An LMI Approach for Differentiated Services Network Robust Congestion Control with Uncertain Time-Variant Delays

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Summary
The growing demand of network applications requires efficient mechanisms for managing network traffic in order to avoid or at least limit the level of congestion. We design and analyzed a robust congestion controller for controlling traffic using information on the status of each queue in the network. This controller is based on a discrete-time model of the network, thus we do not need to simplification and linearization that is often used in congestion controller design. We assume a differentiated-services network framework and formulate our control strategy for three types of services: Premium Service, Ordinary Service, and Best Effort Service. The three differentiated classes of traffic operate at each output port of a router/switch. A robust controller is designed for ordinary output port, with consideration priority of premium services and delay of links. The controller has been applied to an ATM network.

Keywords:
Congestion Control, Linear Matrix Inequality, Time Delay System, Differentiated Services

1. Introduction

The rapid growth of the networks and increased demand to use the networks and Internet for time-sensitive applications necessitate the design and implementation of new network architectures to include more effective congestion control algorithms. The event of congestion occurred when number of packets arrive to a node be more than of capacity of node. Many congestion control algorithms was designed for solve this problem. The development of such effective congestion control protocols will require cooperation between networking and control researchers.

Recently Internet use for many applications and on a network data, voice, video and other packets are transported. Each application in Internet needs corresponding quality of service (QoS). Some of packets are sensitive to delay and jitter (like voice and video streams) and some packets need to arrive to destination without any packet lost (like data packets).

As a result, the Differentiated Services (Diff-Serv) architecture was proposed [1] to prepare QoS in IP networks. Several classes of services are defined in this architecture and network serve each packet regards to corresponding class type.

For guarantee of QoS for each class of services some parameters are required, congestion control is one of the most important parameter for QoS guarantee. Some of common congestion control algorithms like random early detection (RED) are applied to Differentiated services network. There are some studies for diffserv controller design. In [2] a nonlinear controller design and [3] shows an adaptive nonlinear congestion controller has a good performance. In [4] a linear H_∞ controller is designed for diffserv. Fuzzy control theory is another interesting area for congestion control in diffserv [5,6].

In this paper considering the loop delay a robust controller for discrete queue model of differentiated services has been proposed. Linear matrix inequality has been used for design of this controller. At the end, the performance of the controller has been shown by MATLAB simulations considering uncertainties on the propagation delay of packets arriving the network. Since many of the senders do not conform the controller rules, a disturbance signal is added to have a better real situation.

2. Dynamic Model

We divide traffic into three basic types of service: Premium Traffic Service, Ordinary Traffic Service, and Best Effort Traffic Service. The Premium Traffic Service may is designed for applications with stringent delay and loss requirements that can specify upper bounds on their traffic needs and required QoS. It is assumed that the user may contract with the network for use this service. The user has not permission to exceed the peak rate. Typical applications include video on demand, audio, video conferencing, etc.

The Ordinary Traffic Service is the next DiffServ architecture. The Ordinary Traffic Service is intended for applications that have relaxed delay requirements and allow their rate into the network to be controlled. These Services use any left over capacity from the Premium Traffic. Note that to ensure that bandwidth is leftover from the Premium Traffic Service a minimum bandwidth may be assigned, e.g., by using bandwidth allocation between

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services or connection admission. Typical applications include web browsing, image retrieval, e-mail, ftp, etc. Finally, the Best Effort Traffic Service is the last DiffServ architecture. It has no delay or loss expectations. It opportunistically uses any instantaneous leftover capacity from both Premium and Ordinary Traffic Services.

We assume a generic output buffered switch as a reference model. The switch has K input and K output ports. Each output port has a number of physical or logical queues: one for each traffic class. Caused as a result of the rate mismatch between the packets flow into the queue and processing capacity of queue, there is a potential bottleneck at each output port of the switch. Since the cause of the bottleneck is limited link capacity at the output ports of the switch, the congestion control scheme will be explained with respect to a specific output. A congestion controller is designed for each queue. By tightly controlling each output port, the overall performance is also expected to be tightly controlled. At each output port of the switch we assume that dedicated queue size is allocated for each one of the three services (see Fig. 1).

