Design of H_∞ Congestion Controller for TCP Networks Based on LMI Formulation

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Abstract

In this paper, a state feedback H_∞ controller is proposed in order to design an active queue management (AQM) system based on congestion control algorithm for networks supporting TCP protocols. In this approach, the available link bandwidth is modeled as a time-variant disturbance. The purpose of this paper is to design a controller which is capable of achieving the queue size and can guarantee asymptotic stability in the presence of disturbance. An important feature of the proposed approach is that the performance of system, including the disturbance rejection and stability of closed-loop system, are guaranteed for all round-trip times that are less than a known value. The controller design is formulated in the form of some linear matrix inequalities, which can be efficiently solved numerically. The simulation results demonstrate the effectiveness of the proposed methods in comparison with the conventional methods.
Keywords: TCP, AQM, Time delay, H_∞, LMI, Stability, Disturbance rejection.

1. Introduction

Communication networks are an essential part of many applications in science and engineering, such as Web servers, multimedia, and remote control. However, traffic congestion is a major problem in today's Internet. Since the quality of service cannot be guaranteed, the number of users has grown rapidly and unanticipated interferences may occur. Therefore, congestion control techniques monitor network loads in an effort to anticipate and avoid congestion at common network bottlenecks. Congestion control is achieved through packet dropping.

As Clark et al. (1998) and Floyd et al. (1997) declare, active queue management (AQM) is a key congestion control scheme for reducing packet drops and improving network utilization. The random early detection (RED) algorithm is the earliest well-known AQM scheme that eliminates the flow synchronization problem and attenuates the traffic load. Unfortunately, RED causes oscillations and instability due to the parameter variations. Therefore, some modified RED schemes, such as FRED and SRED have been proposed in the literature by Lin et al. (1997) and Qtt et al. (1999). However in those studies, both high network utilization and low packet loss cannot be guaranteed by only setting control parameters. Recently, control theory has been widely applied to the analysis and design of TCP networks and congestion control schemes for them. The theory of stochastic equations has been applied to develop a fluid-based model of the dynamics of the TCP and RED by Misra et al. (2000). Based on this TCP model, the fundamentals of control theory have been used to analyze and develop new AQM schemes. Hollot et al. (2001) developed Proportional-integral (PI) controller for a linearized system and implemented using differential equations. Lin et al. (1997) proposed a sliding mode variable structure control (SMVS) scheme for TCP congestion control. Kim (2006) proposed proportional-integral-derivative (PID) controllers to improve the performance of TCP systems. While great progress has been made in new congestion control schemes, some problems are still not sufficiently addressed. One important problem is the robustness of the congestion control algorithm against the disturbance on the available link bandwidth since it is often time-varying and cannot be exactly measured.

In this paper a H_∞ state feedback control approach has been proposed. The main difference between our approach and the previous studies that have been proposed by Quet et al. (2004), Chen et al. (2005) and Chen et al. (2007) is that, the approach proposed here uses a time-domain H_∞ design method, which can deal with the situation where the round-trip time varies with time, while the previous studies

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use frequency-domain design method, which require that the system under consideration is time invariant.

The organization of the paper is as follows: In section 2, system model and problem statement will be presented. We formulate our problem same as Hollot et al. (2002). In section 3, we discuss how to deal with linear time delay systems. In the next section, a H_∞ state feedback controller is employed to solve the problem for linear time varying systems. In section 4, performance of the closed loop system by using the proposed controller has been discussed in the form of some simulations and the paper is concluded in the section 5.

2. Model of the System

We begin our discussion of AQM by introducing a dynamic model for TCP's congestion control. Misra et al. (2000) developed a dynamic model of TCP behavior by using fluid-flow and stochastic differential equation analysis that is used in this paper. Similar to Hollot et al. (2002) declaration, here a simplified version of that model is used which neglects the TCP timeout mechanism. This model is described through the following coupled and nonlinear delay-differential equations:

$$\begin{cases} \dot{W} = \dfrac{1}{\tau(t)} - \dfrac{W(t)}{2}\dfrac{W(t-\tau(t))}{\tau(t-\tau(t))}p(t-\tau(t)), \\ \dot{q}(t) = \begin{cases} -C(t) + \dfrac{N(t)}{\tau(t)}W(t), & q(t) > 0, \\ \max\left\{0, -C(t) + \dfrac{N(t)}{\tau(t)}W(t)\right\}, & q(t) = 0 \end{cases} \\ \tau(t) = \dfrac{q(t)}{C(t)} + T_p, \end{cases} \tag{1}$$

