A Sliding Mode-based Congestion Control for Time Delayed Differentiated-Services Networks

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Abstract—In this paper robust control techniques are used and investigated for congestion control problem of time-delayed scalable differentiated Services (DiffServ) networks. The robustness capabilities of sliding mode variable structure control (SM-VSC) technique are utilized as a design basis for a new congestion control strategy subject to inaccurate/uncertain network model. The fluid flow model (FFM) adopted in this paper is of low order and simpler than a detailed Markovian queuing probabilistic models. The proposed time-delayed dependent congestion control dynamics is studied analytically to guarantee stability of the closed-loop system. To evaluate the capabilities of our proposed robust control strategy, simulation results are provided for different operating conditions and time-delay values.

Keywords: Time delayed networked control systems, Robust congestion control, Sliding mode-based variable structure control, stability analysis.

I. INTRODUCTION

The emergence of multi services is ineluctable to satisfy better user’s Quality-of-Services (QoS) guarantees even though most of the today’s Internet networks provide a single best effort service. To achieve end-to-end per-flow QoS, the Internet Engineering Task Force (IETF) working group has defined the differentiated services paradigm (DiffServ) [1] that is scalable.

It is widely agreed that congestion control problems are of significant importance in communication networks, and in particular within the DiffServ architecture in which fairness among traffic aggregates with different attributes cannot be adequately achieved with the current end-to-end Transport Control Protocol (TCP) technologies. Several congestion and flow control schemes have been proposed for multi services architectures in the literature. After the first unsuccessful attempt of the Integrated Services model [2] for implementation in real networks (mainly due to scalability problems), this model was combined with the Differentiated Services model to maximize on their advantages [3], [4]. To address bandwidth assurance and packet loss problems in DiffServ networks, the Aggregate Flow Control (AFC) scheme was proposed in [5] to improve fairness among traffic aggregates. To gain fairness among flows in each traffic class of the DiffServ architecture module, Fair Intelligent Congestion Control (FICC) scheme is applied at each queue and for each class of traffic [6]. In [7], an adaptive nonlinear congestion controller called the Integrated Dynamic Congestion Control (IDCC) is proposed using a nonlinear Fluid Flow Model (FFM). In [8], [9] [10], we have proposed Sliding Mode-based Variable Structure (SM-VS) congestion control strategies that are empowered by robustness properties.

In this paper, we extend our robust control approach introduced in [10] by deriving and studying analytically our proposed time delayed congestion control scheme for guaranteeing stability of a two nodes cascaded network. In §I a FFM-based DiffServ architecture is studied similar to what was accomplished in [7]. Design of our proposed robust congestion controller and its stability analysis corresponding to a time delayed dependent control system for both a single node as well as a two nodes cascaded framework are given in §II. In order to evaluate the performance and robustness of our considered time delay dependent networked control system, simulations are performed and results are given in §III. Finally conclusions are stated in §V.

A. Fluid Flow Model (FFM) DiffServ Architecture

In our proposed architecture, the traffic is divided similar to that in [1] and [7]. Specifically, we have three services: Premium service, Ordinary service and Best effort service. The first two services are denoted by p and r, respectively. The Premium Traffic Service requires strict guarantees of delivery within a given delay and loss bounds. The Ordinary Traffic Service allows the network to regulate the input flow, while it tolerates queuing delays but does not tolerate loss of information. It mainly uses the left over capacity from the premium traffic service. The Best Effort Traffic constitutes the third class which is less critical than the above two classes, where it utilizes the left over from the premium and ordinary traffics. The above three mentioned services are represented in our architecture that is illustrated in Figure 1. Generated by three different sources at the edge of the network, our traffic aggregates are separated and buffered at each switch output port. Consisting of three physical or logical queues the later constitutes a potential bottleneck. In our DiffServ architecture we design a robust decentralized congestion controller for a single switch output port that is duplicated to the other output ports of all nodes. Independent of the technology considered, (i.e. TCP/IP or ATM), the proposed control strategy is thus general, model-based and utilizes information on the status of each queue in the network. In this paper our traffic and network are modeled using the FFM approach. It is well known that among a number of formal models that may be used for describing the queuing systems, the FFM is...
A network assisted congestion controller [15]. Using the buffer queue length as feedback information, the later controls locally the queue length of each buffer by acting on the server bandwidth and simultaneously it sends back to the Ordinary source the allowed maximum rate. In virtue of its robustness, the Sliding Mode Variable Structure Control (SM-VSC) technique [16], [17] is utilized to design our proposed congestion control strategy.

