Quantitative Feedback Theory applied to the state model of congestion control

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***Abstract*— Several studies have considered control theory tools for traffic in communication networks, as for example the congestion control in IP (Internet Protocol) routers. In this paper, we will apply the Quantitative Feedback Theory to obtain an improved Active Queue Management control scheme. The resulting control law is validated through numerical network estimations.**

I. INTRODUCTION

TRAFFIC congestion of the Internet is a serious communication problem lived by millions of users. Many works have been done to enhance the internet congestion control performance, and provide a Quality of Service (QoS). From these models, a control theory based approach can be used to design AQM schemes. [1]-[[2] - [4] - [5].

We follow the model introduced in [3]: Fig. 1 shows the theory system structure of the model for wired network and wired–wireless network, and the wired–wireless architectural trend in enterprise 802.11 deployments is shown in Fig. 2, which is included in Fig. 1.

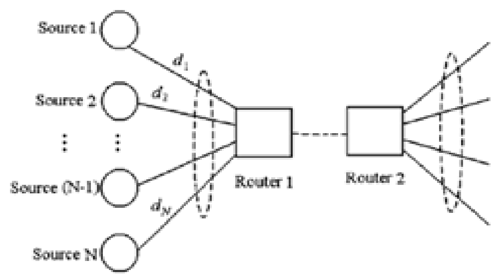

Fig.1 The theory system network model.

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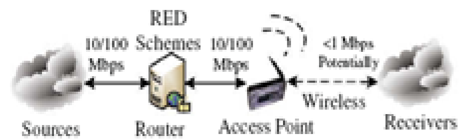

Fig.2 Wired-Wireless architectural trend in entreprise802.11 deployements

As shown in Fig. 1, TCP sources send data packets passing through the routers to their corresponding destinations. The data will be buffered in these routers. The buffer will decide the data packet drop probability p based on the congestion of the current queue. And then it computes p to drive packet dropping. The sending window size of TCP Sender at next time slot will be adjusted based on acknowledgements of Receiver [1].

At follows, we will detail the Quantitative Feedback Theory used to solve the congestion control problem.

II. QUANTITATIVE FEEDBACK THEORY

[16]-[17]-[18]-[19]-[20]-[21] This chapter is dedicated to present an overview of the Quantitative Feedback Theory (QFT), it is specifically applicable to plants with large uncertainty, and it is very effective in achieving tracking and disturbance rejection, also, it is applicable to systems with time delay and unstable cases.

Quantitative feedback theory (QFT) was developed by Isaac Horowitz (Horowitz, 1963; Horowitz and Sidi, 1972); it is a frequency domain technique using the Nichols chart (NC). The QFT is used to achieve a desired robust design over a specified region of plant uncertainty.

Desired time-domain responses are translated into frequency domain tolerances, which lead to bounds on the loop transmission function. The design process is highly transparent, allowing a designer to see what trade-offs are necessary to achieve a desired performance level.

QFT is robust control method which deals with the effects of uncertainty systematically. It is a graphical loop shaping procedure used for the control design of either Single Input Single Output (SISO) or Multiple Input Multiple Output (MIMO) uncertain systems including the nonlinear and time varying cases.

A . Loop shaping

The controller design is undertaken on the NC considering the frequency constraints and the nominal loop L_0(s) of the system. At this point, the designer begins to introduce controller functions (P(s)) and tune their parameters, a process called Loop Shaping, until the best possible controller is reached without violation of the frequency constraints.

The experience of the designer is an important factor in finding a satisfactory controller that not only complies with the frequency restrictions but with the possible realization, complexity, and quality.

For this stage, there are different CAD (Computer Aided Design) packages to make the controller tuning easier. In our case, we will use Scilab.

B. Methodology

Usually, system performance is described as robustness to instability , rejection to input and output noise disturbances and reference tracking. In the QFT design methodology; these requirements on the system are represented as frequency constraints, conditions that the compensated system loop (controller and plant) could not break.

With these considerations, the frequency constraints for the behavior of the system loop are computed and represented on the Nichols Chart (NC) as curves.

