PI Stabilization for Congestion Control of AQM Routers with Tuning Parameter Optimization

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Abstract **— In this paper, we consider the problem of stabilizing network using a new proportional- integral (PI) based congestion controller in active queue management (AQM) router; with appropriate model approximation in the first order delay systems, we seek a stability region of the controller by using the Hermite-Biehler theorem, which isapplicable to quasipolynomials. A Genetic Algorithm technique is employed to derive optimal or near optimal PI controller parameters.**

Keywords **— Congestion Control, Activequeue Management (AQM), Stabilization, PI Controller, First Order Delay System,Genetic Algorithm (GA).**

I. Introduction

Recently and due to the explosive growth of computer networks, several non linear phenomena of the internet have been discovered. For instance, it has been shown that network traffic congestion results in long time delays for data transmission and often makes the queue length in the buffer of the intermediate router overflow, and can even lead to network collapse. To face the congestion problems, TCP chiefly uses a network congestion avoidance which comprehend different aspects of an additive-increase multiplicative-decrease (AIMD) scheme, with other schemes such as slow-start[1][2] and [3].

It was shown that the problem of congestion control and development of AQM could be considered as a problem of regulating. Thus, due to the limitations of packet-dropping probability and the effects of propagation delays in TCP networks, the TCP AQM network was modeled as a time-delayed system based on a fluid-based model of the dynamics of the TCP and RED, developed by the stochastic theory [4][5][6] and [7].

From the control theory, the AQMs types PI [8], PID were built to control the congestion phenomenon. In this paper, we extend our previous work [9] by implementing Genetic Algorithm (GA) in determining PI Controller parameters to compensate the delay in the system. The Genetic Algorithm has been considered as a useful optimization techniques employing the principles of natural genetic systems [10] to search a global solution of the optimization problem.

II. TCP/AQM Model

Our study will focus on the sharing of a communication link between multiple transmitters at remote locations (Fig. 1).

In [6], the authors modeled TCP process with stochastic differential equations without taking slow start and timeoutmechanisms into account. In this model, the congestion window w(t) increase linearly if no packet loss is detected;otherwise it halves. Based on some reasonable assumptions, the following relations were gotten:

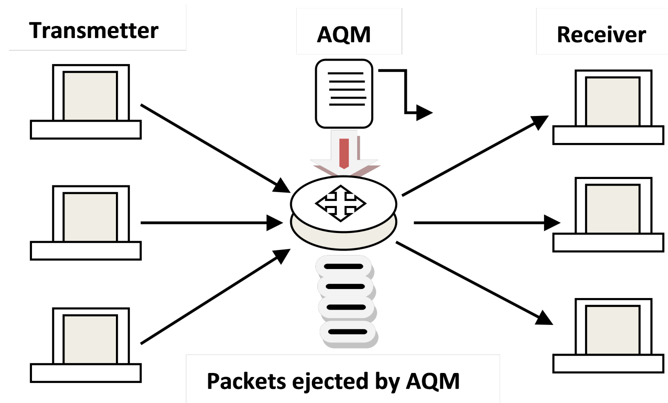

Fig. 1. Topology studied

$$\begin{cases} \dot{w}(t) = \dfrac{1}{R(t)} - \dfrac{w(t).w\big(t-R(t)\big)}{2R\big(t-R(t)\big)} p\big(t-R(t)\big) & (1) \\ \dot{q}(t) = \dfrac{w(t)}{R(t)} N(t) - C & (2) \end{cases}$$

With $R(t) = \frac{q(t)}{C} + Tp,$ where Tp is the propagation delay, $q(t)$ is the queue length at the router, C is the router's transmission capacity, thus $\frac{q(t)}{C}$ is the queuing delay and $R(t)$ is the round trip time delay, $N(t)$ denotes the TCP load factor.

