Transport Control Protocol Based Computer Wireless Network Performance Enhancement

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***Abstract*— This work aims at developing a robust compensator for TCP queue based wireless network using H2 optimization technique. The objectives of this work are to improve the performance of the TCP by reducing the tracking error, settling time and to improve the stability of the system by increasing the gain margin to be greater than or equal to 20dB and increasing the phase margin to be greater than or equal to 60deg. The TCP is a vital organ in every wireless network and due to the increasing reliance on the wireless network by most human activities, it has suffered from disturbances most especially traffic congestion. The H2 optimization technique was applied to improve the performance and stability of the system while considering the disturbance and system output error. The H2 compensated TCP (H2-TCP) queue achieved a reduced settling time of 0.000419sec and a 0dB reference tracking error which showed good network throughput. The H2-TCP queue system recorded a gain margin of 20.3dB and 78.9deg phase margin. It was concluded that the H2-TCP network achieved improved performance and robust stability and hence can maintain optimal performance and stability even in the presence of high disturbances.**

Keywords—TCP; H2 Synthesis; Wireless Network; Tracking Error; Stability Margins

I. INTRODUCTION

The rapid increase in the amount of network traffic causes difficulty of data transfers in computer networks and this difficulty is described as congestion. This congestion in computer networks is a problem which must be solved in order to achieve optimal function of the network. The information exchange in the computer networks are better controlled by the Transmission Control Protocol (TCP) which is one of the common transport protocols whereby a sender has authority to set its transmission rate using a window flow-control mechanism. However, the TCP network traffic control method has drawbacks such as low efficiencies of communications because this method uses the mechanism to avoid congestion after congestion once appears in computer networks [1]. Congestion has been a common challenge of the high traffic communication network due to the tremendous amount of information exchange.

TCP has no information of network mechanisms contributing to packet loss – such as the congested router. Thus, routers must assume a role in network management by sensing congestion and preemptively signaling TCP rather than have it react to non-received packets [2]. The simplest form of the active queue management (AQM), termed drop tail, drops arriving packets when the router's buffer is full. Drawbacks of this scheme include flow-synchronization, in [3] and performance degradation due to the excessive time-outs and restarts arising when the trailing end of a sequence of data packets is dropped. Motivated by drop-tail's inefficiencies, the random early detection (RED) scheme was introduced in [3]. Rather than waiting for buffer overflow to occur, RED anticipates congestion by measuring the router's average queue length and throttling the sender's rate accordingly. Since TCP is an end-to-end protocol, RED achieves this signaling indirectly by randomly marking packets and routing them to the receiver. The receiver, in turn, completes the feedback by acknowledging the receipt of marked packets to the sender. Upon receipt of such acknowledgments, the sender adjusts its rate according to the TCP algorithm. The randomness in RED's packet-marking scheme was meant to eliminate flow-synchronization and introduce fair-marking while queue-averaging was introduced to attenuate the effects of bursty traffic on the feedback signal [2]. Incidentally, there is a crucial drawback in deploying RED stems from tuning difficulties where the performance of RED can approach that of a drop-tail router. Due to these deficiencies in the basic RED mechanism, researchers have continued to propose modifications to solve them as presented in [4, 5].

Many other control measures have been implemented to improve the performance of the TCP/AQM wireless network system such as the Proportional Integral (PI) controller which was confirmed in [6] to outperform RED significantly. However, PI has the ability to improve the stability of the system by achieving an improved steady state error but it has some limitations such as poor performance in disturbance rejection. Advanced robust control techniques, such as H2-synthesis or H2 optimization technique, were formulated to include the plant model. H2 -optimization technique finds a controller which minimizes the H2 norm of the closed-loop transfer function and internally stabilizes the system [7].

In this work, a robust compensator was developed for the TCP/AQM system performance and stability improvement and robustness using H2 synthesis. To achieve the performance and stability improvement and robustness, the reference tracking error must be reduced possibly to 0dB, settling time must be reduced to less than one second, the gain and phase margins (i.e., stability margins) must be greater than or equal to 20dB and 60deg [8] respectively.