To achieve the problem requirements, a set of rules on the Open Loop Transfer Function, for the nominal plant: L_0(s) = G(s) P_0 (s) may be found. That means the nominal loop is not allowed to have its frequency value below the constraint for the same frequency, and at high frequencies the loop should not cross the Ultra High Frequency Boundary (UHFB), which has an oval shape in the center of the NC.

C. Specifications and Architecture

Consider a two degree freedom feedback system configuration where P(s) ,G(s) are uncertain linear time-invariant plant and the controller be designed respectively.

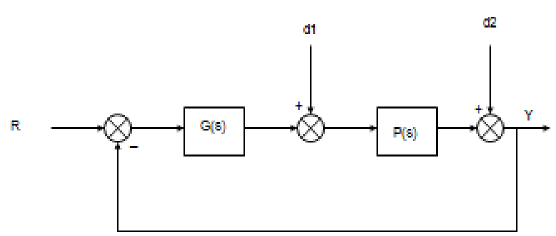

Fig.3. The Two Degree-of-Freedom Structure in QFT

The open loop transmission function is defined as:

$$L(s)=G(s)P(s)$$

And the nominal open loop transmission function is:

$$L_0(s) = G(s)\,P_0(s)$$

The objective in QFT is to synthesize G(s) and F(s) such that the various stability and performance specifications are met for all P(s) ε P. In general following specifications are considered in QFT:

- Robust stability margin:

$$L(j\omega)/(1 + L(j\omega)) \leq Ws \quad (1)$$

- Robust tracking performance:

$$T_L(j\omega) \leq \frac{F(j\omega)L(j\omega)}{(1 + L(j\omega))} \leq T_U(j\omega) \quad (2)$$

- Robust input disturbance rejection performance:

$$\frac{G(j\omega)}{1+L(j\omega)} \leq W_{di} \quad (3)$$

- Robust output disturbance rejection performance:

$$\frac{1}{1+L(j\omega)} \leq W_{do} \quad (4)$$

In practice, the objective is to satisfy the given specifications over design frequency set Ω. The design procedure which is to be followed for applying QFT robust design technique is as follows:

D. QFT Design

- Synthesize the desired model,
- Specify the plant models that define the region of plant parameter uncertainty,
- Obtain the plant templates at specified frequencies that describe the region of plant parameter uncertainty on the Nichols Chart,
- Select the nominal plant transfer function $P_0(s)$,
- Determine the stability contour on the Nichols Chart,
- Determine tracking and optimal bounds on the Nichols Chart,
- Synthesize the nominal loop transmission function L_0(s) = G(s) P_0 (s) that satisfies all the bounds and stability contour,
- Synthesize the pre-filter F(s).

III. TCP/AQM MODEL

[1]-[2]-[4]-[5] A fluid model of TCP dynamical behavior was developed; it uses the theory of stochastic differential equations. The model describes the evolution of the variables on the network such as TCP Window size and Queue length. Fig. 4 shows the links between the variables on the network [3] - [8]:

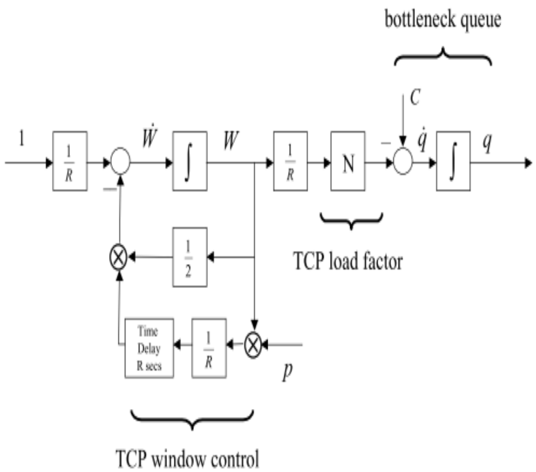

Fig.4 Block-Diagram of TCP connection

Based on some reasonable assumptions, we get the following relations [9]:

$$\begin{cases} \dot{W}(t) = \dfrac{1}{\tau(t)} - \dfrac{W(t)}{2}\dfrac{W(t-\tau(t))}{\tau(t-\tau(t))}p(t-\tau(t)), & (5) \\ \dot{q}(t) = \begin{cases} -C(t) + \dfrac{N(t)}{\tau(t)}W(t), \\ \text{when}: q(t) \succ 0, \\ \max\left\{0, -C(t) + \dfrac{N(t)}{\tau(t)}W(t)\right\}, \\ \text{when}: q(t) = 0 \end{cases} & (6) \\ \tau(t) = \dfrac{q(t)}{C(t)} + T_p, \end{cases}$$