$\dot{w}(t)$ and $\dot{q}(t)$ denote the time-derivative of $W(t)$ and $q(t)$, respectively $p(t)$ is the probability of packet mark due to the AQM mechanism at the router.

The linearization of (1) and (2) about the operating point is carried out in (1) and the perturbed variables about the operating point satisfy

$$\begin{cases} \delta\dot{w}(t) = -\dfrac{N}{R_0^2 C}\big(\delta w(t) + \delta w(t-R_0)\big) & (3) \\ -\dfrac{1}{R_0^2 C}\big(\delta q(t) - \delta q(t-R_0)\big) - \dfrac{R_0 C^2}{2N^2}\delta p(t-R_0) & \\ \delta\dot{q}(t) = \dfrac{N}{R_0}\delta w(t) - \dfrac{1}{R_0}\delta q(t) & \end{cases}$$

From (3) and (4) we derive the transfer function from $\delta p$to δq:

$$\frac{\delta q(s)}{\delta p(s)} = -\frac{R^3 C^3}{2\,N^2}\frac{A(s)e^{-Rs}}{1 + A(s)Rse^{-Rs}} \qquad (5)$$

Where $A(s) = \dfrac{1}{\frac{R^3 C}{N}s^2 + \left(R + \frac{R^2 C}{N}\right)s + 2}$ (6)

Considering a negative feedback control system with the AQM being the controller, the system to be controlled is given by[9]:

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$$G(s) = \frac{R^3C^3}{2\,N^2}\frac{A(s)e^{-Rs}}{1 + A(s)Rse^{-Rs}} \tag{7}$$

$$= \frac{R^3C^3}{2\,N^2}\frac{e^{-Rs}}{\frac{R^3C}{N}s^2 + \left(R + \frac{R^2C}{N}\right)s + 2 + Rse^{-Rs}} \tag{8}$$

III. AQM for Congestion Control

A. Approximation of the control model of a first order delay system

In the process control industry, most systems can be roughly modeled as a first order system with delay:

$$\hat{G}(s) = \frac{Ke^{-Ls}}{Ts+1} \tag{9}$$

Where K, T and L represent respectively the state gain, the constant time and the time delay of the plant. These three parameters are supposed to be positive.

We already carry out this approximation calculation in [9], we found:

$$\begin{cases} K = \frac{R^3C^3}{4N^2} \\ T = R\left(\frac{R^4C^2}{4N^2} + \frac{2RC}{N} - \frac{2R^2C}{N} + 2\right)^{\frac{1}{2}} \\ L = \frac{R^2C}{2N} + 2R - T \end{cases} \tag{10}$$

B. Preliminary results

Large number problems in process control engineering are related to the presence of delays. These delays are involved in the dynamic models whose equations characteristics are of the following form [12, 13]:

$$\delta(s) = d(s) + e^{-L_1 s}n_1(s) + e^{-L_2 s}n_2(s) + \cdots + e^{-L_m s}n_m(s) \tag{11}$$

Where: d(s) and n(s) are polynomials with real coefficients and Li represent time delays. These characteristic equations are recognized as quasi-polynomials. We consider the case which meets the following assumptions:

$$\text{A1: } 0 < L_1 < L_2 < \cdots < L_m \tag{12}$$

$$\text{A2: } \operatorname{desg}(d(s)) = n \text{ and } \deg(n_i(s)) < n \tag{13}$$

$$i = 1,2,3,\dots,m$$

One can consider the quasi-polynomials δ*(s) described by:

$$\delta^*(s) = e^{L_m s}\delta(s)$$

$$\delta^*(s) = e^{L_m s}d(s) + e^{(L_m - L_1)s}n_1(s) + e^{(L_m - L_2)s}n_2(s) + \cdots + n_m(s) \tag{14}$$

The zeros of δ(s) are identical to those of δ*(s) since $e^{L_m s}$ does not have any finite zeros in the complex plan. However, the quasi-polynomial δ*(s) has a principal term since the coefficient of the term containing the highest powers of s and e^s is nonzero. If δ*(s) does not have a principal term, then it has an infinity roots with positive real parts [15].