A. Proposed congestion controller design

For a differentiated services framework as illustrated in Figure 1, the sliding mode congestion controller given by the following theorem is designed in the error state space by defining the error variables $e_i = x_i - x_{i,ref}$, $\hat{e}_i = \dot{x}_i - \dot{x}_{i,ref}$. By substituting them in model (1), the following error dynamics is obtained

$$
\begin{align*}
\dot{e}_i(t) &= -C_\mu(t) e_i(t) + x_{i,ref} + 1 + \lambda_i - \hat{x}_{i,ref}; (i = p, r) \\
y_i(t) &= e_i(t) + x_{i,ref}
\end{align*}
\tag{2}
$$

Theorem: (Congestion Control in Diff-Serv Architectures)

For the differentiated services architecture, having a buffer queuing model as described by the Fluid Flow Model (2), a nonlinear feedback-based control law exists

$$
\begin{align*}
C_p &= E_p^{-1}[\mu_p \rho_p + \mu_p \Omega_p \sgn(e_p) + \lambda_p - \hat{x}_{p,ref}] \\
\lambda_T &= C_T E_r - \mu_r \Omega_r \sgn(e_r) + \hat{x}_{r,ref}
\end{align*}
\tag{3}
$$

where $E_i = \frac{x_i}{x_i + 1} = \frac{e_i + x_{i,ref}}{e_i + x_{i,ref} + 1}$ with $i = p, r$ is the buffer occupancy, $\gamma_i = \mu_i \Omega_i$ with $\mu_i$, $\Omega_i$ are design parameters, $C_r(t) = C_{max} - C_p(t)$ with $C_p$, $C_r$ are the premium and ordinary buffer capacities, $C_{max}$ is the maximum available capacity that ensures asymptotic convergence of the error dynamics (2) in closed loop. Therefore,

$$
\dot{e} = -Ae - B\text{sgn}(e)
\tag{4}
$$

where $A = \text{diag}[\mu_p \mu_r], B = \text{diag}[\mu_p \Omega_p \mu_r \Omega_r]$ and $\sgn(e_i) = \text{col}[\sgn(e_p), \sgn(e_r)]$ is an asymptotically stable system if $\mu_1$ and $\Omega_1$ are selected as positive parameters.

Proof: Choose a candidate Lyapunov function $V(e, t) = e^T e$, where $e^T = [e_p \ e_r]$ such that for all $e \neq 0 \Rightarrow V(e, t) > 0$. The time derivative of the Lyapunov function along the trajectories of (4) is given by

$$
\dot{V}(e, t) = -\sum_{i=p, r} \mu_i e_i^2(t) - \sum_{i=p, r} \gamma_i e_i(t) \sgn(e_i(t))
\tag{5}
$$

It follows that since $\sgn(e_i(t)) = \frac{e_i(t)}{|e_i(t)|}$ with $(i = p, r)$, $\dot{V}(e, t)$ is strictly negative definite whenever the design parameters $\mu_i$ and $\Omega_i$ are selected to be positive, and hence $e_i(t) \rightarrow 0$.