Where W is the TCP window size (in packets), q the queue length in the router (in packets), τ the round-trip time (in Sec), C the available link capacity (in packets/s), T_p propagation delay (in Sec.), N the number of TCP sessions, and p the probability of packet mark. It is assumed that $q \in [0, \bar{q}]$ and $W \in [0, \bar{W}]$, where $\bar{q}$ and $\bar{W}$ denote buffer capacity and maximum window size, respectively. The marking probability p belongs to the interval [0,1]. In practical networks, the available link capacity changes with time and it is difficult to measure. Therefore, it is taken as a disturbance in a lot of studies such as Cavandish et al. (2004), Fan et al. (2007) and Mascolo (1999). In this paper, it is supposed that the nominal value of $C(t)$, say C_0, is known, while $\delta C(t) \triangleq C(t) - C_0$ is unknown and considered as a disturbance for the system. Take (W, q) as the states and p as the input of the system. For a given triplet of network parameters (N, C_0, T_p), any triplet (W_0, q_0, p_0) that is in the set

$\Omega = \{(W_0, q_0, p_0) : W_0 \in [0, \bar{W}], q_0 \in [0, \bar{q}], p_0 \in [0,1],$ $\tau_0 = \dfrac{q_0}{C_0} + T_p, W_0 = \dfrac{\tau_0 C_0}{N}, p_0 = \dfrac{2}{W_0^2}\}$ is a possible operating point. Now define

$\delta W = W - W_0,\quad \delta q = q - q_0,\quad \delta p = p - p_0,\quad \delta C = C - C_0.$

We can obtain the linearized version of (1) as follows

$$\begin{cases} \delta\dot{W} = -\dfrac{N}{\tau_0^2 C_0}\left[\delta W(t) + \delta W(t-\tau_0)\right] \\ \quad -\dfrac{1}{\tau_0^2 C_0}\left[\delta q(t-\tau_0)\right] \\ \quad -\dfrac{\tau_0 C_0^2}{2N^2}\delta p(t-\tau_0) + \dfrac{\tau_0 - T_p}{\tau_0^2 C_0}\left[\delta C(t) - \delta C(t-\tau_0)\right] \\ \delta\dot{q} = \dfrac{N}{\tau_0}\delta W(t) - \dfrac{1}{\tau_0}\delta q(t) - \dfrac{T_p}{\tau_0}\delta C(t). \end{cases} \tag{2}$$

In contrast to the case of linear systems without delay, the solution for the H_∞ control problem for time delay systems is quite different.

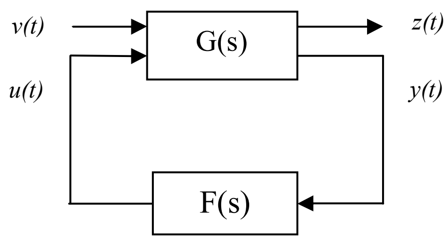

Fig. 1. A general setting for the H_∞ control design

When the delay appears only in the state variables, there are lots of results such as Lee et al. (2007) and Yang et al. (2006). But for the case where the time delay also appears in control variables, there is not any obvious solution.

This paper attempts to develop a H_∞ design approach for the problem of AQM-based congestion control based on the dynamic model (2), which guarantees the ratio between the norms of some desired variables and that of the disturbance being less than some specified value. Furthermore, this specified value for the ratio can be minimized for a given group of network parameters. To this end, we will first study the H_∞ control of general linear time delay systems and then apply the result to the above mentioned system.

3. H_∞ Control Of Linear Time Delay Systems

As is well-known, the primary goal of a control algorithm is to guarantee that the closed-loop system is stable. For linear time-invariant single-input-single-output (SISO) plant without delay, this goal can be easily achieved by using classical controller design approaches, developed in the 1950s and 1960s. Furthermore, the gain and phase margin indicated in these classical approaches provide a good measure for the robustness of closed-loop systems. However, it is difficult to apply these approaches to the controller design of a multi-input-multi-output (MIMO) plant or a time delay system. On the other hand, dealing with model uncertainty and disturbance is a main concern of control engineers. Therefore, various robust controller design approaches for complex plants have been developed since the 1980s. The H_∞ design is one of these approaches.