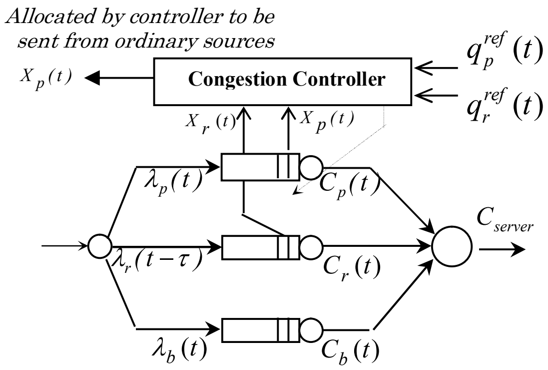

Fig. 1 Implementation of the control strategy at each switch

Premium Service needs strict guarantees of transport, within desired packet loss and delay bounds. At the connection phase, any regulation of this type of traffic has to be achieved. Once admitted into the network the network has to offer service in accordance with the given guarantees. This is the task of the Premium Traffic Controller. Ordinary Traffic on the other hand allows the network to regulate its flow (pace it) into the network. It cannot tolerate loss of packets. It can however tolerate queuing delays. This is the task of the Ordinary Traffic Controller. Best Effort Service on the other hand offers no guarantees on either loss or delay. It makes use of any instantaneous leftover capacity. For Premium Traffic Service, our approach is to tightly control the length of the Premium Traffic queue to be always close to a reference value, chosen by the network operator, so as to indirectly guarantee acceptable bounds for the maximum delay and loss. The capacity for the Premium Traffic is dynamically allocated, up to the physical server limit, or a given maximum. In this way, the Premium Traffic is always given resources, up to the allocated maximum to ensure the provision of Premium Traffic Service with known bounds. Due to the dynamic nature of the allocated capacity, whenever this service has excess capacity beyond that required to maintain its QoS at the prescribed levels (as set by the queue length reference value) it offers it to the ordinary traffic service. This algorithm uses the error between the queue length of the premium traffic queue $x_P(t)$ and the reference queue length as x_P^{ref} the feedback information and calculates the capacity $C_P(t)$ to be provisioned to premium traffic, to minimize the error. By considering the length of the ordinary traffic queue and the available capacity, the ordinary traffic service controller controls the flow of ordinary traffic into the network. The length of the ordinary traffic queue is compared with the reference value and using a robust control strategy it calculates and informs the sources of the maximum allowed rate they can transmit over the next control interval. This algorithm takes into account leftover capacity $C_r(t) = \max[0, C_{server} - C_P(t)]$, uses error between queue length $x_r(t)$ of Ordinary Traffic queue and reference queue length x_r^{ref}, and calculates the common rate $\lambda_r(t)$ to be allocated to the Ordinary Traffic users once every control interval T_s ms, based on the robust control algorithm. Once the common rate is calculated it is sent (feedback) to all upstream sources. Based on the received common rate, the source does not allow its transmission rate to exceed this value over the next control interval. Note that any excess source demand (above received common rate) is queued at the source queues, rather than be allowed to enter the network, and thus cause congestion.

The best effort traffic service uses any instantaneous left over capacity. Unlike other studies about diffserv networks [2-5] we use discrete time model to design desired controller. In other works fluid flow model used. For example for premium and ordinary traffic they used flowing model:

$$\dot{x}_p(t) = \mu C_P(t)\left(\frac{x_P(t)}{1+x_P(t)} + \Delta\right) + \lambda_P(t) \tag{1}$$

$$\dot{x}_r(t) = \mu C_r(t)\left(\frac{x_r(t)}{1+x_r(t)} + \Delta\right) + \lambda_P(t-\tau) \tag{2}$$

In this section a discrete state space equation for queue is presented. The model has been extended to consider traffic delays and include modeling uncertainties. A diagram of a sample queue is depicted in figure 1. As it is shown $\lambda(n)$ is the arrival packet and $C(n)$ is the departure rate and $q(n)$ is the queue length at each time sequence.