II. LITERATURE REVIEW

A. Transport Control Protocol

TCP is a network communication protocol designed to send data packets over the Internet through the International Standard Organization (OSI) layer. It is a transport layer

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protocol in the OSI layer and it is used to create a connection between remote computers by transporting and ensuring the delivery of messages over supporting networks and the Internet. The message sender continuously probes the network's available bandwidth and increases its window size to garner maximum share of network resource after every successful transmission. For every successful end-to-end packet transmission, TCP increases the sender's window size. On the other hand, TCP reduces or cuts the window size in half whenever a sender's packet does not reach the receiver and this causes packet loss. Such packet losses can affect network performance and reliability by decreasing the sender's effective transmission rate and increasing delay due to packet retransmission. Some of the drawbacks of this scheme include flow-synchronization [3] and performance degradation due to the excessive time-outs and restarts arising when the trailing end of a sequence of data packets is dropped [2].

B. *Active Queue Management (AQM)*

AQM is a controller mechanism to identify congestion before the router buffers become full [9]. Thus, it detects congestion at the early stage. It was designed to maintain dropping/marking probabilities, the routers probabilistically drop or mark packets before the queue is full. An Active Queue Management system is used to control the length of a queue so that it does not run full, adding its maximum (usually bloated) delay under load. Such management also enables TCP to do its job of sharing links properly, without which it cannot function as intended. AQM behavior is influenced by variations in main network parameters such as link capacity and number of TCP sessions. Generally, these parameters do not have static values, but in some conditions, it is possible to assume their variations negligible. Most of AQM methods are designed for networks with limited parameter variations.

C. *H2 Synthesis*

H2 control theories have been active areas of research for the years and have been successfully introduced to many engineering applications [7]. It is a method of robust controller design which makes use of weights to form an augmented form of the plant to be controlled and produces a controller through loop-shaping. H2 -optimization finds a controller which minimizes the H2 norm of the closed-loop transfer function and internally stabilizes the system [7]. The H2 norm of a signal is the mean energy with respect to the frequency. If there are uncertainties in the system model, some quantity combining the H2 synthesis can be a desirable measure of a system's robust performance. Thus the H2 performance criterion provides an interesting measure for the controller evaluation. The theory of H2 synthesis was discussed in [10, 11] and the theoretic motivation for the H2 control problem was discussed in [12]. The same method is used for convex parameterization of fixed-order H-infinity controllers in [13]. The robustness capabilities and application of H2 and its iteration limits are discussed in [14].

D. *Fluid-Flow Model of TCP Behaviour*

The TCP/AQM has been modeled in [15, 16, 17] using the fluid flow modeling method. This mathematical model is described by a second-order system with time delay. The dynamic model of TCP flows is developed by using a fluid flow model without considering slow start and timeout mechanisms [18]. Based on this system, a type of AQM is constructed, which takes into account delays into the network. This model is described by the following non-linear differential equations. This model is described by the following non-linear differential equations [17]:

$$\begin{cases} \dot{W}(t) = \frac{1}{R(t)} - \frac{W(t-R(t))}{R(t-R(t))}p\big(t-R(t)\big) \\ \dot{q}(t) = \frac{W(t)}{R(t)}N(t) - C \\ R(t) = \frac{q(t)}{C(t)} + T_p \end{cases} \qquad (1)$$

where $\dot{W}(t)$ and $\dot{q}(t)$ denote the time-derivatives of $W(t)$ and $q(t)$, respectively. $W(t)$ denotes the TCP window size, $q(t)$ denotes the queue length in the router.