Where:

TABLE I

Description of Network parameters

Parameter	*Description*
W(t)	Window length
q(t)	Queue length
C	Transmission Capacity
R	RTT made up of two items
Tp	Propagation delay
N	Number of TCP connections
P	Probability of packet dropping

The equilibrium point is defined by:

$\dot{w}=0$ and $\dot{q}(t)=0$,

And the linearization of (5) and (6) at this point gives:

$$\delta\dot{w}(t) = \frac{-2N}{R^2C}w(t) - \frac{Rc^2}{2N^2}p(t-R) \quad (7)$$

$$\delta\dot{q}(t) = \frac{N}{R}w(t) - \frac{1}{R}q(t) \quad (8)$$

We apply Laplace Transformation to (7) and (8), and, then we get:

$$sW(s) = \frac{-2N}{R^2C}W(s) - \frac{RC^2}{2N^2}e^{-Rs}\,p(s) \quad (9)$$

$$sQ(s) = \frac{N}{R}W(s) - \frac{1}{R}Q(s) \quad (10)$$

This leads to:

$$P(s) = \frac{Q(s)}{p(s)} = \frac{ke^{-Rs}}{(T_1s+1)(T_2S+1)} \quad (11)$$

Where:

$$k = \frac{(RC)^3}{4N^2}; T_1 = \frac{R^2C}{2N}; T_2 = R$$

So, the linearization of equations can be modeled as a two-order with delay plant transfer function.

As demonstrated in [1], the second order of Padé approximation is adequate to approach the true system.

We will consider the Second order Padé approximation which is given by:

$$e^{-Rs} = \frac{1 - \frac{Rs}{2} + \frac{(Rs)^2}{12}}{1 + \frac{Rs}{2} + \frac{(Rs)^2}{12}}$$

And apply it to (11);

So, the new Transfer function is:

$$P(s) = \frac{k(1 - \frac{Rs}{2} + \frac{(Rs)^2}{12})}{(T1s+1)(T2s+1)(1 + \frac{Rs}{2} + \frac{(Rs}{12}} \quad (12)$$

This plant can be written as:

$$P(s) = \frac{b_0 + b_1s + b_2s^2 + b_3s^3}{p_0 + p_1s + p_2s^2 + p_3s^3 + s^4} \quad (13)$$

With:

$$b_0 = \frac{24k}{R^5c^2}; b_1 = \frac{12k}{R^4c}; b_2 = \frac{2k}{R^3c}; b_3 = 0$$

And:

$$p_0 = \frac{24N}{R^5 c}; p_1 = \frac{36N}{R^4 c} + \frac{12}{R^3};$$
$$p_2 = \frac{14N}{R^3 c} + \frac{18}{R^2}; p_3 = \frac{2N}{R^2 c} + \frac{7}{R}$$

As a result, the values of coefficients in the Transform Function have a range of uncertainty. Therefore, in QFT simulations, every parameter of this function is included into an interval of possible values, and the system may be represented by a family of plants rather than by a standalone expression.

IV RESULTS OF APPLYING THE QFT DESIGN TECHNIQUE

- Transfer Function:

First, we recall the Active Queue Management Transfer Function:

$$P(s) = \frac{b_0 + b_1 s + b_2 s^2 + b_3 s^3}{p_0 + p_1 s + p_2 s^2 + p_3 s^3 + s^4}$$

- Parameter uncertainty:

Let R ε [0.06; 0.9] s, C ε [15; 60] Mb/s, and N ε [10; 100]

So, the plant uncertainties are:

p_0 = [6.7740×10-5 ; 205.7613];

p_1 = [16.4610; 5.5574×104];

p_2 = [22.2223; 5000];

p_3 = [7.7778; 116.6704]

So then, we synthesize the desired model, and specify the plant models that define the region of plant parameter uncertainty,

- Step Responses without controller:

Fig. 5 gives the step response of 50 values of P(s) without controller. The system is very oscillatory, so, the challenge is to obtain a robust controller for all these (P(s)).