The stability of the system with characteristic equation (13) is equivalent to the condition that all the zeros of δ*(s) must be in the open left half of the complex plan. We said that δ*(s) is Hurwitz or is stable. The following theorem gives a necessary and sufficient condition for the stability of δ*(s).

Theorem 1[11][12][13][14][15]

Let $\delta^*(s)$ be given by (3) and write:

$$\delta^*(j\omega) = \delta_r(\omega) + j\delta_i \tag{15}$$

Where $\delta_r(\omega)$ and $\delta_i(\omega)$ represent respectively the real and imaginary parts of $\delta^*(j\omega)$. Under conditions (A1) and (A2), $\delta^*(s)$ is stable if and only if:

1: $\delta_r(\omega)$ and $\delta_r(\omega)$ have only simple, real roots and these interlace,

2: $\delta_i'(\omega_0)\delta_r(\omega_0) - \delta_i(\omega_0)\delta_r'(\omega_0) > 0$ for some ω_0 in $[-\infty, +\infty]$ Where $\delta_r'(\omega)$ and $\delta_i'(\omega)$ denote the first derivative with respect to ω of $\delta_r(\omega)$ and $\delta_i(\omega)$, respectively.

A crucial stage in the application of the precedent theorem is to verify that and have only real roots. Such a property can be checked while using the following theorem.

Theorem 2 [8][12][13][14][15]

Let M and N designate the highest powers of s and e^s which appear in $\delta^*(s)$. Let η be an appropriate constant such that the coefficient of terms of highest degree in $\delta_r(\omega)$ and $\delta_i(\omega)$ do not vanish at $\omega = \eta$. Then a necessary and sufficient condition that $\delta_r(\omega)$ and $\delta_i(\omega)$ have only real roots is that in each of the intervals $-2l\pi + \eta < \omega < 2l\pi + \eta, l = l_0, l_0 + 1, l_0 + 2 \ldots$

$\delta_r(\omega)$ or $\delta_i(\omega)$ have exactly $4lN + M$ real roots for a sufficiently large l_0.

C. Stabilization using PI Controller

We consider now the feedback control system shownin Fig. 2, where r is the command signal, y is the output of the plant, Ĝ(s) is the plant to be controlled, and C(s) is the controller.

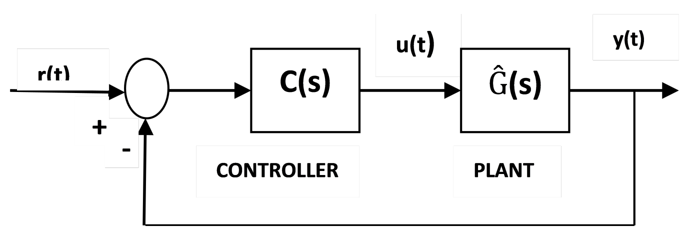

Fig. 2. Feedback control system.

We will focus on the case when the controller is the PI controller described by the following transferfunction:

$$C(s) = K_p + \frac{K_i}{s} \tag{16}$$

The objective is to determine the set of controller parameters (Kp, Ki) for which the closed-loop system is stable.

Theorem 3 [11][12][13][14][15]

The range of K_p value, for which a solution to PI stabilization problem for a given stable open-loop plant exists, is given by:

$$-\frac{1}{K} < K_p < \frac{T}{KL}\sqrt{\alpha_1^2 + \frac{L^2}{T^2}} \tag{17}$$

Where α_1 *the solution of the equation* $tan(\alpha) = -\frac{T}{L}\alpha$ *in the interval* $[\frac{\pi}{2}, \pi]$

The proof of this theorem is detailed in[9].

To determine the stabilizing PI parameters for a first order delayed system, analgorithm has been proposed deduced from the theorems above [9].