$p(t\ )$ denotes the probability packet marking/dropping $(p(t) \in [0,1])$. $R(t)$ denotes the round-trip time, $C(t)$ denotes the link capacity. T_p denotes the propagation delay. $N(t)$ denotes the load factor (Number of TCP sessions). The first differential equation in equation (1) describes the TCP window control dynamic and the second equation models the bottleneck queue length. The queue length and window size are positive, bounded quantities, i.e., $q\in [0,\bar{q}]$, $W \in [0,\bar{W}]$window size, respectively. Also, the marketing probability p takes value only in [0,1]. In this model, the congestion window $W(t)$ increases linearly if no packet loss is detected; otherwise it halves. Although an AQM router is a non-linear system, in order to analyze certain types of properties and design controllers, a linear model is needed. To linearize (1), first it was assumed that the number of TCP sessions and link capacity are constant, i.e., $N(t) \equiv N$,$C(t) \equiv C$.

Taking (W, q) as the state and p as input, the operating point (W_0, q_0, p_0) is then defined by $\dot{W} = 0$ and $\dot{q} = 0$ so that $\dot{W} = 0$, $W_0^2 p_0 = 2$, $\dot{q} = 0$, $W_0 = \frac{R_0 C}{N}$, $R_0 = \frac{q_0}{C} + T_p$.

Linearizing (1) about the operating point to obtain:

$$\begin{cases} \delta\dot{W}(t) = -\frac{N}{R_0^2 C}\big(\delta W(t) + \delta W(t-R_0)\big) - \frac{R_0 C^2}{2N^2}\delta p(t-R_0) \\ \delta\dot{q}(t) = \frac{N}{R_0}\delta W(t) - \frac{1}{R_{045}}\delta q(t) \end{cases} \qquad (2)$$

Where $\delta W = \dot{W} - W_0$, $\delta\dot{q} = q - q_0$, $\delta\dot{p} = p - p_0$ represent the perturbed variables around the operating point.

For typical network conditions [18],

$$\frac{N}{R_0^2} = \frac{1}{W_0 R_0} \ll \frac{1}{R_0}$$

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$$\begin{cases} \delta \dot{W}(t) = -\frac{2N}{R_0^2 C}\delta W(t) - \frac{R_0 C^2}{2N^2}\delta P(t - R_0), \\ \delta \dot{q}(t) = \frac{N}{R_0}\delta W(t) - \frac{1}{R_0}\delta q(t) \end{cases} \quad (3)$$

Considering the following dynamics and performing Laplace transform on (3), gives:

$$\begin{cases} G_{TCP}(s) = \frac{\frac{R_0 C^2}{2N}}{\left(s+\frac{2N}{R_0^2 C}\right)} e^{-sR_0} \\ G_{queu}(s) = \frac{\frac{N}{R_0}}{\left(s+\frac{1}{R_0}\right)} \end{cases} \quad (4)$$

where $G_{TCP}(s)$ is the TCP's dynamic, $G_{queue}(s)$ is the queue's dynamic

E. Related Works

Robustness has been an important issue in control-systems design [19]. Robust control is a vital area in control design that is gaining more popularity and interest every day. Recently, it has been considered in the most automatic control because of its control goals. A successfully designed control system should be always able to maintain stability and performance level in spite of uncertainties in system dynamics and/or in the working environment to a certain degree [19]. Design requirements such as gain margin and phase margin in using classical frequency-domain techniques are solely for the purpose of robustness [19]. In [20] a robust Controller/Observer for TCP/AQM network was designed: First application to intrusion detection systems for drone fleet. Their work aims at realizing a robust congestion control system for TCP/AQM network of the drone fleet. This an important aspect of the robust control application because the drone requires a reliable and stable congestion control despite significant disturbances it may experience due to its required speed of control signal communications. The analyses for the controller design were mostly carried out in time domain which does not determine the appropriate robustness characteristics such as the gain and phase margins for a controlled system. The trajectory tracking error was not determined; this shows the proper performance of the system output for performance robustness was carried in [2]. Some recent works have shown the benefit of using proportional feedback in TCP/AQM networks. By using proportional feedback, the marking probability is proportional to the instantaneous queue length. They worked on addressing the nonlinearities directly and establishing some stability results when the marking is proportional. In the case of delay free marking, they showed the system's equilibrium point to be asymptotically stable for all proportional gains.