B. Proposed time-delayed dependent control dynamics

Let us derive the FFM-based congestion control dynamics in presence of unknown but constant time delays. As illustrated in Figure 1, to study the sensitivity of our

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**Fig. 1.** The control strategy implemented at each switch output port
closed loop control system to time delays we introduce three block delays \( \tau_p, \tau_r \) and \( \tau_i \) in the Premium, Ordinary and Best effort channels, respectively. They capture and correspond to any delay/latency in the network due to propagation, processing, transmission, etc. factors. In presence of these delays, the FFM model (2) on which our proposed congestion controller is designed will then be time dependent and is given by

\[
\begin{align*}
\dot{e}_i(t) &= -C_i(t) \left( e_i(t) + x_{iref} + 1 + \lambda_i(t - \tau_i) - \dot{x}_{iref} \right) \\
y_i(t) &= e_i(t) + x_{iref}
\end{align*}
\]

where \( \tau_i \) is an unknown but constant delay coefficient.

**Assumption 1:** Given that the delay \( \tau_i \) is constant and bounded, the time delay signals may be approximated by their first-order representation as

\[\lambda_i(t - \tau_i) = \lambda_i(t) - \tau_i \dot{\lambda}_i(t)\]

Although the controller designed in the previous subsection does not assume any explicit information about the time delay, by substituting the control law (3) into the time delayed error dynamics (6), it follows that in the overall closed loop dynamics (given by (7)), the presence of time delay \( \tau \) will be different from that given by equations (4) corresponding to the non delayed closed loop system, namely we have

\[
\begin{align*}
\dot{e}_p &= -\mu_pe_p - \mu_p \Omega_p \text{sgn}(e_p) - \tau_p \dot{\lambda}_p \\
\dot{e}_r &= -D_0^{-1} \mu_r e_r - D_0^{-1} \mu_r \Omega_r \text{sgn}(e_r) - \tau_r D_0^{-1} P_r
\end{align*}
\]

where \( D_0 = (1 - \mu_r \tau_r) \) and \( P_r = -\mu_r \Omega_r \frac{d(\text{sgn}(e_r))}{dt} + \ddot{x}_{iref} + \frac{d(C_i E_r)}{dt} \).

**Lemma 1:** Under Assumption 1 and using the control law given by Theorem 1, the error dynamics described by (7) of the time delay dependent control system illustrated in Figure 1 is asymptotically stable whenever the design parameters \( \mu_i \) and \( \Omega_i \) in the control law (3) are positive and the ordinary delay \( \tau_r \leq \tau_{max} \), where \( \tau_{max} \) is the ordinary delay upper bound.

**Proof:** According to the two dynamics in (7), the premium buffer queue dynamics corresponds to the time delayed independent premium dynamics given in (4) with the presence of an additional disturbance \( \delta_p = -\tau_p \dot{\lambda}_p \). It is well known that such a system is stable whenever the disturbance \( \delta_p \) is bounded, implying that both \( \tau_p \) and the derivative of the premium traffic \( \dot{\lambda}_p \) will be bounded.

With respect to the ordinary buffer queue dynamics in (7), it corresponds to the time delay independent ordinary dynamics (4) that is now divided by \( D_0 \), a function of delay \( \tau_r \) and \( \mu_r \), and then augmented with one additional term. Note that since this additional term is nonlinear with respect to the state error \( e_r \), the overall ordinary error dynamics is now nonlinear and time delay dependent. We may thus conclude that a) the premium error dynamics is stable whenever the premium input traffic and the delay in the premium channel are bounded, and b) the ordinary error dynamics is nonlinear and time delay dependent.

In the following derivation we aim to show that the ordinary error dynamics is indeed sensitive to the time delay, but stability may be ensured if the time delay does not exceed a certain upper bound. Stability of the time delayed dependent ordinary dynamics may be investigated by studying the stability of the overall linearized dynamics around a certain operating point \( e_r \).

