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Robust Controller Including a Modified Smith Predictor for AQM Supporting TCP Flows

Mihail Voicu

"Gheorghe Asachi" Technical University of Iaşi Romania
(*e-mail: mvoicu@tuiasi.ro*).

Abstract: Based on the fluid-flow model of TCP dynamics a new control structure relying on a modified Smith predictor is proposed for which some design procedures ensuring robust stability are presented. The simplest design solution has in view the cancellation of the plant poles in the ideal case by an appropriate PID controller constituted by the components of the modified Smith predictor. Another solution consists in the application of Coefficient Diagram Method which mainly allows the simultaneous design of the characteristic polynomial of the closed-loop system and of the controller on the basis of some sufficient stability conditions.

Keywords: Fluid-flow TCP model, variable time-delay, modified Smith predictor, stability robust controller

1. INTRODUCTION

The Internet is a shared resource, where the users compete for a finite network bandwidth. Too many user demands can cause congestion, which in turn leads to long queuing delays and/or packet loss. In this respect the main problem of the Internet traffic, which needs theoretical/practical solutions, is to prevent its congestion. The mechanism for flow and congestion control on the Internet, built and developed following heuristic arguments, is the Active Queue Management (AQM) for Transmission Control Protocol (TCP) flows. Nevertheless, due to the variable transmission delays, which have a negative impact on the feedback control stability, and to the rapid changes in Internet traffic, AQM/TCP does not generally work as well as when it was designed. Many researchers have addressed these problems in different ways (Mascolo (1999), Gunnarsson (2000), Mascolo (2000), Hollot *et al.* (2001), Hollot *et al.* (2002), Low *et al.* (2002), Ryu *et al.* (2003), Cela *et al.* (2005), Rafe' *et al.* (2007), Al-Hammouri (2008), De Cicco *et al.* (2011), Tolaimate and Elalami (2011)). Their main objective is to maintain local stability for arbitrary network delays, link capacities, and routing topologies.

In this paper, based on the fluid-flow model of TCP dynamics developed in (Misra *et al.* (2000)), a new control structure for AQM/TCP flows is proposed. The controller includes a modified Smith predictor (Hamamci *et al.* (2001)) for which some design procedures ensuring robust stability are presented.

2. FLUID-FLOW MODELS OF TCP BEHAVIOUR

According to the fluid-flow model of TCP (Misra *et al.* (2000), Hollot *et al.* (2002)), its dynamic behaviour is described by the following system of nonlinear time-variant differential equations:

$$\dot{w}(t) = \frac{1}{r(t)} - \frac{w(t)}{2}\frac{w(t-r(t))}{r(t-r(t))}\,p(t-r(t)),$$
$$\dot{q}(t) = \begin{cases} -c(t) + \dfrac{n(t)}{r(t)}w(t), & q > 0, \\ max\,[0, -c(t) + \dfrac{n(t)}{r(t)}w(t)], & q = 0, \end{cases} \tag{1}$$

with

$$r(t) = T_p + q(t)/c(t), \tag{2}$$

where

- $w(t) \in [0, \overline{w}]$ (with $\overline{w} = \text{const.} > 0$) is the average TCP window size (in packets),
- $q(t) \in [0, \overline{q}]$ (with $\overline{q} = \text{const.} > 0$) is the average queue length (in packets),
- $r(t) \in [0, \overline{r}]$ (with $\overline{r} = \text{const.} > 0$) is the round-trip time,
- $c(t) \in [0, \overline{c}]$ (with $\overline{c} = \text{const.} > 0$) is the link capacity,
- $n(t) \in [0, \overline{n}]$ (with $\overline{n} = \text{const.} > 0$) is the load factor,
- $p(t) \in [0,1]$ is the probability of packets mark, and
- $T_p > 0$ is the propagation delay.