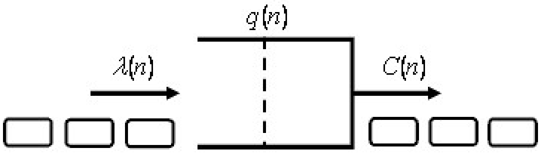

Fig. 2. Discrete time queue model

When the sum of the sources data transmission rates at an intermediate node along the virtual paths exceeds either the pre-specified packet delay or buffer capacity the congestion occurs. It is necessary to inform the bottleneck its current network status or control signal to throttled sources or up-stream sources at distant locations. The status update is used to determine the appropriate source transmission rate for subsequent incoming cells of the throttled sources. Such status information consists of the service rate, buffer occupancy and incoming traffic rate toward the throttled node.
Then for each queue we can write a dynamic discrete time model like below:

$$q(n+1)=q(n)+\lambda(n)-C(n) \tag{3}$$

In our diffserv queuing architecture we should formulate queue dynamic for each queue disciplinary. In premium traffic services we regulate service rate or capacity allocated to premium type traffic ($C_P(t)$) to track desired queue size x_P^{ref}. Thus in this traffic type the command control signal $U_P(k)$ is $C_P(t)$ as blow:

$$q_P(k+1)=q_P(k)+\lambda_P(k)-U_P(k) \tag{4}$$

In ordinary traffic type the controller regulate the ordinary traffic sender rate $\lambda_r(t)$ to track desired queue length. For this reason controller transmit a command signal to senders to set their sending rate as calculated suitable rate. Thus in every time k, entrance packets to router/switch are corresponding to calculating rate time *k-nT*, the *nT* is the round trip time between switch/router and sender. Note that we have many senders with different propagation delay. The ordinary traffic is modelled as below:

$$q_r(k+1)=q_r(k)+\sum_{d=0}^{D} I_d U_r(k-d+1)-C_r(k) \tag{5}$$

The source traffic reaching the congested node is delayed by d time units where d ranges from 0 to D. In this model I_d is the number of senders those have d time units delay.

Consider we have only one sender with n time units delay, we can realize the network model as below:

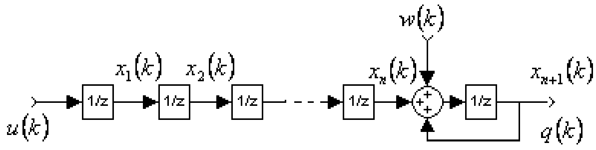

Fig. 3. Realization of discrete time queue model

Then we can define state variables:

$$x_1(k+1)=u(k)$$
$$x_2(k+1)=x_1(k)$$
$$\vdots$$
$$x_{n+1}(k+1)=x_{n+1}(k)+x_n(k)+w(k)$$
$$q(k)=x_{n+1}(k)$$

And then the state space equations are defined:

$$\begin{bmatrix} x_1(k+1) \\ x_2(k+1) \\ \vdots \\ x_n(k+1) \end{bmatrix} = \begin{vmatrix} 0 & 0 & \cdots & 0 & 0 \\ 1 & 0 & \cdots & 0 & 0 \\ \vdots & & \ddots & & \vdots \\ 0 & 0 & \cdots & 1 & 1 \end{vmatrix} \begin{bmatrix} x_1(k+1) \\ x_2(k+1) \\ \vdots \\ x_n(k+1) \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} u(k) + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} w(k)$$

$$y(k)=\begin{vmatrix} 0 & 0 & \cdots & 1 \end{vmatrix} \begin{bmatrix} x_1(k+1) \\ x_2(k+1) \\ \vdots \\ x_n(k+1) \end{bmatrix}$$

In this realization for n unit delay we have n state.

3. Robust Control Design

In this section we design a robust H_∞ controller for diffserv model. In premium traffic we have a linear discrete time system without any delay and disturbance and we do not have any complex problem. But in ordinary traffic the system has both delay in input signal and disturbance. In this paper our concentration is design of robust H_∞ controller for ordinary traffic.
We use linear matrix inequality approach to solve our problem because solving Riccati equation with many state space variables is very difficult.