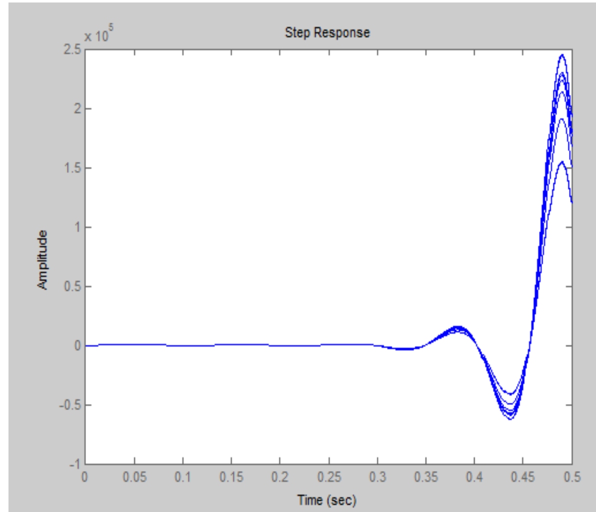

Fig.5 Time characteristic diagram step response of 50 values of P(s)

- Nominal Transfer Function:

Now, we choose a nominal transfer function:

Let $P_0(s)$ be the transfer function of the nominal system;

$$P_0(s) = \frac{1.125\text{x}10^{12}\, s^2 + 1.125\text{x}10^{14}\, s + 4.5\ \text{x}10^5}{s^4 + 62.22\, s^3 + 2511\, s^2 + 2.78\ \text{x}10^4\, s + 102.9}$$

in Fig.6 and Fig 7, there are simulations of the open loop : bode, Nyquist, Nichols, Step response and the pole-Zero map.

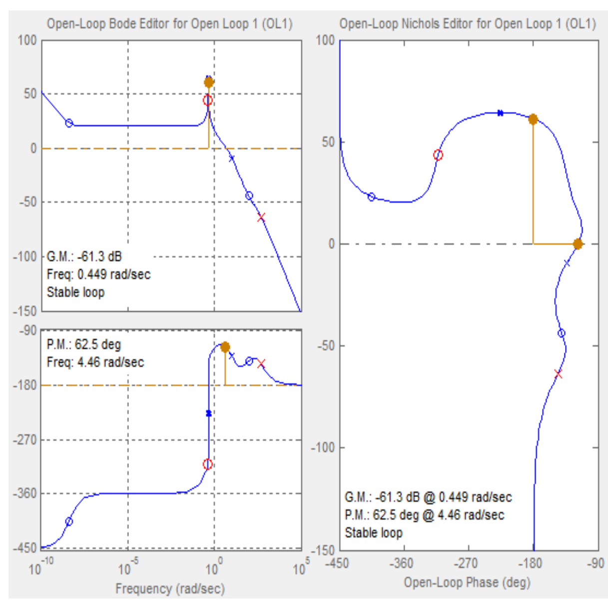

Fig.6 Bode and Nichols diagrams of the nominal open loop

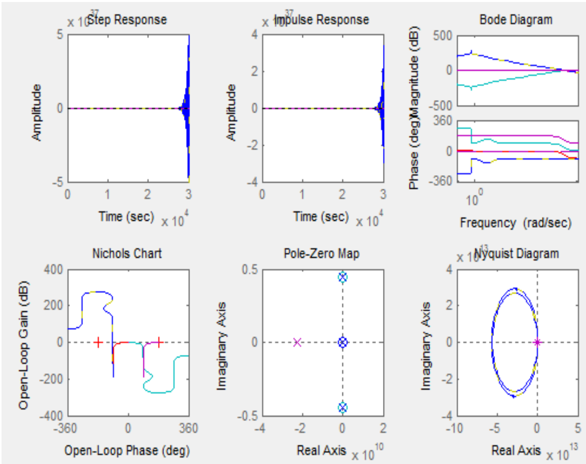

Fig.7 Step , impulse response, Bode and Nichols diagram and pole zero Map of the nominal open loop

- Design Specifications

The specifications in section II will be considered: Performance specifications:
Minimize the sensitivity functions as much as possible, and disturbance rejection.
Robustness specifications:
–20 dB/decade roll-off slope and –20 dB loop gain at1rad/s. Both specs can be accommodated by taking as the desired loop shape $G_d(s)=1/s$
We consider also a settle time <0.2 sec.
These specifications are tuned using Scilab.