To linearize equations of model (1) around a constant operating point (w_0, q_0, p_0) we obtain first the non-linear time-invariant differential equations according to following hypotheses: operating point (w_0, q_0, p_0) satisfies (1) and $n(t) = N = \text{const.}$, $c(t) = C = \text{const.}$; if $r(t)$ appears as an argument of a function we consider $r(t) = R = \text{const.}$;

$\dot{w}=0 \Rightarrow w_0^2 p_0 = 2;\quad \dot{q}=0 \Rightarrow w_0 = RC/N,\ R = T_p + q_0/C$. Hence, denoting by $\Delta w = w - w_0$, $\Delta q = q - q_0$ the perturbed state variables and by $\Delta p = p - p_0$ the perturbed control, all about the operating point (w_0, q_0, p_0), we obtain the following results:

– the system of nonlinear time-invariant equations associated to (1) and (2):

$$\dot{w}(t) = \frac{1}{\dfrac{q(t)}{C}+T_p} - \frac{w(t)}{2}\frac{w(t-R)}{\dfrac{q(t-R)}{C}+T_p}p(t-R),$$
$$\dot{q}(t) = \begin{cases} -C + \dfrac{N}{R}w(t), & q>0, \\ max[0, -C+\dfrac{N}{R}w(t)], & q=0; \end{cases} \tag{3}$$

– and respectively, the system of linearized time-invariant equations associated to (3):

$$\Delta\dot{w}(t) = -\frac{N}{R^2C}\left[\Delta w(t)+\Delta w(t-R)\right]-$$
$$-\frac{1}{R^2C}\left[\Delta q(t)+\Delta q(t-R)\right]-\frac{RC^2}{2N^2}\Delta p(t-R), \tag{4}$$
$$\Delta\dot{q}(t) = \frac{N}{R}\Delta w(t) - \frac{1}{R}\Delta q(t).$$

For practical purposes, the linearized model (4) may be decomposed in a *nominal part* (containing the delay, the window dynamics and the queue dynamics), which may be taken as plant model for the TCP behaviour, and a *high frequency residual* which may be treated as model uncertainties. Applying the Laplace transform to equations (4), after some manipulations / substitutions of equations, it results the block-diagram given by Fig. 1, where

$$P(s) = \frac{k}{(Rs+1)(Ts+1)}, \tag{5}$$
$$\text{with } k = (C^3R^3)/(4N^2),\ T = (R^2C)/(2N),$$

is the transfer function of the linearized model (4) without delay (window dynamics and queue dynamics) and

$$H(s) = \frac{2N^2 s}{R^2C^3}(1-e^{-Rs}) \tag{6}$$

is the transfer function expressing the high frequency residual.

The block-diagram of Fig. 1 evidences an input delayed system with model uncertainties under multiplicative form and also the role of the operating points p_0, q_0.

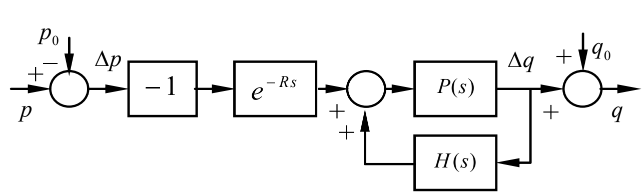

Fig. 1. Block-diagram of the linearized TCP dynamics

3. CONTROLLER BASED ON MODIFIED SMITH PREDICTOR FOR TCP DYNAMICS

The implementation of the modified Smith predictor (Hamamci *et al.* (2001)) with the nonlinear TCP dynamics (1), evidencing also the role of the operating points p_0, q_0, is shown in Fig. 2, where q_{ref} is the queue reference generating q_0. The nonlinear TCP dynamics does not include the sign (–1) existing in the second term of the first equation of (1). Nevertheless, this sign is taken into consideration by the block [–1] situated before the nonlinear TCP dynamics. The modified Smith predictor includes:

– the controller transfer functions $C_1(s), C_2(s), C_3(s)$,

– the nominal models $\hat{P}(s)$ of $P(s)$ and $e^{-\hat{R}s}$ of e^{-Rs}.

For the linearized TCP dynamics given in Fig. 1 and for the perturbed variables $\Delta q_{ref}, \Delta p, \Delta q$, the block-diagram corresponding to the system of Fig. 2 is given in Fig. 3.

It is easy to see that in the ideal case, i.e. for

$$R=\hat{R}, k=\hat{k}, T=\hat{T},$$
$$P(s)=\hat{P}(s)=\frac{\hat{k}}{(\hat{R}s+1)(\hat{T}s+1)}, H(s)\approx 0, \tag{7}$$

by some simple block-diagram manipulations the system with modified Smith predictor represented in Fig. 3 is equivalent to the system represented in Fig. 4.