IV. Genetic Algorithm Optimization

GeneticAlgorithms (GAs) are adaptive heuristic search algorithm based on the evolutionary ideas of natural selection and genetics. As such they represent an intelligent exploitation of a random search used to solve optimization problems. The main idea in this technique is derived from natural evolution so there are some biological operators such as Crossover, Mutation and Selection [16]. The evolution from one generation to the following is based on the use of the three operators; selection, crossover and mutation which are applied to all the elements of the population. There are three part of this process which are randomly generated, namely the Initial Population, the Crossover and the Mutation. In the first step of the process, the Initial Population in the Genetic Algorithm generates some random solutions. In the second step, the random value of Crossover aid to make new offspring and in the third step, with random value of Mutation let to change a few of gens [17][22][23].

The principle of regulator parameters optimization by the Genetic Algorithms is shown by Fig. 3. It is about the search of parameters k_p and k_i in the area of stability.

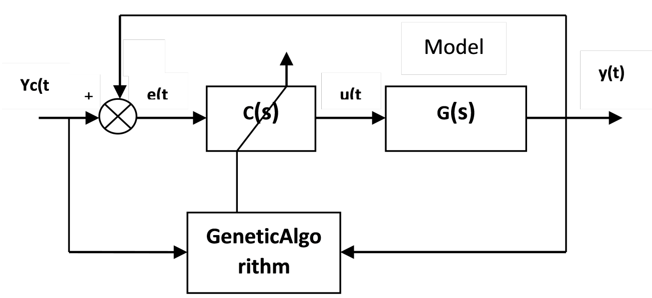

Fig. 3. The optimization principle by genetic algorithm.

A. The objective functions fitness values

The most crucial step in applying GA is to choose the objective functions that are used to evaluate fitness of each chromosome. Some works, like [18] and [19] use performance indices as the objective functions.The both authors use Integral of Time multiplied by Absolute Error (ITAE), Integral of Absolute Magnitude of the Error (IAE), and Integral of the Squared Error (ISE). Here we use all three performance indices stated above and Integral of Time multiplied by the Squared Error (ITSE) to minimize the error signal e(s) and compare them to find the most suitable one. The performance indices are defined as follow:

$$ISE = \sum_0^{t_{max}} e(t)^2, \quad IAE = \sum_0^{t_{max}} |e(t)|, \tag{18}$$

$$ITAE = \sum_0^{t_{max}} t|e(t)|, \qquad ITSE = \sum_0^{t_{max}} te(t)^2$$

Where e(t) is the error signal in time domain.

If we want to minimize the tuning energy, the ITAE criteria and the IAE are considered. In the case where we privilege the rise time, we take the ITSE criterion. In order to guarantee the tuning energetic cost, we choose the ISE criterion.

The calculation steps of the control law are summarized by the following algorithm [20]:

1. Introduction of the following parameters:
   - max_{pop} individuals number by population.
   - initial population.
   - gen_{max} generation number.
2. Initialization of the generation counter ($gen = 1$).
3. Initialization of the individual counter ($j = 1$).
4. For $t = 1s$ to $t = t_{max}$ efficiency evaluation of j^{th} population individual.
5. Individual counter incrementing ($j = j + 1$).
   - If $j < max_{pop}$, going back to step 4.
   - If not: application of the genetic operators (selection, crossover, mutation) for founding a newpopulation.
6. Generation counter incrementing $gen = gen + 1$,
7. If $gen < gen_{max}$; going back to step 3.
8. Taking $K_p opt$ and $K_i opt$ which correspond to the best individual in the last population (individual making the best fitness).

On the following, the genetic algorithm is characterized by generation number equal to 100, Pc = 0.8, Pm =0.08 and individual number by population equivalent to 50.

We now present an example that illustrates the application of the results presented in this section.