After computing the derivative of the term \( \frac{d(C_i E_r)}{dt} \) in the error dynamic (7), the ordinary error dynamics can be written as follows

\[
\dot{e}_r = -D_1 e_r - D_2 \text{sgn}(e_r) - D_3 \text{sgn}(e_r) - D_4 - D_5 P_r - D_6 P_r
\]

where \( D_1 = \frac{\mu_r}{D_0}, D_2 = \frac{\mu_p D_0}{D_0}, D_3 = -\frac{\mu_r \Omega_r}{D_0}, D_4 = \frac{\tau_r \dot{x}_{iref}}{D_0}, D_5 = -\frac{\tau_r \dot{C}_i}{D_0}, D_6 = \frac{\tau_r \dot{\lambda}_p}{D_0}, \text{sgn}(e_r) = \frac{d(\text{sgn}(e_r))}{dt} \) and \( P_r = \left( e_r + x_{iref} + 1 \right) \). Note that \( D_1, i = 0, \ldots, 6 \) contains mainly ordinary buffer delay \( \tau_r \). The sign function terms in the error dynamics (8) may be approximated by using different approaches. In [10], we approximated \( \text{sgn}(e_r) \) with \( \frac{e_r}{|e_r|} - 1 \), and subsequently the resulting continuous error dynamics is linearized. In this paper, we may show that the same results may be obtained by substituting \( \text{sgn}(e_r) \) by \( \frac{e_r}{|e_r|} \).

Let us substitute in the ordinary error dynamics (8), \( \text{sgn}(e_r) = \frac{e_r}{|e_r|} \) and \( \frac{d(\text{sgn}(e_r))}{dt} = \frac{e_r}{|e_r|^2} \), such that the nonlinear time delayed ordinary dynamics may be written as follows

\[
\dot{e}_r = L_1 \sum_{i=2}^{6} L_i
\]

where \( L_1 = D_3 K_1 + D_0 K_2 + K_3, L_2 = -D_1 K_4 \) with \( K_4 = \mu_p |e_r|^2 (e_r + x_{iref}) + 1 \), \( L_3 = -D_2 K_4 \) with \( K_5 = K_4 / |e_r| \), \( L_4 = -D_3 K_4 \) with \( K_6 = K_4 / |e_r| \), \( L_5 = -D_4 K_7 \) with \( K_7 = |e_r|^3 (e_r + x_{iref}) (e_r + x_{iref} + 1) \), \( L_6 = -D_5 K_8 \) with \( K_8 = |e_r|^3 (e_r + x_{iref}) \) are new variables introduced for sake of simplifying the notations.

The linearization of equation (9) leads to the following conventional representation

\[
\dot{e}_r = \tilde{\delta}_e_r + \tilde{e}_r e_r + \Phi
\]

where the Jacobian

\[
\delta_e_r = \frac{\partial \dot{e}_r}{\partial e_r} \mid_{e_r=0} \frac{e_r}{|e_r|}
\]

with

\[
\begin{align*}
B_1 &= -\mu_r \Omega_r Z_1 - \mu_r Z_2 + Z_3 \\
B_2 &= -\mu_r |\Omega_r|^2 Z_1 + \Omega_r Z_0 + Z_2 + |\mu_r \Omega_r Z_1| + Z_0 \\
B_3 &= \mu_p |\Omega_r|^2 Z_1 + Z_2
\end{align*}
\]