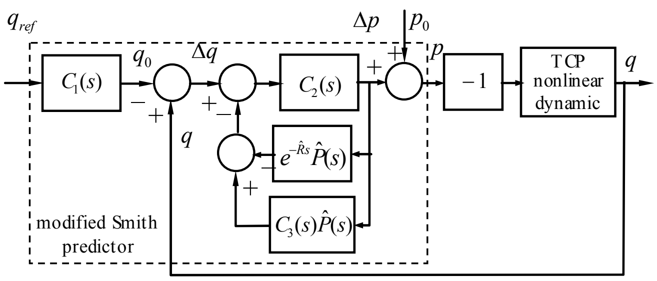

Fig. 2. Implementation of the modified Smith predictor with the nonlinear TCP dynamics

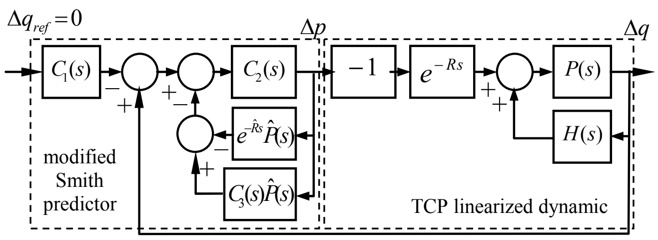

Fig. 3. Implementation of the modified Smith predictor with the linearized TCP dynamics

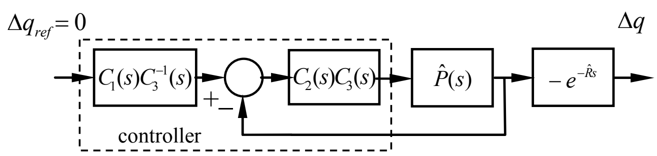

Fig. 4. Ideal block-diagram corresponding to Fig. 3 and to (7)

The ideal block-diagram represented in Fig. 4 and its input – output (closed-loop) transfer function

$$\hat{G}_0(s) = C_1(s)C_3^{-1}(s)\frac{C_2(s)C_3(s)\hat{P}(s)}{1+C_2(s)C_3(s)\hat{P}(s)}[-e^{-\hat{R}s}] \tag{8}$$

evidence the elimination of the delay exponential $-e^{-\hat{R}s}$ from the closed-loop and from the denominator of $\hat{G}_0(s)$. These facts confirm the essential feature of the modified Smith predictor in the ideal case. Notice here that the stability properties of the ideal closed-loop system are concentrated in the denominator of $\hat{G}_0(s)$.

4. DESIGN OF CONTROLLER ENSURING ROBUST STABILITY

To design the controller (based on modified Smith predictor) included in the system given in Fig. 4), we have to synthesize the transfer functions $C_1(s), C_2(s), C_3(s)$.

$C_1(s)$ has to be chosen for the system depicted in Fig. 2, which must realise $q = q_{ref}$ in the steady state regime. $C_2(s), C_3(s)$ must be designed such that to ensure the asymptotic stability in the ideal case (7) and, more important, its robustness for slight modelling mismatch with respect to the ideal case (7).

4.1. Robustness results

It is well known (Palmor (1980, 2000)) that for slight modelling mismatch with respect with the ideal case (7), the non-ideal closed-loop system may go unstable. For the purposes of this paper, let us remind some definitions and theorems regarding the modified Smith predictor.

Definition 1
A system that is asymptotically stable in the ideal case but became unstable for infinitesimal-modelling mismatches is called a *practically unstable* system.
In the contrary case, it is called a *practically stable* system.

In order to formulate some known results let us define the following ideal closed-loop transfer function

$$Q(s) = \frac{C_2(s)C_3(s)\hat{P}(s)}{1+C_2(s)C_3(s)\hat{P}(s)}, \tag{9}$$

which corresponds to the ideal closed-loop system depicted in Fig. 4, but without the delay exponential $-e^{-\hat{R}s}$.

Theorem 1
For the system with a Smith predictor to be closed-loop practically stable, it is necessary that:

$$\lim_{\omega\to\infty} |Q(j\omega)| < 1/2. \tag{10}$$

Remark 1
If only mismatches in the propagation delay R are considered, then condition (10) is sufficient as well.

Remark 2
For $Q(s)$ to satisfy condition (10), it must be at least a proper rational function. If it is strictly proper, then the system is practically stable.