Theorem: Suppose a discrete time linear time invariant system:

$$\begin{cases} x(k+1) = Ax(k) + Bw(k) \\ z(k) = Cx(k) + Dw(k) \end{cases} \tag{6}$$

Where *w(k)* is exogenous input and *z(k)* is objective signal. The transfer function of system is:

$$H_{wz} = D + C(zI - A)^{-1} B \tag{7}$$

Then

$$\begin{cases} \|H_{wz}\|_{\infty}^{2} < \mu \\ A \quad asymptotically \quad stable \end{cases} \tag{8}$$

if and only if there exist a symmetric matrix like P such that the blow linear matrix inequality has a feasible solution:

$$\begin{bmatrix} P & AP & B & 0 \\ PA^T & P & 0 & PC^T \\ B^T & 0 & I & D^T \\ 0 & CP & D & \mu I \end{bmatrix} > 0 \tag{9}$$

For ordinary traffic we consider the premium packets (that use an undetermined section capacity of link) as disturbance.
We solve our delay problem by considering that the system has the maximum value of delay *D* and solve the LMI and then in next section evaluate our design.

4. Simulation Results

In this section we represent the simulation results for the proposed model and evaluate the performance and effectiveness of the system to three different input delays. The controller is designed to regulate queue length of a network with 250ms input delay and we examine two scenarios and show each scenario's results. An arbitrary input is injected to the system to illustrate the performance of the controller in the vicinity of disturbance.

In this simulation we consider only ordinary services because design of premium service congestion controller in absent of delay is not difficult. For 250 milliseconds delay, we choose 40 times per second for queue sampling and sending suitable rate for senders. For this situation we have 10 units delay in RTT and we can model the ordinary service like (5) as below:

$$q_r(k+1) = q_r(k) + U_r(k-d+1) - w_r(k)$$

And in this form we have 10 state variables. We solve LMI that described in (9) in MATLAB and find proper P . the minimum μ in this format calculated as 44.7834 and the proper full information feedback is:

$$U_r(k) = K_1 X(k) + K_2 w_r(k)$$

when:

$K_1 = [2.8378 \quad 4.6106 \quad 6.2804 \quad 7.8100 \quad 9.1653 \quad 10.3158 \quad 11.2360 \quad 11.9053 \quad 12.3088 \quad 12.4374 \quad 12.4374]$

and

$K_2 = 6.0410$

Then the P is:

$$\begin{bmatrix}
88.1229 & -44.5041 & -0.0615 & -0.0037 & 0.0006 & -0.0002 & 0.0002 & 0.0000 & -0.0001 & 0.0000 & 0.0000 \\
-44.5041 & 88.1659 & -44.5325 & -0.0551 & -0.0032 & 0.0006 & -0.0001 & 0.0002 & -0.0000 & -0.0001 & 0.0000 \\
-0.0615 & -44.5325 & 88.2094 & -44.5612 & -0.0486 & -0.0026 & 0.0005 & -0.0001 & 0.0001 & -0.0000 & -0.0000 \\
-0.0037 & -0.0551 & -44.5612 & 88.2531 & -44.5901 & -0.0420 & -0.0021 & 0.0004 & -0.0001 & 0.0001 & -0.0000 \\
0.0006 & -0.0032 & -0.0486 & -44.5901 & 88.2971 & -44.6192 & -0.0354 & -0.0016 & 0.0003 & -0.0000 & 0.0000 \\
-0.0002 & 0.0006 & -0.0026 & -0.0420 & -44.6192 & 88.3414 & -44.6486 & -0.0286 & -0.0011 & 0.0002 & 0.0000 \\
0.0002 & -0.0001 & 0.0005 & -0.0021 & -0.0354 & -44.6486 & 88.3860 & -44.6781 & -0.0217 & -0.0007 & 0.0001 \\
0.0000 & 0.0002 & -0.0001 & 0.0004 & -0.0016 & -0.0286 & -44.6781 & 88.4308 & -44.7079 & -0.0148 & -0.0002 \\
-0.0001 & -0.0000 & 0.0001 & -0.0001 & 0.0003 & -0.0011 & -0.0217 & -44.7079 & 88.4759 & -44.7378 & -0.0076 \\
0.0000 & -0.0001 & -0.0000 & 0.0001 & -0.0000 & 0.0002 & -0.0007 & -0.0148 & -44.7378 & 88.5212 & -44.7682 \\
0.0000 & 0.0000 & -0.0000 & -0.0000 & 0.0000 & 0.0000 & 0.0001 & -0.0002 & -0.0076 & -44.7682 & 44.7757
\end{bmatrix} > 0$$