and where the terms \( Z_j \) with \( (j = 1, \ldots, 11) \) are not given here explicitly due to space limitations, are algebraic combinations of parameters \( \mu_{ro} \) and \( \Omega_r \) from \( e_{ro}, x_{iref}, C_{max} \) and \( C_{ro} \). It is worth noting that the obtained linear dynamics (10) is of the first order whose Jacobian corresponds to its pole. This pole represents the sufficient condition for stability of our ordinary dynamics which is subject to time delay \( \tau_r \). In other words, to analyze stability of the resulting linear system, we need
to determine the condition on the time delay $\tau_r$ that makes the eigenvalue $\frac{\partial \phi_j}{\partial \tau_r}|_{\tau_r=0}$ lies in the left half of the complex plane. The negativity of this eigenvalue implies also the negativity of the numerator in (11), i.e., $B_1\tau_r^2 + B_2\tau_r + B_3$, whose characteristic is parabolic in $\tau_r$. It is well known that depending on the coefficients $B_1$, $B_2$ and $B_3$, such characteristic may have two roots $\tau_{r1}$ and $\tau_{r2}$ that are negative and positive, respectively. The numerator is negative if $\tau_{r1} < \tau_r < \tau_{r2}$, whereas it is positive elsewhere for $B_1 > 0$. In fact, this stability condition shows that the time delay $\tau_r$ should be less than an upper bound $\tau_{r_{\text{max}}} = \tau_{r2}$ and positive. Therefore, the previous condition reduces to $0 < \tau_r < \tau_{r_{\text{max}}}$.

One may thus conclude that the stability of the error dynamics (7) is ensured whenever the design parameters $\mu_i$ and $\Omega_i$ in the control law given by Theorem 1 are positive, the derivative of the premium traffic $\dot{\mu}_i$ is bounded, and $\tau_{r1} < \tau_r < \tau_{r2}$ is its upper bound. Furthermore, since $\tau_{r2}$ is a function of the coefficients $B_1$, $B_2$ and $B_3$ which depends on the controller parameters $\mu_r$ and $\Omega_r$, then one may conclude that there is a constraint on these parameters in order to ensure stability.

C. Nodes cascade in differentiated-services framework: Time delay independent case

Corresponding to the nodes cascaded architecture illustrated in Figure 2, the congestion control strategy adopted consists of first controlling locally the bandwidth of both premium and ordinary buffers and then controlling the ordinary flow rates by sending back the messages to all upstream sources sharing this buffer the maximum allowed transmission rate.

Let us first extend the state space equation of our FFM (6) to the time delay independent two nodes cascade as shown below

$$\dot{e}_{ij}(t) = -C_{ij}(t)E_{ij} + \lambda_{ij}(t) - \dot{x}_{ij\text{ref}}; \quad (i = p, r; j = 1, 2)$$

(13)

where $E_{ij} = \frac{e_{ij}(t) + x_{ij\text{ref}}}{e_{ij}(t) + x_{ij\text{ref}} + 1}$.

Lemma 2: Given that the differentiated-services framework shown in Figure 2 is described by the open loop dynamics (13), then the control law

$$C_{pj} = E_{pj}^{-1}[\mu_{pj}e_{pj} + \mu_p\Omega_{pj}sgn(e_{pj}) + \lambda_{pj} - \dot{x}_{pj\text{ref}}]$$

$$\lambda_{rj} = C_{rj}E_{rj} - \mu_{rj}e_{rj} - \mu_{rj}\Omega_{rj}sgn(e_{rj}) + \dot{x}_{rj\text{ref}}$$

(14)

will ensure that the closed loop error dynamics of the two nodes cascade described as follows

$$\begin{align*}
\dot{e}_{pj} &= -\mu_{pj}e_{pj} - \mu_p\Omega_{pj}sgn(e_{pj}); \quad (j = 1, 2) \\
\dot{e}_{rj} &= -\mu_{rj}e_{rj} - \mu_{rj}\Omega_{rj}sgn(e_{rj}) \\
\dot{e}_{rj} &= \dot{e}_{rj} + C_{rj}E_{rj} - C_{rj}E_{rj} + \dot{x}_{rj\text{ref}} - x_{rj\text{ref}}
\end{align*}$$

(15)

where $\bar{j}$ is the complement of $j$, is asymptotically stable whenever the design parameters $\mu_i$ and $\Omega_i$ are selected as positive.