III. METHODOLOGY

The performance enhancement or optimization of every physical system requires capturing the behaviors of the system in a mathematical equation which makes it possible to easily analyze and enhance the system more adequately. However, the mathematical equation or model of a physical system does not show completely the system. Hence there is always a difference between the real physical system and its mathematical model. This difference is therefore controlled using a controller which has especially some robustness characteristics. Considering the fluid flow model of the TCP/AQM mathematical equation in (4) The TCP queue system can simplified as follows:

$$G(s) = \frac{B}{Q(s)} e^{-R_0 s} \quad (5)$$

Where: $B = \frac{C^2}{2N}$, $Q(s) = \left(s + \frac{2N}{R_0^2 C}\right)\left(s + \frac{1}{R_0}\right)$

As the network parameter {N, C, R_0} are positive, where $R_0 > 0$ is the time delay, and $C(s)$ is the first order controller having the form.

Substituting B and Q in equation (5), gives:

$$G = \frac{R_0^3 C^3 e^{-R_0 s}}{2R_0^3 CN s^2 + 2R_0^2 CNs + 4R_0 N^2 s + 4N^2} \quad (6)$$

A. Robust Compensator Development Using H2 Synthesis

Considering the closed-loop AQM system with $K(s)$ as the transfer function of the compensator, and $G(s)$ as the transfer function of the plant dynamic as shown in figure 1, the output of the system is measured, fedback and compared with the reference input or the desired output to produce an error signal which is to be controlled or compensated by the compensator. This model presents the dynamics of the queue and the congestion window as a time delay system. Taking into account this characteristic, it is expected to reflect the TCP queue behavior in control congestion.

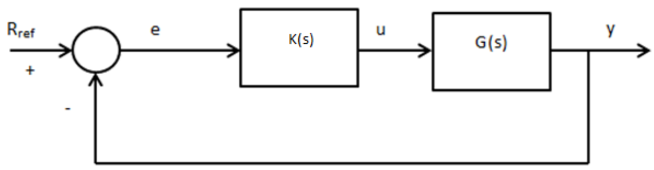

Figure 1: Block diagram of the TCP queue system plant

The mathematical model of the controlled TCP plant in figure 1 is expressed as follows:

$$T_{CL} = \frac{R_0^3 C^3 K e^{-R_0 s}}{2R_0^3 CN s^2 + 2R_0^2 CNs + 4R_0 N^2 s + 4N^2 + R_0^3 C^3 e^{-R_0 s}} \quad (7)$$

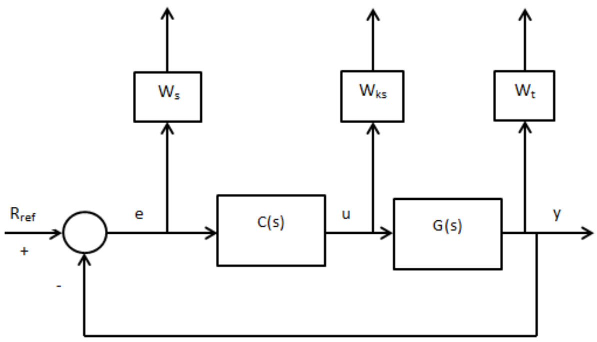

Figure 2: TCP Queue plant Closed-loop control with the weights

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Applying the weighting functions Ws, Wks and Wt to the TCP plant G(s) as shown in figure 2 and applying the H2 synthesis syntax to generate the controller K for the system optimization. The augmented function P, is generated as follows:

$$P = aug(G, W_s, W_{ks}, W_t) \tag{8}$$

Then the compensator is developed in state space format as follows:

$$[K] = h2syn(P) \tag{9}$$

To generate the controlled system function CL the expression becomes:

$$[K, CL, GAM] = h2syn(P, 1,1) \tag{10}$$

The developed robust compensator K was applied in equation (7) to analyze the behavior of the H2 compensated TCP queue system.