A general setting for the H_∞ design is illustrated in Fig. 1, where u is a control input, v the exogenous disturbance, z is the controlled output, and y is the measured output. The controlled output means the variable we want to regulate by designing a controller F. The objective of the H_∞ control design is to find a controller F such that

$$\|F_{zv}\| \le \gamma \tag{3}$$

Clearly, γ describes a kind of disturbance rejection ratio between the controlled variable and the exogenous disturbance. Comparing system (2) to Fig. 1, and setting, $z(t) = q(t)$, $v(t) = \delta C$, It can be seen that, under a H_∞ control scheme, the queue length of the router will be maintained level, which is implied by the asymptotical stability of the system, with minimum sensitivity to the fluctuation of the available link bandwidth, which is implied by the minimum of the disturbance rejection ratio. Therefore, it is a nature desire to develop a H_∞ design approach to the congestion control problem. Now consider the following system

$$\begin{aligned} \dot{x}(t) &= A_0 x(t) + A_1 x(t-\tau(t)) + B_0 u(t) + \\ &\quad B_1 u(t-\tau(t)) + D\upsilon(t) \\ z(t) &= Hx(t) \end{aligned} \tag{4}$$

Where $x(t) \in \Re^n$ is the system state, $u(t) \in \Re^{n_u}$ the control input, $\upsilon \in \Re^n$ the exogenous disturbance, $z \in \Re^{n_z}$ the controlled output, and τ the time-delay involved. Suppose that τ is upper-bounded by $\tau_m : 0 \le \tau \le \tau_m$. All matrices are of appropriate dimensions. Throughout this section, it is defined that $A = A_0 + A_1$ and $B = B_0 + B_1$. For a prescribed scalar $\gamma > 0$, define the performance index as

$$J(\gamma) = \int_0^\infty (Z^T(t)z(t) - \gamma^2 \upsilon^T(t)\upsilon(t))dt. \tag{5}$$

The objective is to find a control law of the type $u(t) = Kx(t)$ such that the closed-loop system satisfies $J(\gamma) < 0$ for any $\upsilon \in L_2^{n_\upsilon}[0,\infty)$. Furthermore, minimize γ if possible. Note that the requirement $J(\gamma) < 0$ means that

$$\frac{\|z\|}{\|\upsilon\|} \underline{\underline{\Delta}} \frac{\sqrt{\int_0^\infty z^T(t)z(t)dt}}{\sqrt{\int_0^\infty \upsilon^T(t)\upsilon(t)dt}} < \gamma \tag{6}$$

where $\|\ .\ \|$ refers to the 2-norm in the space $L_2^{n_\upsilon}[0,\infty)$. Eq. (6) says that the ratio between the norm of the controlled output and that of the disturbance is less than a specified scalar γ . To solve the above problem, the bounded real lemma (BRL) for time delay systems is needed. Fridman et al. (2001) and Shaked et al. (1998) have proposed several versions of BRL in literature. In this paper, we use formulation of Fridman et al. (2001) to solve the problem.

Lemma 1. Consider system (4) with $u(t) \equiv 0$. If there exist matrices $R > 0$ and $P \underline{\underline{\Delta}} \begin{bmatrix} P_1 & 0 \\ P_2 & P_3 \end{bmatrix}$ with $P_1 > 0$ such that the following linear matrix inequality (LMI)

$$\begin{bmatrix} P^T \begin{bmatrix} 0 & 1 \\ A & -1 \end{bmatrix} + \begin{bmatrix} 0 & A^T \\ 1 & -1 \end{bmatrix} P + \begin{bmatrix} H^T H & 0 \\ 0 & \tau_m R \end{bmatrix} & P^T \begin{bmatrix} 0 \\ D \end{bmatrix} & \tau_m P^T \begin{bmatrix} 0 \\ A_1 \end{bmatrix} \\ [0 \quad D^T]p & -\gamma^2 I & 0 \\ \tau_m [0 \quad A_1^T]p & 0 & -\tau_m R \end{bmatrix} < 0 \tag{7}$$

holds, then system (3) achieves $J(\gamma) < 0$. Based upon Lemma 1, the following theorem can be established.