Proof: It is readily seen that the error dynamics of the premium and the ordinary $j$ buffers are the same as that for the stable single node error dynamics given in (4). Regarding the ordinary error dynamics given by (15), let us first rewrite it in a concise form given as

$$\dot{e}_{rj} = -C_{rj}e_{rj}(t) + x_{rj\text{ref}} + \Delta_{ij}$$

(16)

where $\Delta_{ij} = -\mu_{rj}e_{rj} - \mu_{rj}\Omega_{rj}sgn(e_{rj}) + C_{rj}E_{rj} + \dot{x}_{rj\text{ref}} - \dot{x}_{rj\text{ref}}$. Note that $\Delta_{ij}$ is bounded, since it mainly depends on error dynamics $j$ which is already shown to be stable and the reference signal $\dot{x}_{rj\text{ref}}$ is also bounded. The stability of (16) may be verified through its linearized dynamics around $e_{rj0}$ whose Jacobian is $-C_{rj}(e_{rj0} + \dot{x}_{rj\text{ref}})^{-2}$, and which is always negative.

D. Nodes cascade in differentiated-services framework: Time delay dependent case

In presence of delays, the open loop error dynamics of the two nodes cascaded is as follows

$$\dot{e}_{ij} = -C_{ij}(t)E_{ij} + \lambda_{ij}(t - \tau_{ij}) - \dot{x}_{ij\text{ref}}; \quad (i = p, r; j = 1, 2)$$

(17)

where $E_{ij} = \frac{e_{ij}(t) + x_{ij\text{ref}}}{e_{ij}(t) + x_{ij\text{ref}} + 1}$.

Lemma 3: Provided that Assumption 1 holds for the time delay dependent architecture depicted in Figure 2, the application of the control law given by Lemma 2 to the error dynamics (17), will result in the closed loop error dynamics given by

$$\begin{align*}
\dot{e}_{pj} &= -\mu_{pj}e_{pj} - \mu_p\Omega_{pj}sgn(e_{pj}) - \tau_{pj}\lambda_{pj} \\
\dot{e}_{rj} &= -D_{ij}\lambda_{rj}e_{rj} - D_{ij}\mu_{rj}e_{rj} - D_{ij}\mu_{rj}\Omega_{rj}sgn(e_{rj}) - D_{ij}\tau_{rj}E_{ij} \\
\dot{e}_{rj} &= -D_{ij}\lambda_{rj}e_{rj} - D_{ij}\mu_{rj}e_{rj} - D_{ij}\mu_{rj}\Omega_{rj}sgn(e_{rj}) + D_{ij}\tau_{rj}E_{ij} - \dot{x}_{rj\text{ref}}
\end{align*}$$

(18)

where $D_{ij} = (1 - \mu_{pj}\tau_{pj})$, $D_{ij} = (1 - \mu_{rj}\tau_{rj})$, $D_{ij} = C_{ij}\frac{d}{dt}sgn(e_{rj}) + \dot{x}_{rj\text{ref}} + \frac{d(C_{ij}E_{rj})}{dt}$, $D_{2j} = C_{rj}E_{rj} - C_{rj}\tau_{rj}E_{rj} + \dot{x}_{rj\text{ref}} - \dot{x}_{rj\text{ref}}$, $\dot{D}_{3j} = -\mu_{rj}\tau_{rj}E_{rj} + \frac{d}{dt}sgn(e_{rj}) + \dot{x}_{rj\text{ref}} + \frac{d}{dt}(C_{ij}E_{ij})$ and $\gamma_{ij} = \mu_{ij}\Omega_{ij}$ with $(i = p, r)$ which is now asymptotically stable whenever the design parameters $\mu_i$ and $\Omega_i$ are selected to be positive, the delay of the ordinary channel $\tau_{rj} < \tau_{r_{\text{max}}}$, where $\tau_{r_{\text{max}}}$ is its upper bound, and the delay of the ordinary channel satisfies $\tau_{rj} < \tau_{r_{\text{max}}}$. The delay of the ordinary channel satisfies $\tau_{rj} < \tau_{r_{\text{max}}}$.

