriving data and on the consumed bandwidth h. Assuming that before the connection is established there are no packets in the buffer, the queue length $y(kT \geq 0)$ may be expressed as

$$y(kT) = \sum_{p=1}^{m}\sum_{i=0}^{k-1}\frac{1}{m}u\left(iT - RTT_p\right) - \sum_{i=0}^{k-1}h\left(iT\right) = \sum_{j=1}^{n_m}\frac{\beta_j}{m}\sum_{i=0}^{k-j-1}u\left(iT\right) - \sum_{i=0}^{k-1}h\left(iT\right) \quad (3)$$

The network can also be described in the state space as

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

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

$$\mathbf{A} = \begin{bmatrix} 1 & a_{n-1} & a_{n-2} & \cdots & a_1 \\ 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & 1 \\ 0 & 0 & 0 & \cdots & 0 \end{bmatrix} \quad \mathbf{b} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix} \quad \mathbf{o} = \begin{bmatrix} -1 \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix} \quad \mathbf{q} = \begin{bmatrix} 1 \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix} \quad (5)$$

and the system order $n = n_m + 1$. Since $\sum_{j=1}^{n_m}\beta_j = m$, the elements of the first row of matrix $\mathbf{A}$, $a_j = \beta_j/m$, satisfy $\sum_{j=1}^{n-1}a_j = 1$.

3. PROPOSED CONTROL STRATEGY

In this section a discrete-time SM controller for the considered network is designed. The key issue in the design is the selection of an appropriate sliding plane. In this paper, LQ optimization is applied to obtain the hyperplane parameters. The system with the proposed controller implemented is shown to be asymptotically stable.

Let us introduce a sliding hyperplane described by the following equation

$$s(kT) = \mathbf{c}^T \mathbf{e}(kT) = 0 \tag{6}$$

where $\mathbf{e}(kT) = \mathbf{x_d} - \mathbf{x}(kT)$ denotes the closed-loop system error and $\mathbf{c}^T = [c_1 \ c_2 \ \dots \ c_n]$ is such a vector that $\mathbf{c}^T\mathbf{b} \neq 0$. Substituting (5) into equation $\mathbf{c}^T\mathbf{e}[(k+1)T] = 0$, the following feedback control law can be derived

$$u(kT) = \left(\mathbf{c}^T \mathbf{b}\right)^{-1} \mathbf{c}^T \left[\mathbf{x_d} - \mathbf{A}\mathbf{x}(kT)\right] \tag{7}$$

which after substituting the matrix and vector variables takes the following form

$$u(kT) = c_n^{-1} \left\{ c_1 \left[y_d - x_1(k) - a_{n-1} x_2(k) \right] - \sum_{j=3}^{n} \left(c_1 a_{n-j+1} + c_{j-1} \right) x_j(k) \right\} \tag{8}$$

It is clear from (8) that the properties of the SM controller will be determined by the appropriate choice of the sliding plane parameters $c_1, c_2, \dots, c_n$. In the further part of the paper the elements of vector $\mathbf{c}$ are selected for the LQ optimal control law.

We may define the aim of the control action as bringing the system state to the desired value without an excessive control effort, or, alternatively, as reducing the closed-loop system error to zero using a reasonable and smoothly varying data flow rate. Therefore, we seek a control $u_{opt}(kT)$, which minimizes the following quality criterion

$$J(u) = \sum_{k=0}^{\infty} \left\{ u^2(kT) + w\left[y_d - y(kT) \right]^2 \right\} \tag{9}$$

where w is a positive constant applied to adjust the influence of the controller command and the output variable on the value of cost functional J.

According to [11], for time-invariant discrete time system (5) the optimal control $u_{opt}(kT)$, minimizing criterion (9), can be presented as

$$u_{opt}(kT) = -\mathbf{g}\mathbf{x}(kT) + r \tag{10}$$

where

$$\mathbf{g} = \mathbf{b}^T\mathbf{K}\left(\mathbf{I_n} + \mathbf{b}\mathbf{b}^T\mathbf{K}\right)^{-1}\mathbf{A}$$
$$r = \mathbf{b}^T\left[\mathbf{K}\left(\mathbf{I_n} + \mathbf{b}\mathbf{b}^T\mathbf{K}\right)^{-1}\mathbf{b}\mathbf{b}^T - \mathbf{I_n}\right]\mathbf{k} \tag{11}$$
$$\mathbf{k} = -\mathbf{A}^T\left[\mathbf{K}\left(\mathbf{I_n} + \mathbf{b}\mathbf{b}^T\mathbf{K}\right)^{-1}\mathbf{b}\mathbf{b}^T - \mathbf{I_n}\right]\mathbf{k} - w\mathbf{q}y_d$$

and semipositive, symmetric matrix $\mathbf{K}$ ($\mathbf{K}^T = \mathbf{K} \geq 0$) is determined according to the following Riccati equation

$$\mathbf{K} = \mathbf{A}^T\mathbf{K}\left(\mathbf{I_n} + \mathbf{b}\mathbf{b}^T\mathbf{K}\right)^{-1}\mathbf{A} + w\mathbf{q}\mathbf{q}^T \tag{12}$$