The following network parameters were used for the simulation and adopted from (Testouri et al., 2012): N=60, C=3750 packets/s and R_0= 0.25s.

IV. RESULTS AND DISCUSSION

Figures 3 and 4 show the TCP Queue responses in time and frequency domains.

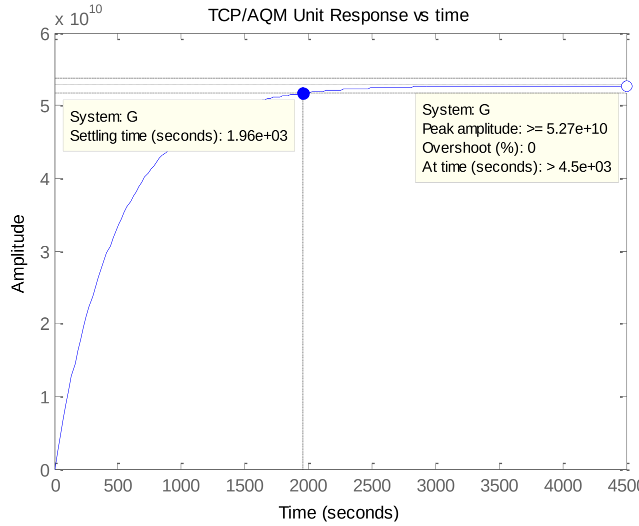

Figure 3: TCP Queue response in time

The TCP queue recorded a settling time of 1.96e+03 seconds which is very high and it shows a very low speed characteristic.

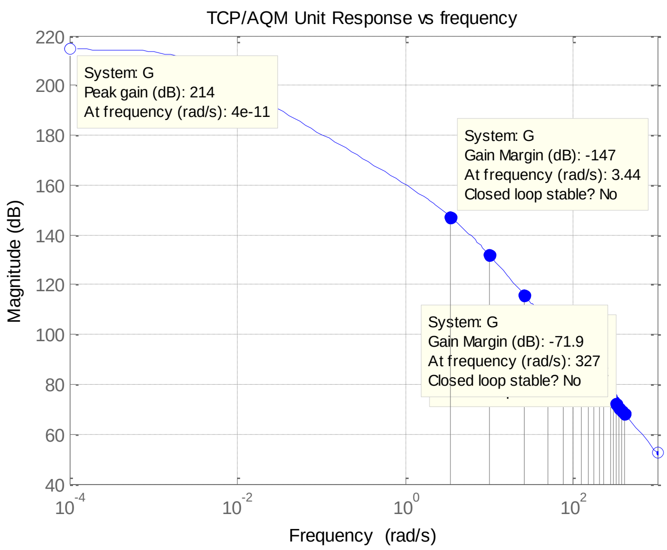

Figure 4: TCP queue response in frequency

The TCP queue recorded 214 seconds of peak magnitude which is an improvement. However, it recorded a negative gain margin of -71.9d which shows that the system is unstable.

A. H2 Compensated TCP Queue Analysis Results

The weights that achieved the desired loop shape of the optimization are presented as follows:

$$W_s = \frac{s+10000}{s+10} \tag{11}$$

$$W_{ks} = tf\left(\frac{1}{0.1}\right) \tag{12}$$

Figure 5 shows the H2 compensated TCP Queue response in time domain while figure 6 shows the H2 compensated TCP Queue response in frequency domain. Figure 7 shows the H2 compensated TCP Queue sensitivity plot. Figure 8 shows the H2 compensated TCP Queue open loop gain graph while figure 9 shows the H2 compensated TCP Queue open loop phase graph.