Proof: First note that as expected the premium error dynamics remains asymptotically stable whenever the design parameters $\mu_{pj}$, $\Omega_{pj}$ are positive, and also as in a single node case the term $\tau_{pj}\lambda_{pj}$ is bounded. As far as the ordinary error dynamics is concerned, the case remains the same as that of a single node error dynamics whose stability is subject to boundedness of $\tau_{rj}$, that is
\[ \tau_{rj} < \tau_{rj,max} \]. Now for the remaining error dynamics \( \dot{j} \), it readily follows that it may be written in the same form as in (16), that is

\[
\dot{e}_{rj} = -D_{ij}e_{rj}(t) + \frac{x_{rj,ref}}{\tau_{rj}} + 1 + D_{ij} \Delta_{2j} \tag{19}
\]

where \( \Delta_{2j} = -D_{ij}p_{rj}e_{rj} - D_{ij}p_{rj}x_{rj,ref} + D_{ij}e_{rj}x_{rj,ref} - \frac{x_{rj,ref}}{\tau_{rj}} - x_{rj,ref} \). Under Assumption 1, and assuming that the above stability condition \( \tau_{rj} < \tau_{rj,max} \) holds for the error dynamics \( j \), the term \( \Delta_{2j} \) is also bounded. Therefore, stability of the dynamics (19) corresponds to stability of its linearized error dynamics whose Jacobian corresponds to the one for (16) multiplied by \( D_{ij}^{-1} \). Hence, stability of the ordinary dynamics \( j \) is ensured whenever the condition \( \tau_{rj} < \mu_{rj} \) ensures the negativity of the corresponding Jacobian.

### III. Simulation Results

In order to show the effectiveness of our proposed FFM-based congestion control strategy for differentiated-services architecture, three simulation cases are conducted. First, we study the influence of time delay on our proposed congestion control system, second we show the relationship between the time delay and the controller parameters, and finally we evaluate the performance of our congestion control approach for a wide range of operating conditions in presence of delay and premium traffic stimuli. In all the simulation results presented the sampling time is set to \( T_s = 1\text{ms} \) and the proposed control parameters are set to \( \mu_p = 1000, \mu_r = 500, \) and \( \Omega_p = \Omega_r = 10^{-4} \). The premium traffic random input \( \lambda_p \) has a mean of 3000 and a variance of 1000, and it is bounded such that \( 0 \leq \lambda_p \leq 4000 \). The premium and ordinary buffer capacities are finite and their queues are bounded according to the following constraints, \( 0 \leq X_{1p} \leq 128 \) and \( 0 \leq X_{1r} \leq 1024 \), respectively. Finally, the constraints on the maximum available service capacity are \( 0 \leq C_{max} \leq 40000 \) for both services. With respect to the time delay, as illustrated in Figure 1, two delay blocks are introduced between each source-buffer to simulate and reflect any system time delay due to either propagation, transmission, processing delays, etc. factors.

The corresponding simulation results are presented in three steps. First, by setting the premium and ordinary buffer queue references to \( x_p = 100 \) and \( x_r = 1000 \), respectively, Figure 3 shows a set of buffer queue step responses obtained using our proposed congestion controller by varying the time delay from 0 to 30ms (Figure 3-a & b). According to the graphs of Figure 3-a, we can observe that except a delay in transmission there is no other influence on the premium traffic channel. On the other hand, the plot in Figure 3-b, corresponding to the ordinary buffer queues obtained by using our proposed congestion control approach shows the sensitivity of the ordinary service dynamics to the variations in the time delay. It is worth mentioning that for zero time delay the control system achieves excellent performance and stability, and by increasing \( \tau_r \) oscillations increase where beyond a certain upper bound the controller fails. This effectively confirms by simulations the time delay range \( 0 < \tau_r < \tau_{r2} \) that was obtained in the Proof of Theorem 1.