Classical approaches for solving (12), as suggested in the literature (e.g. [12]), are mainly suitable for numerical calculations and systems with predefined dimensions. However, in our case an analytical solution of the Riccati equation needs to be found for a system of arbitrary order n. The new method proposed here is based on the iterative substitution of $\mathbf{K}$ into the expression on the right hand side of (12) and comparison with its left hand side so that at each step the number of independent variables k_{ij}, where k_{ij} denotes the element in the i-th row and j-th column of $\mathbf{K}$, is reduced. In order to eliminate oscillations and negative rate signals resulting from the exact solution, a modification of the optimization is introduced, which neglects the products $a_i a_j \ll 1$. The vector describing the enhanced, suboptimal sliding plane is determined as

$$\mathbf{c}^T = \begin{bmatrix} 1 & a_{n-1} & (a_{n-1} + a_{n-2}) & \ldots & (a_{n-1} + \ldots + a_1) \end{bmatrix}\alpha \tag{13}$$

where $\alpha = \left(\sqrt{w(w+4)} - w\right)/2$, and the SM control law

$$\begin{aligned} u(kT) &= \alpha\left[y_d - x_1(kT) - \sum_{j=2}^{n}\left(\sum_{i=1}^{j-1} a_{n-i}\right)x_j(kT)\right] \\ &= \alpha\left\{y_d - y(kT) - \frac{1}{m}\sum_{j=1}^{n_m}\beta_j\sum_{i=1}^{j}u[(k-i)T]\right\} \end{aligned} \tag{14}$$

The system is asymptotically stable if all the roots of the characteristic polynomial of the closed-loop state matrix $\mathbf{A_c} = [\mathbf{I_n} - \mathbf{b}(\mathbf{c}^T\mathbf{b})^{-1}\mathbf{c}^T]\mathbf{A}$ are located within the unit circle. The roots of the polynomial

$$\det\left(z\mathbf{I_n} - \mathbf{A_c}\right) = z^n + (\alpha - 1)z^{n-1} = z^{n-1}\left[z - (1 - \alpha)\right] \tag{15}$$

are located inside the unit circle, if $0 < \alpha < 2$. Since $\forall w\ \alpha$ is positive and smaller than one, the system is stable, and no oscillations appear at the output.

4. PROPERTIES OF THE PROPOSED CONTROLLER

The properties of the proposed algorithm will be formulated as three theorems. The first theorem defines the memory requirements for the buffers at the bottleneck node which guarantee the loss-free transmission. The second proposition imposes a constraint on the demand queue length necessary to obtain the full resource usage in the network. Finally, the third theorem states that the transfer speed assigned for the sources is always nonnegative and bounded, which is a critical prerequisite in the design of feasible network controllers.

Theorem 1: If the proposed strategy is applied, then the queue length is always upper-bounded, i.e.

$$\forall_{k \geq 0} \; y(kT) \leq y_d \tag{16}$$

Theorem 2: If the proposed strategy is applied, and the demand queue length satisfies

$$y_d > d_{\max} \left(\frac{1}{mT} \sum_{p=1}^{m} RTT_p + \frac{1}{\alpha} \right) \tag{17}$$

then for any $k \geq n$ the queue length is strictly positive implying the entire bandwidth usage.

Theorem 3: If the proposed strategy is applied, then the transmission rate is always nonnegative and bounded, i.e.

$$\forall_{k \geq 0} \; 0 \leq u(kT) \leq \max\left(\alpha y_d, d_{\max}\right) \tag{18}$$

5. CONCLUSIONS

In this paper, a sliding-mode flow controller for multi-source connection-oriented networks has been proposed. The design procedure focused on the minimization of the quadratic cost functional and the solution of the resultant matrix Riccati equation for the n-th order discrete-time system. For the obtained control law, the closed-loop system stability was demonstrated, and conditions for data loss elimination and full available bandwidth utilization were formulated. Since the rates generated by the controller are always nonnegative and limited, the proposed strategy can be applied in real telecommunication networks. Moreover, since the control law is given in a closed form, which results from the analytical solution of the optimization problem, it can be easily and efficiently implemented in practical systems.

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STEROWANIE PRZEPŁYWEM DANYCH W POŁĄCZENIOWYCH SIECIACH TELEINFORMATYCZNYCH

Streszczenie

W pracy zaprojektowano nowy algorytm sterowania przepływem danych dla połączeniowych sieci teleinformatycznych. Do tego celu wykorzystano zaawansowane metody teorii sterowania – dyskretne sterowanie ślizgowe oraz dyskretne sterowanie optymalne z kwadratowym wskaźnikiem jakości. Pokazano, że zaproponowany algorytm pozwala wyeliminować ryzyko gubienia danych przy jednoczesnym pełnym wykorzystaniu dostępnego pasma.

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