For simulation we consider a network topology like Fig. 4. The delays and number of senders in each scenario are different.

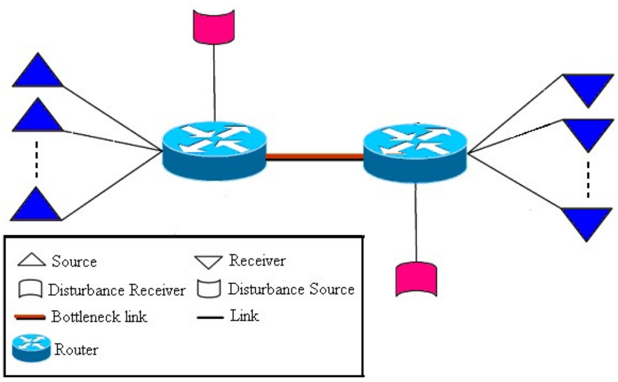

Fig. 4. Simulation Topology

A: First scenario

The delay of link is adjusted on 250ms as a nominal design value. The simulation result is depicted in Fig. 4.

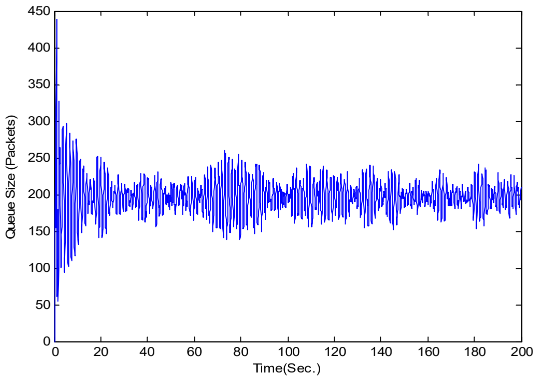

Fig. 5. Network queue length with 250ms input delay

B: Second scenario

We maintain disturbance as previous scenario. For evaluation of controller we consider 10 packet senders: 2 senders with 100ms delay, 5 senders with 160ms delay, and 3 senders with 220 ms delay. The result of queue monitoring is illustrated in Fig. 5.

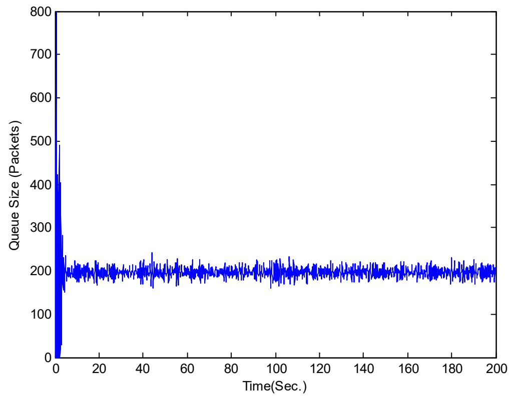

Fig. 6. Network queue length for under estimate delays

5. Conclusions

In this paper, we have introduced a new approach for robust control design for discrete time model congestion control. The proposed controller is based on linear matrix inequality. In order to validate and demonstrate the performance of the proposed algorithm and the robustness of the controller against various propagation delays and disturbance we provide step response results for two different scenarios. Simulation results prove the robustness of the controller against various input delays.

We suggest designing an optimal controller for this model considering because we solve sub optimal problem and evaluation the robustness of the model.

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