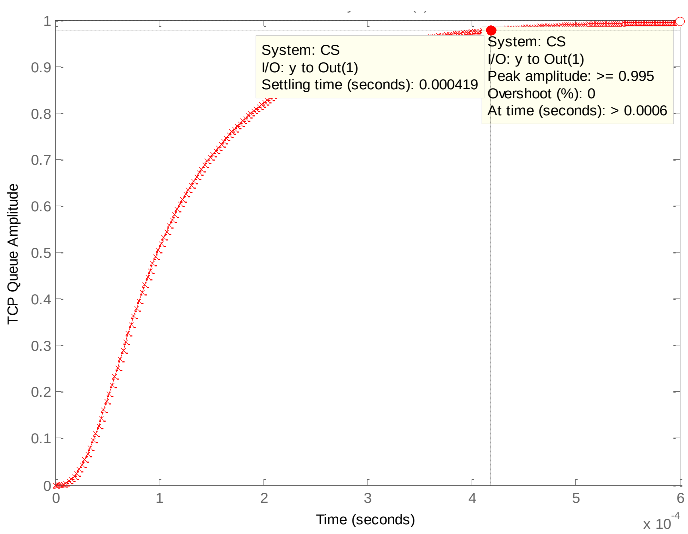

Figure 5: H2 Compensated TCP queue complementary sensitivity in time domain

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Settling time in figure 5 was reduced to 0.000419 seconds which can support fast information transfer.

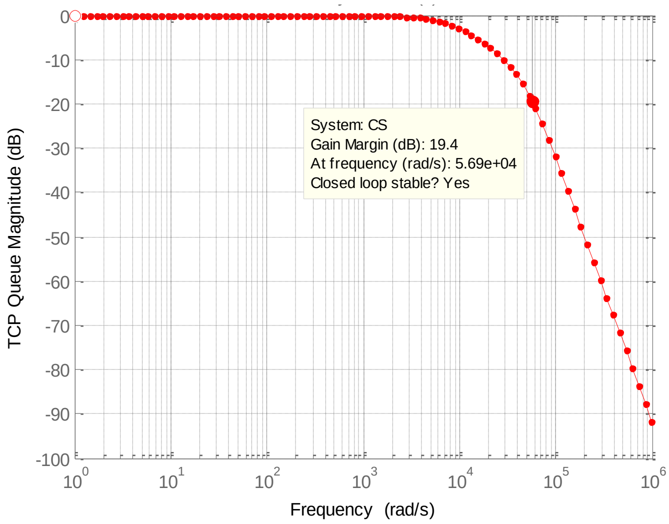

Figure 6: H2 Compensated TCP Queue complementary sensitivity in frequency domain

The H2 compensated TCP queue recorded a reference tracking error of 0dB and it tracked the 0dB for long frequency range. This shows enhanced performance of the H2 compensated TCP queue system.

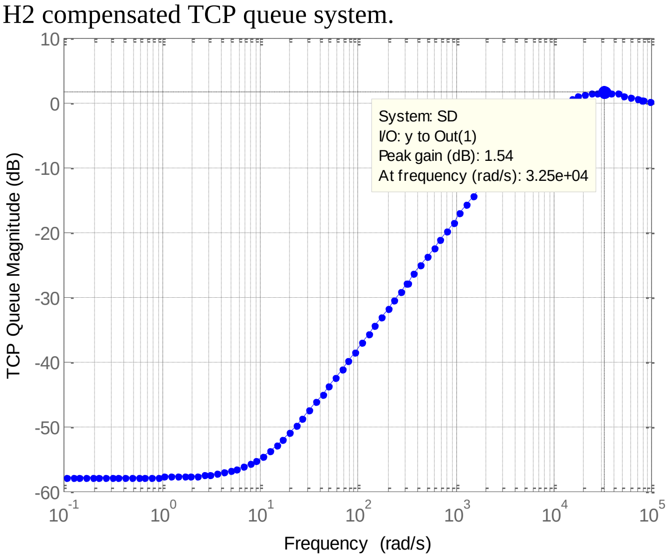

Figure 7: H2 Compensated TCP Queue sensitivity plot

The sensitivity graph recorded peak gain of 0.024dB which means the system recorded less sensitivity to disturbance.