In another set of simulations depicted in Figure 4, the effects of the controller parameter \( \mu_r \) on the overall closed loop stability for a fixed time delay are investigated. By setting the time delay to 30ms and varying the controller parameter \( \mu_r \) from 28 to 1400, one may note from Figure 4a (corresponding to the premium buffer queue step response) that no effect is observed and stability is always guaranteed. This confirms that both premium and ordinary dynamics are decoupled. On the other hand, by increasing \( \mu_r \), we increase the oscillation amplitudes of the ordinary buffer queue step responses as shown in Figure 4b. Note that the lower value of \( \mu_r \) of 28 corresponds to the minimum value that ensures convergence of the ordinary buffer queue state to the desired reference. Therefore, we may conclude that \( \mu_r \) belongs to a range of values in which stability is ensured. The simulation results show that the upper bound of the time delay for ensuring stability is inversely proportional to \( \mu_r \). This inverse proportionality might actually be seen in the stability condition \( 0 < \tau_r < 1/\mu_r \) of the ordinary buffer queue dynamics (7), when this dynamics is approximated by its linear representation \( -D_{j1}\mu_r e_r \).

![Fig. 3. Effects of delay on system response: (a), (b) the equivalent control-based congestion controller (unstable for 30ms and 160ms delays); (c), (d) our proposed congestion controller](image)

![Fig. 4. Influence of controller parameters on performance of congestion control system in presence of time delay of 30ms using our proposed congestion controller](image)

The last simulation results depicted in Figures 5-6 in which the delay is set to zero and 10ms, respectively consist of showing the evolution of the congestion control system characteristics for a wide range of operating conditions in presence of premium traffic stimuli and
time delays. The results are provided corresponding to the time delays of 0 and 10ms, that might reflect the distances between the considered nodes and sources (for example for the LAN and WAN ATM, respectively). In each figure, plots (a) and (b) illustrate the premium and ordinary buffer queues, respectively, and (c) and (d) show the premium and ordinary service capacities. By setting the premium and the ordinary queue reference states to $x_{1p} = \{100, 50\}$ and $x_{1r} = \{800, 1000\}$, respectively, and the mean of the input traffic to $\lambda_p = \{3000, 6000\}$, one may observe that either with or without time delay and in both services the states (a) and (b) converge to their desired values. In terms of time domain response, our proposed congestion controller exhibits good performance in both premium and ordinary delay independent control dynamics and acceptable chatter in the ordinary service dynamics in presence of time delay. In virtue of the sliding mode robustness it is expected that our proposed congestion controller compensates for the added stimuli in the premium traffic.

Fig. 5. Simulation results in the tracking mode using our proposed congestion controller in presence of premium traffic stimuli (without time delay).

Fig. 6. Simulation results in the tracking mode using our proposed congestion controller in presence of premium traffic stimuli (with time delay of 10ms).

IV. CONCLUSION

A new robust congestion control approach for a time delayed dependent and scalable Differentiated Services network is introduced in this paper. Based on a simple and low order fluid flow model (FFM) that has been validated by several researchers before, the proposed congestion controller is designed using the Sliding Mode Variable Structure (SMVS) technique. Furthermore, the proposed congestion control dynamics is derived analytically and investigated in order to guarantee closed loop stability of the time delay dependent nodes cascaded architecture. In addition, we may conclude that the premium buffer queue dynamics which is the most critical traffic in the differentiated services framework achieves excellent performance and is insensitive to time delays, whereas a sufficient condition on the time-delay upper bound should be satisfied for the ordinary buffer queue dynamics in order to ensure stability. To confirm and substantiate these results, a number of simulations are conducted for different unknown but constant time-delays and corresponding to a wide range of network operating conditions.

REFERENCES