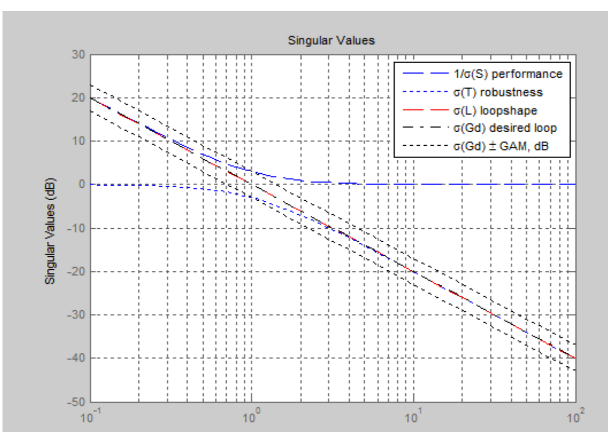

Fig.8 specifications

Now, we tune the PID controller,
Using Scilab, we get:

$$G = \frac{9.1033 * 10^{-12}\,(1 + 2.3s)}{s(1 + 0.002s)}$$

Then, we simulate the controller; verify the performance of designed controller as shown in fig 9. It is verified for a set of uncertain plant, the bode diagram, shown in fig10. We verify that step responses for the uncertainty verify the settle time<0.2sec(fig.9), and as an exemple, we see the robustness specifications verified for the nominal system(fig.10)

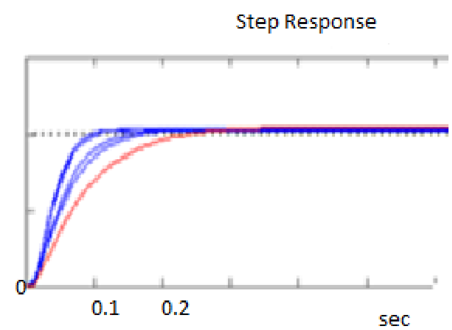

Fig.9 step response for all uncertainties

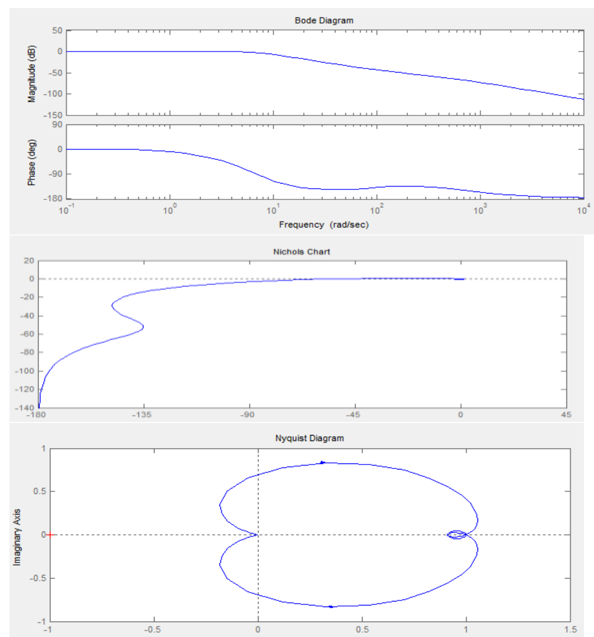

Fig.10.Robustness Performance verified for the nominal system

V. CONCLUSION

This paper presents an application of the Quantitative Feedback Theory to the TCP/AQM networks based on fluid flow models with delay. In a first time, we formulate a robust control problem as QFT control problem, we choose a set of uncertainties for the internal values R, C and N, and apply the strong methodology of the QFT .So, we guarantee the robust stability of the system for a large bound of uncertainty and frequencies . Impossible result when we use controllers proposed in the literature such as RED (Random Early Detection) or PID or H2/H∞. These controllers give good performance under certain conditions, but they become unstable if the input delay or/and the parameters of the networks change beyond some limits.

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