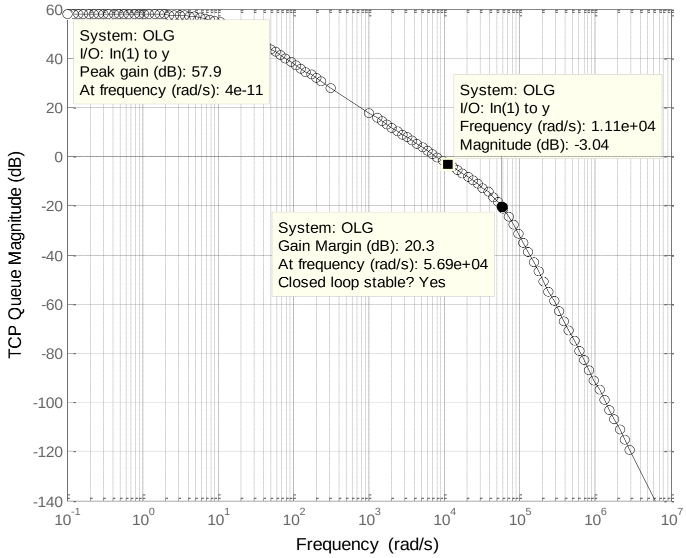

Figure 8: H2 Compensated TCP Queue open loop gain graph

In figure 8, the loop gain recorded peak magnitude of 57.9dB and gain margin of 20.3dB. This means that the system achieved good stability.

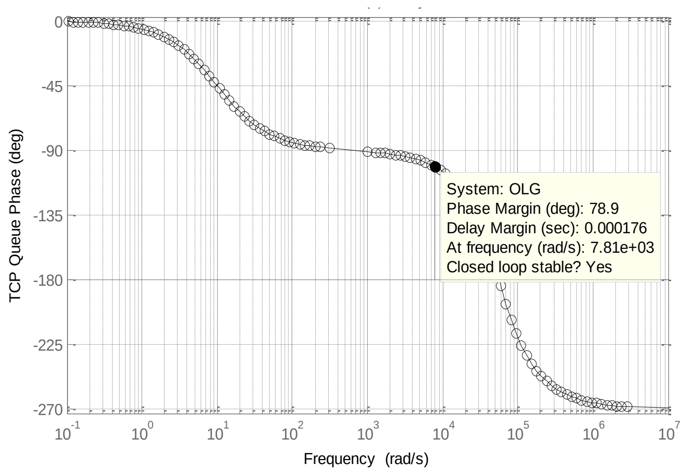

Figure 9: H2 Compensated TCP Queue open loop phase graph

In figure 9 the system recorded phase margin of 78.9deg. This shows that the improved system is robustly stable. The H2 compensated TCP achieved reduced settling time of 0.000419 seconds and overshoot of 0%, which show that system improved in performance. The system achieved gain margin of 20.3dB and phase margin of 78.9deg. This means that the H2 compensated TCP queue system achieved robust performance and stable. The generated compensated K transfer function is expressed as follows:

$$K = \frac{-20000s - 557120000}{3237000000s + 32363000000} \tag{13}$$

V. CONCLUSION

The aim of this work which is to enhance the performance and stability of the TCP queue network system using H2 synthesis technique was successfully achieved. In order to improve the performance and stability of the TCP queue

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network system so that it can maintain optimal performance and good stability even in the presence of significant disturbance, a robust compensator was designed using H2 synthesis technique.

The TCP model was analyzed and it was observed that the system was unstable and very slow with high settling time. The H2 optimized TCP (H2-TCP) was able to achieve improved performance with reduced settling time of 0.000419 seconds which means that the system becomes faster in addressing congestion issues and other disturbances. The H2-TCP queue system also achieved 0dB tracking error and robust stability margins of 20.3dB gain margin and 78.9degrees phase margin.

It was concluded that the H2 synthesis optimization achieved TCP queue improved performance and stability robustness characteristics [21] with good network throughput.

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