Supposing that condition (10) is satisfied, it still remains to distinguish between two possible cases: (a) the design is stability-wise, completely insensitive to mismatches in the propagation delay R; (b) there is a finite maximum mismatch in the propagation delay R below which the system remains stable. Let us denote the mismatch of the propagation delay by

$$\Delta R = R - \hat{R}. \tag{11}$$

Theorem 2
(a) The closed-loop system is asymptotically stable for any ΔR if

$$|Q(j\omega)| < 1/2 \quad \forall\, \omega \ge 0. \tag{12}$$

(b) If

$$|Q(j\omega)| < 1 \ \forall\, \omega \ge 0 \ \text{ and } \ \lim_{\omega\to\infty}|Q(j\omega)| < 1/2, \tag{13}$$

then there exists a finite positive $(\Delta R)_m$ such that the closed-loop system is asymptotically stable for all $|\Delta R| < (\Delta R)_m$.

Remark 3
A rough (and frequently conservative) estimate of $(\Delta R)_m$ is given by

$$(\Delta R)_m = \pi/(3\omega_0), \tag{14}$$

where ω_0 is the pulsation above which $|Q(j\omega)| < 1/2$.

4.2. PID controller for cancellation of plant poles

The simplest solution for the design of controller components $C_2(s), C_3(s)$ has in view the cancellation of the plant poles in the ideal case (7) by considering an adequate PID controller. In this case let us adopt

$$C_2(s) = \frac{\hat{R}s+1}{a_1 s}, C_3(s) = Ts+1, \tag{15}$$

i.e. the PID controller

$$C_2(s)C_3(s) = \frac{(\hat{R}s+1)(Ts+1)}{a_1 s} = \frac{\hat{R}+T}{a_1} + \frac{1}{a_1 s} + \frac{\hat{R}T}{a_1}s. \tag{16}$$

With (7) and (16), transfer function (9) becomes

$$Q(s) = \frac{k}{a_1 s + k}. \tag{17}$$

Controller parameter a_1 may be calculated with

$$a_1 \approx k t_s / 3 \tag{18}$$

where t_s is the *prescribed settling time* of the closed-loop step response.

Remark 4
According to (17) and to the robustness results presented in 4.1, it follows that, by using the pole cancelling PID controller (16), the closed-loop system given in Fig. 3 is:

- practically stable;
- asymptotically stable for all $|\Delta R| < \pi/(3\omega_0)$, with

$$\omega_0 \geq 3\sqrt{3}/t_s. \quad (19)$$

4.3. Application of Coefficient Diagram Method (CDM)

CDM (Manabe (1998), Kim and Manabe (2001), Hamamci *et al*. (2001), Manabe (2002a, 2002), Öcal *at al*. (2009)) mainly allows the simultaneous design of the characteristic polynomial of the closed-loop system and of the controller on the theoretical basis of sufficient stability conditions of (Lipatov and Sokolov (1978)).

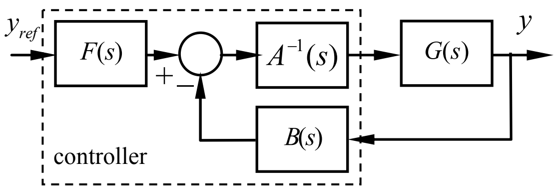

Fig. 5. Block-diagram for CDM

The basic block-diagram of CDM is shown in Fig. 5 (in our approach is taken without any disturbances), where y_{ref} is the reference input, y is the output, $G(s)$ is the known plant expressed by

$$G(s) = \frac{N(s)}{D(s)} \quad (20)$$

($N(s), D(s)$ being known polynomials), and $A(s)$, $B(s)$ and $F(s)$ represent the unknown controller with $A(s)$ – the denominator polynomial, $B(s)$ – the numerator feedback polynomial, and $F(s)$ – the reference transfer function.

According to Fig. 5, the closed-loop transfer function has the following form:

$$G_0(s) = F(s)\frac{N(s)}{A(s)D(s) + B(s)N(s)}, \quad (21)$$

where

$$A(s)D(s) + B(s)N(s) \quad (22)$$

is the closed-loop characteristic polynomial.