Theorem 1. Consider system (4). If there exist matrices $Q_1 > 0$, Q_2 , Q_3 , Y and positive scalar ε such that the matrix inequality (11) holds, then the closed-loop system achieves $J(\gamma) < 0$ with the controller

$$u(t) = Kx(t), \quad K = YQ_1^{-1}. \tag{8}$$

Remark 1. From Theorem 1, we can see an interesting feature of the approach: the system performances, including the disturbance rejection ratio γ and the implied stability of the closed-loop system, are guaranteed for all time delay that is less than τ_m. This feature is especially important for the congestion control problem since the round-trip time is actually state-dependent and hence time-varying, whereas its upper bound can be roughly estimated.

In congestion control, one important problem is to find maximum allowable upper bound of the time delay such that the network can still be stabilized or a H_∞ performance index can still be guaranteed. This problem can be easily dealt based on the following corollary.

Corollary 1. Consider system (4). For a given positive scalar γ , if there exist matrices $Q_1 > 0$, $\overline{Q_1} > 0$, Q_2 , Q_3 , Q_4 and positive number ε such that the following matrix inequalities

$$\begin{bmatrix} \psi_2 & \eta_1 & \eta_2 \\ \eta_1^T & -\varepsilon\overline{Q_1} & 0 \\ \eta_2^T & 0 & -\frac{1}{\varepsilon}\overline{Q_1} \end{bmatrix} < 0 \tag{9}$$

$$\overline{Q_1} < \frac{1}{\tau_m} Q_1 \tag{10}$$

hold, where

$$\begin{bmatrix} Q_2 + Q_2^T & Q_1A^T + Y^TB^T - Q_2^T + Q_3 & 0 & 0 & Q_1H^T & Q_2^T \\ AQ_1 + BY - Q_2 + Q_3^T & -Q_3 - Q_3^T & D & \tau_m(A_1Q_1 + B_1Y) & 0 & Q_3^T \\ 0 & D^T & -\gamma^2 I & 0 & 0 & 0 \\ 0 & \tau_m(Q_1A_1^T + Y^TB_1^T) & 0 & -\tau_m\varepsilon Q_1 & 0 & 0 \\ HQ_1 & 0 & 0 & 0 & -I & 0 \\ Q_2 & Q_3 & 0 & 0 & 0 & -\frac{1}{\tau_m\varepsilon}Q_1 \end{bmatrix} < 0 \tag{11}$$

$$\psi_2 = \begin{bmatrix} Q_2 + Q_2^T & Q_1A^T + Y^TB^T - Q_2^T + Q_3 & 0 & Q_1H^T \\ AQ_1 + BY - Q_2 + Q_3^T & -Q_3 - Q_3^T & D & 0 \\ 0 & D^T & -\gamma^2 I & 0 \\ HQ_1 & 0 & 0 & -I \end{bmatrix} \quad \eta_1 = [0 \quad (A_1Q_1 + B_1Y)^T \quad 0 \quad 0]^T, \qquad \eta_2 = [Q_2 \quad Q_3 \quad 0 \quad 0]^T \tag{12}$$

then the closed-loop system achieves $J(\gamma) < 0$ with the controller

$$u(t) = Kx(t), \qquad K = YQ_1^{-1} \tag{13}$$

Furthermore, parameter τ_m can be maximized by solving the generalized eigenvalue problem defined by (9) and (10). It can give us the maximum allowable time delay for the system that closed loop system can be stable yet.

4. H_∞ Controller Performance

In this section, the result obtained in the former section will be applied to the RED-based congestion control problem. The short-lived http flows are introduced into the router and modeled with δC as a birth-and-death process. Specifically, construct δC as:

$$\delta C = B_{av}k(t)$$

Where $k(t)$ is a birth-and-death process with the birth and death rates being λ and μ, respectively, and B_{av} is the average transmission rate of http flows. According to Bertskas (1992), it is appropriate to use a birth-and-death process to model http flows. Note that the value of the available link capacity at the equilibrium may be also over-estimated, so δC might take negative values too. Considering this fact, $k(t)$ is allowed to take negative values. It is natural to assume that the birth rate and death rates are equal. Thus such a process is null-recurrent, i.e., the process does not keep visiting any state frequently. Therefore, gain $k(t)$ will diverge inevitably. Obviously, this does not match the practical situation. To remedy it, we place lower and upper bounds for $k(t)$, namely $-k_{\max} \le k(t) \le k_{\max}$, where $k_{\max}$ is a positive number. Thus $k(t)$ can be viewed as a modified birth-and-death process with lower and upper barriers. This is realized in simulation by simply removing the constraint $k \ge 0$ in the original model of the birth _death process and placing the new constraint $-k_{\max} \le k(t) \le k_{\max}$ on it.