V. Simulation Results

The performance of the closed-loop system with the new PI controller is tested by simulation. The number of TCP flows is taken to be N = 60, the link capacity C = 3750 packets/sec, round trip time R = 400s, the desired queue size q_0= 150 packets, and the buffer size q_{max} = 200 packets [9].

We obtain the stability region in Kp, Ki plane, presented in Fig. 4:

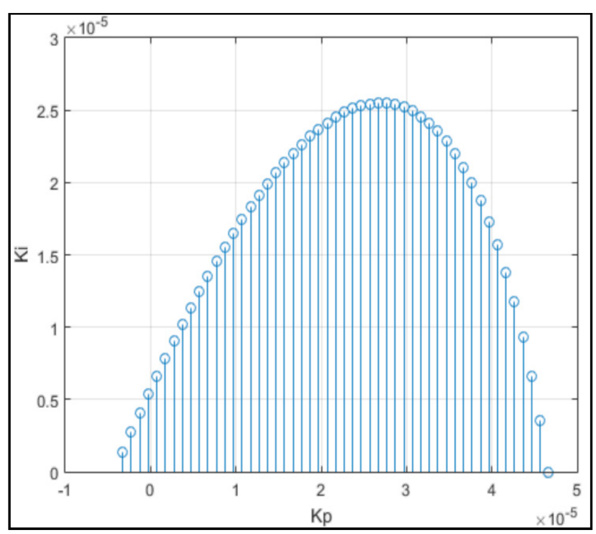

Fig. 4. Stability region of the system

The closed loop step responses of PI conroller optimum parameters supplied by Genetic Algorithm are illustrated in the following Fig. 5:

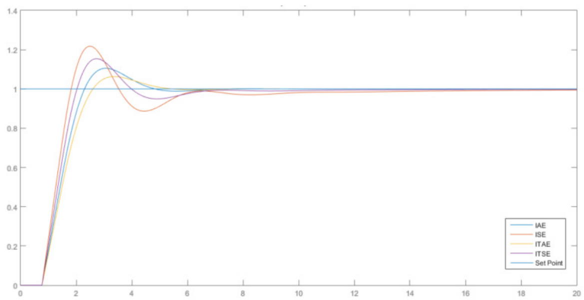

Fig. 5. Step response for the different optimal PI controllers.

The performances are rise time, settling time and overshoot. The aim of the controllers is to minimize the transient state response performances. Numerical values of these performances of the closed loops are given in Table 1 for comparison:

TABLE 1:
NUMERICAL VALUES OF STANDARD PERFORMANCE MEASURES.

Criterion	ISE	IAE	ITAE	ITSE
$\boldsymbol{K_p}opt(10^{-4})$	0.22	0.1642	0.1489	0.0296
$\boldsymbol{K_i}opt(10^{-4})$	0.0293	0.0325	0.0296	0.0321
Rise Time (s)	0.8183	1.1453	1.3229	0.9630
Settling Time (s)	9.7619	4.4026	4.6105	6.1405
Overshot (%)	21.7792	10.5320	6.3206	15.4224

A. *Standard performance measures:*

It can be seen from Table 1 that GA optimized by the four criterions provides a very small rise time which is beneficial for the congestion control of the AQM routers, chiefly the one obtained by the ISE criterion. The best value of the settling time is provided by IAE and ITAE and that of the overshoot is given by GA optimized by ITAE.

VI. Conclusion

Congestion is one of the most important problems faced in communications networks. In this paper we proposed to solve this problem by applying a new approach to compute the stability region for first order delay system controlled by PI controllers. This result is based on an extension of the Hermite-Biehler Theorem to quasipolynomials. Then, we were interested in search of optimal PI for performance criteria, inside the stability region by resorting to the Genetic Algorithm techniques as a method of optimization.

Finally, it is pointed out that the effectiveness of the proposed approach has been verified via simulation.

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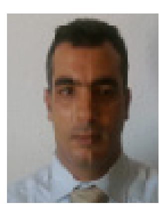

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