a. Target characteristic polynomial and stability indices

A possibility to design the controller is to follow the algebraic procedure under the matching condition. This consists in synthesizing first a target characteristic polynomial

$$D_0(s) = \sum_{k=0}^{n} d_{0k}s^k, \quad (23)$$

according to some design prescriptions. Let us introduce the *stability indices* $\gamma_k, k = \overline{0,n}$, the *time constant* τ, and the *stability limits* $\gamma_k^*, k = \overline{1,n-1}$, by the following relations:

$$\gamma_k = d_{01}^2/(d_{0k+1}d_{0k-1}), k = \overline{1,n-1},\ \gamma_0 = \gamma_n = \infty, \quad (24)$$

$$\tau = d_{01}/d_{00}, \quad (25)$$

$$\gamma_k^* = 1/(\gamma_{k+1} + 1/\gamma_{k-1}), k = \overline{1,n-1}. \quad (26)$$

Accordingly, from (24), (25) it follows that the coefficients d_{0k}, $k = \overline{1,n}$, of target characteristic polynomial $D_0(s)$ may be expressed in terms of d_{00}, τ and γ_i by

$$d_{0k} = \frac{d_{00}\tau^k}{\prod_{j=1}^{k-1}\gamma_j^{k-j}}, k = \overline{1,n}. \quad (27)$$

b. Sufficient conditions based on stability indices

Using the stability indices, (Lipatov and Sokolov (1978)) formulated the following conditions, which, although only sufficient conditions, are much simpler as the well-known necessary and sufficient conditions.

Theorem 3

Polynomial $D_0(s)$ is Hurwitzian (i.e. system (21) is asymptotically stable) if one of the following two sets of conditions holds:

$$\sqrt{\gamma_k\gamma_{k+1}} > 1.4656,\ k = \overline{1,n-2}; \quad (28)$$

$$\gamma_k \geq 1.12374\gamma_k^*,\ k = \overline{2,n-2}. \quad (29)$$

Theorem 4

Polynomial $D_0(s)$ is non-Hurwitzian (i.e. system (21) is unstable) if the following set of conditions holds:

$$\gamma_k\gamma_{k+1} \leq 1,\ \text{for some}\ k = \overline{1,n-2}. \quad (30)$$

Conditions (28), (29) can be graphically expressed in CD as it is shown in (Manabe (1998), Kim and Manabe (2001), Manabe (2002a, 2002b), Kim *et al.* (2002)). In CDM, sufficient conditions (29) are mainly used because they are also almost necessary conditions. At the same time, sufficient conditions (28) show that they are fulfilled for $\gamma_k > 1.4656, k = \overline{1,n-2}$. It follows that using $\gamma_k \in [1.5, 4]$, $k = \overline{1,n}$, in (27) a Hurwitzian target characteristic polynomial $D_0(s)$ may be synthesized. Based on these background, for a target closed-loop transfer function defined by

$$G_{0T}(s) = \frac{d_{00}}{D_0(s)}, \quad (31)$$

(Manabe (1998, 2002b) proposed the following *standard form* of the stability indices and of the time constant respectively:

$$\gamma_1 = 2{,}5,\ \gamma_k = 2,\ k = \overline{2,n-1}, \quad (32)$$

$$\tau = t_s/2.3095, \quad (33)$$

where t_s is the prescribed settling time of the target closed-loop system. Setting (32) and (33) ensure that the step response of the closed-loop system has almost no overshoot and the same transient behaviour irrespective to n.

To cover other concrete situations, some different standard forms have been proposed in (Kim and Kim (1999)).

c. Controller design under the matching condition

First, by replacing (32) and (33) into (27), a Hurwitzian target characteristic polynomial (23) can be calculated and adopted as starting point of the controller design. Then, equating (22) and (23), the following Diophantine equation may be stated:

$$A(s)D(s)+B(s)N(s)=D_0(s)\,, \tag{34}$$

where $D(s)$, $N(s)$, $D_0(s)$ are given, and $A(s), B(s)$ are the unknown controller polynomials. Equation (34) is the instrument of the algebraic design of $A(s), B(s)$ under the matching condition. This equation has a unique solution if

$$\deg B(s)=\deg D(s)-1\,, \tag{35}$$

$$\deg A(s)\geq \deg B(s)\,. \tag{36}$$

$F(s)$ has to be chosen such that to obtain

$$G_0(s)=G_{0T}(s)\,, \tag{37}$$

from which, according to (21), (31) and (34) it results:

$$F(s)=\frac{d_{00}}{N(s)}\,. \tag{38}$$

Now, for the equivalent block-diagram of Fig. 4 (with (7) and excepting $[-e^{-\hat{R}s}]$), after comparing it with that one given in Fig. 5, the following identifications may be stated:

$$C_1(s)=F(s),\; C_2^{-1}(s)=A(s),\; C_3(s)=B(s)\,, \tag{39}$$

$$G(s)=\hat{P}(s)=\frac{\hat{k}}{(\hat{R}s+1)(\hat{T}s+1)}\,, \tag{40}$$

$$N(s)=k,\quad D(s)=\hat{R}\hat{T}s^2+(\hat{R}+\hat{T})s+1\,. \tag{41}$$

With (40), Diophantine equation (34) becomes:

$$[\hat{R}\hat{T}s^2+(\hat{R}+\hat{T})s+1)]A(s)+\hat{k}B(s)=D_0(s)\,. \tag{42}$$

First, according to (35), (36), with (37), (41), it follows that $\deg B(s)=1$, $\deg A(s)\geq 1$. Correspondingly,

$$C_2^{-1}(s)=A(s)=a_1s+a_0,\; C_3(s)=B(s)=b_1s+b_0 \tag{43}$$

may be adopted. According to (23), (27), (32) and (33) the target characteristic polynomial may be stated as:

$$\begin{aligned}&D_0(s)=d_{03}s^3+d_{02}s^2+d_{01}s+d_{00},\\ &d_{01}=(t_s/2.3095)d_{00},\; d_{02}=(t_s/2.3095)^2d_{00}/2.5,\\ &d_{03}=(t_s/2.3095)^3d_{00}/(12.5),\end{aligned} \tag{44}$$

where $\gamma_1=2,5, \gamma_2=2$ and τ depends on settling time t_s according to (33).

Under these circumstances, the solution of Diophantine equation (42), with (43) which contains the unknown coefficients a_0, a_1, b_0, b_1, can be uniquely obtained by solving the equivalent linear equation:

$$\begin{bmatrix}\hat{R}\hat{T} & 0 & 0 & 0\\ \hat{R}+\hat{T} & \hat{R}\hat{T} & 0 & 0\\ 1 & \hat{R}+\hat{T} & \hat{k} & 0\\ 0 & 1 & 0 & \hat{k}\end{bmatrix}\begin{bmatrix}a_1\\ a_0\\ b_1\\ b_0\end{bmatrix}=\begin{bmatrix}d_{03}\\ d_{02}\\ d_{01}\\ d_{00}\end{bmatrix}. \tag{45}$$

Using (7), (9) and (43) it follows that

$$Q(s)=\frac{\hat{k}(b_1s+b_0)}{(a_1s+a_0)(\hat{R}s+1)(\hat{T}s+1)+\hat{k}(b_1s+b_0)}. \tag{46}$$

Remark 5

According to the robustness results presented in 4.1 and to (46), it follows that by the design under the matching condition the closed-loop system given in Fig. 5 is

- practically stable;
- asymptotically stable for any ΔR if condition (12) with (45), (46) is met.

If condition (13) with (45), (46) is met, then there exists a finite positive $(\Delta R)_m$ such that the closed-loop system is asymptotically stable for all $|\Delta R|<(\Delta R)_m$.

d. Controller design with coefficient shaping on the coefficient diagram (CD)

CDM may be also applied following the coefficient shaping on the CD. In many cases, a lower order controller may be designed under matching condition. Nevertheless, practically, if certain controller parameters have to depend on other ones as design conditions (like that ones related to robust stability presented in paragraph by 4.1 or in Remark 5), it is not too easy to solve the problem analytically. This means that the existence of a solution can not be guaranteed. For such situations, using CDM, the problem can be dealt with by adjusting γ_i and τ to obtain a feasible solution (Kim and Manabe (2001)). In the design process, the resulting characteristic polynomial is easily drawn by moving up and down as much as the controller's parameter in the same order. Therefore, it can be directly seen by CD how much the overall system is sensitive to parameter adjustments. For the coefficient shaping it is to make the curve characteristic polynomial coefficients to be a smoothly concave shape and the controller parameters may be immediately obtained from the CD (Kim and Manabe (2001)).

5. CONCLUSION

In this paper a new controller using a modified Smith predictor for AQM supporting TCP flows is proposed for which some design procedures ensuring robust stability are presented. Among these procedures, the simplest is the classical PID controller for cancellation of plant poles. As a future work and according to the structure depicted in Fig. 2, it remains to evaluate and illustrate by simulation:

(a) the effectiveness and qualities of the design procedures presented in this paper;

(b) the impact of the propagation delay on the performances of the non-ideal closed loop system.

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