Note that in model (2), the delayed version of the exogenous disturbance also appears in the dynamics of the system. To take into account of this fact, define

$$\overline{\upsilon}(t) = [\delta C(t) \quad \delta C(t - \tau_0)]^T$$

and change the objective function for H_∞ control design as

$$\bar{J}(\gamma) = \int_0^\infty (z^T(t)z(t) - \gamma^2\overline{\upsilon}^T(t)\overline{\upsilon}(t))dt. \tag{14}$$

It is clear that the performance $J(\gamma) < 0$ is satisfied if the closed-loop system achieves $\bar{J}(\gamma) < 0$.

Associating model (2) with the general system model (4), we can extract A_0, A_1, B_0, B_1, D matrices. The matrix H is chosen as $H = [0 \ 1]$ for all cases to be studied. The approach proposed here is compared with the performance of P and PI controllers that have been proposed by Hollot et al. (2002). Therefore, constant parameters of model extract from [10]. Where C=3750 packets/s, N=60 flows and τ_0 =*0.246 Sec*.

$$x(t)=\begin{bmatrix}\delta W(t)\\ \delta q(t)\end{bmatrix},$$

$$A_0=\begin{bmatrix}-\frac{N}{\tau_0^2C_0} & \frac{1}{\tau_0^2C_0}\\ \frac{N}{\tau_0} & \frac{1}{\tau_0}\end{bmatrix}, A_1=\begin{bmatrix}-\frac{N}{\tau_0^2C_0} & -\frac{1}{\tau_0^2C_0}\\ 0 & 0\end{bmatrix},$$

$$B_0=0,\ B_1=\begin{bmatrix}-\frac{\tau_0 C_0{}^2}{2N^2}\\ 0\end{bmatrix},\ D=\begin{bmatrix}\frac{\tau_0-T_P}{\tau_0^2C_0} & -\frac{\tau_0-T_P}{\tau_0^2C_0}\\ \frac{T_p}{\tau_0} & 0\end{bmatrix}$$

By substitution of the constant parameters in the above matrices, we have the following results:

$$A_0=\begin{bmatrix}-0.2644 & -0.0044\\ 243.9024 & -4.0650\end{bmatrix}$$

$$A_1=\begin{bmatrix}-0.2644 & 0.0044\\ 0 & 0\end{bmatrix}$$

$$B_0=0$$

$$B_1=\begin{bmatrix}-480.4688\\ 0\end{bmatrix}$$

$$D=\begin{bmatrix}2.3487*10\wedge(-10) & -2.3487*10\wedge(-10)\\ -0.7833 & 0\end{bmatrix}$$

In this case the PI controller has a transfer function

$$C(s)=K_{PI}\frac{(\frac{s}{z}+1)}{s}$$

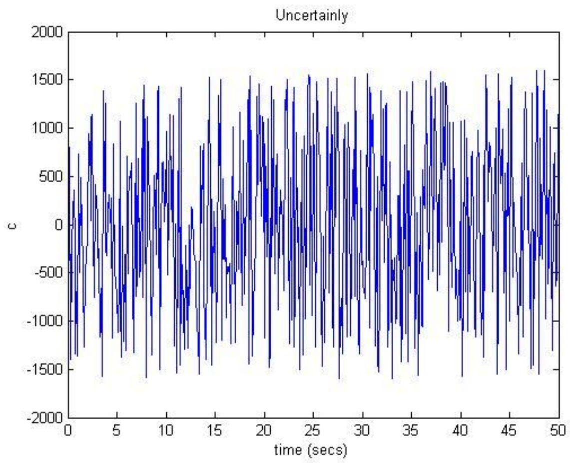

Fig. 2. The disturbance on the available link bandwidth

With $K_{PI}=9.64\times10^{-6}$ and $z=0.53$. The P controller has transfer function $C(s)=K_P$ With $K_P=5.8624\times10^{-5}$.

For design of H_∞ controller based on LMI formulation, we first use constant parameters to calculate A_0 , A_1 , B_0 , B_1 , D matrices. Then we determine the maximum delay which the controller is robust against it. We solve (11) to find the state feedback K as follows

K = [-1.5357e-003 2.3272e-005]

In all simulations, the initial windows size of every source and the initial queue length of the router are set to be zero. For each case controller, the same disturbance profile on the available link bandwidth is used for PI, P and H_∞ controllers.

From Fig. 2, we can see the disturbance on the available link bandwidth which is the result of birth and death process with $B_{av}=32$ and $k_{\max}=50$.

From Figures 3 and 4, we can see that, by using the H_∞ controller, a stable operating condition can be built up and maintained even in the situations where the available link bandwidth is subjected to presence of disturbance and the round-trip varies with different TCP sessions, while PI controller fail to do so. This is due to the lag of the response of the conventional PI controller to the sudden change of the network operating condition.

The responses of the queue size for the duration of time from 0 to 5 s can be observed in Fig. 3 and Fig. 4, respectively. It is clear that both H_∞ and P controllers yield lower overshoot than PI, and yield almost bigger rise time than PI. Also from Table 1, it is obvious that the maximum overshoot in H_∞ is smaller than P and PI controllers in both queue length and window size states.

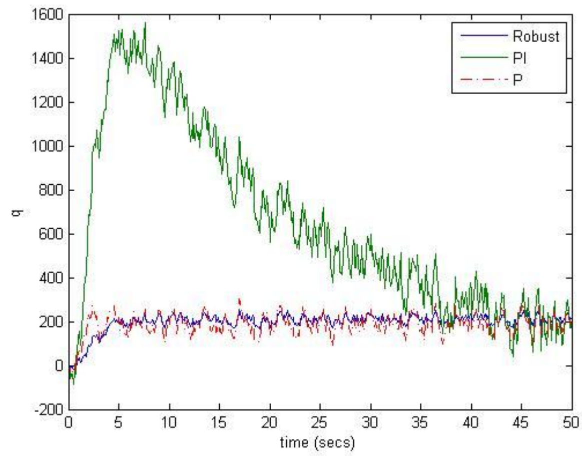

Fig. 3. Queue length responses using H_∞, P and PI controllers

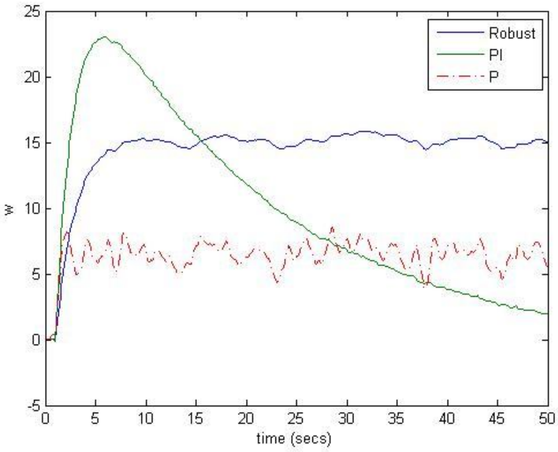

Fig. 4. Window size responses using H_∞, P and PI controllers

Table 1
compare performance of H∞, PI and P controllers

Characteristics	H∞	PI	P
Queue length maximum overshoot	6.6%	50%	40%
Window size maximum overshoot	25%	67.5%	50%

5. Conclusion

In this paper, a new design method for the H_∞ congestion controller of the TCP was developed based on the LMI technique. In this approach, the available link bandwidth is modeled as a nominal constant value, which is known to the link, plus a time-variant disturbance, which is unknown.

The proposed approach can theoretically guarantee the system performance, including the disturbance rejection and the implied stability of the closed-loop system for all round-trip times that are less than a known value. Finally, it is pointed out that the effectiveness of the proposed approach has been verified only via simulation in MATLAB. Further verification via packet-based simulation tools such as NS2 or via experimental studies is recommended.

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