CEDTECH International Journal of Engineering & Applied Science
Volume 4, Number 1, March 2023
http://www.cedtechjournals.org
ISSN: 2756-4533

MINIMIZING THE TIME DELAY IN GEO SATELLITE SYSTEM TCP MECHANISM FOR ENHANCED THROUGHPUT USING H-INFINITY TECHNIQUE

***Isioto, Nte N.[1], Nwabueze, Christopher. A[2], Akaneme S. A [3], Dickson Rachael[4]**
Department of Electrical/ Electronic Engineering,
Chukwuemeka Odumegwu Ojukwu University, Anambra State, Nigeria.
nnisioto@gmail.com, canwabueze09@gmail.com and ca.nwabueze@coou.edu.ng,
silas.akaneme@gmail.com, richowaji@yaho.com

ABSTRACT

This research work focuses on minimizing the cumulative time delay in the mechanism of geostationary earth orbit (GEO) satellite system Transport Control Protocol (TCP) in a bid to enhancing the system throughput using h-infinity synthesis technique. The satellite system has become the solution-bridge to the problem of long range communication medium and achieving global ubiquitous network coverage cheaply. TCP over satellite is a critical structure in the communication network; but due to the long propagation satellite channel path and the increasing reliance on the wireless network especially the internet, the protocol has witnessed increased traffic congestion and severe delays which can snowball into data queue and more delays if not checked. Also, TCP over satellite is a slow protocol due to its mechanisms of flow control and congestion avoidance, geared toward reliable service delivery. Hence, the high latency or time delays in satellite channels. The delay from the long propagation path alone, accounts for more than 70% of the system delay. If the system time delay is not minimized, the system performance is affected adversely. To minimize these delays and improve the performance of the TCP over satellite communication system a robust control method is needed which can consider the high level of disturbances in the design by improving the settling time, the tracking error and the stability margins of the system. H-infinity synthesis technique is an advanced and robust feedback control technique which uses weights to achieve robust controller characteristics through loop-*shaping. In this work, the H-infinity synthesis technique was applied to improve the throughput of TCP over satellite system by minimizing the* time delays. The computation and simulation were carried out in MATLAB application software. From the results, the existing TCP over satellite system recorded a very high settling time of 356 seconds which indicates that the system has slow speed. However, H-infinity controlled TCP over satellite model recorded a very low settling time of 0.0394 seconds which indicates 99.99% improvement of the system. These results indicate high speed response to disturbance. Therefore, H-infinity controlled TCP over satellite system achieved low latency, enhanced TCP throughput and overall system performance.

Keywords: *Satellite communication, time delay, TCP performance, robust control, enhanced throughput, round trip time, low latency, system performance,*

INTRODUCTION

The satellite system provides communication medium for Internet Protocol (IP) traffic which ensures very highly secured means of communicating data without compromising the content of such data. Inherently, the IP traffic is coupled with other protocols, most often Transport Control Protocol (TCP) for its transport control, hence the famous TCP/IP protocol suite [1]. TCP/IP is used over satellite links for more reliable and secured information communication, but many factors specific to satellite communications such as high latency or time delay adversely affect TCP mechanisms, thereby yielding to poor performance of the satellite network [1]. The transmission control protocol as presented in many research work is a reliable and most widely used transport protocol for the popular internet applications such as the World Wide Web (www) and FTP etc. TCP was designed and tuned to operate in fixed networks, where the key functionality and major goal is to utilize the available bandwidth and avoid overloading the network. Basically, TCP sender adapts its use of the bandwidth based on the feedback from the receiver [2]. This adaptation can be obtained by implementing a number of TCP mechanisms including slow start/congestion avoidance, fast retransmit/fast recovery, and Selective Acknowledgements (SACK) [3]. Although these mechanisms work properly in wired networks, they have negative impacts on the performance of TCP in satellite environment, thereby causing poor performance of the satellite network [4]. The large latencies, bandwidth and path asymmetries, and occasionally high error rates on satellite channels provide TCP with a challenging environment to operate. This is because, these satellite channel features or disturbances are identified by the transport control protocol as error. Unfortunately, TCP notices or identifies error during data transport or transfer as it cuts its window into half. This TCP mechanism feature affects the general performance of the system because it slows down the data transfer and can also cause data loss and introduce more error into the system.

Satellite Communications

A satellite in general can be described as any natural or artificial body moving around a celestial body such as a planet or a star. The artificial satellites are put into the desired orbit and have payloads depending upon the intended application [5]. In the context of this work, reference is made only to artificial GEO satellites, placed at about 36,000km above earth's surface [6] and orbiting the planet Earth. The exchange of information between source and destination using satellite channel is known as satellite communications. This communication involves a lot of interacting functions of interacting groups. This is modelled into an architecture called the OSI reference model.

OSI/ISO seven-layer reference model

In order to master interactions and facilitate design, it is important to identify and group responsibilities or tasks of similar nature, and clarify the interactions between the various groups in a well-structured architecture called the OSI reference model. The system communication functions are therefore divided into layers, with sets of rules referred to as protocols[7] as shown in figure 1, taking care of exchange of information between the layers.

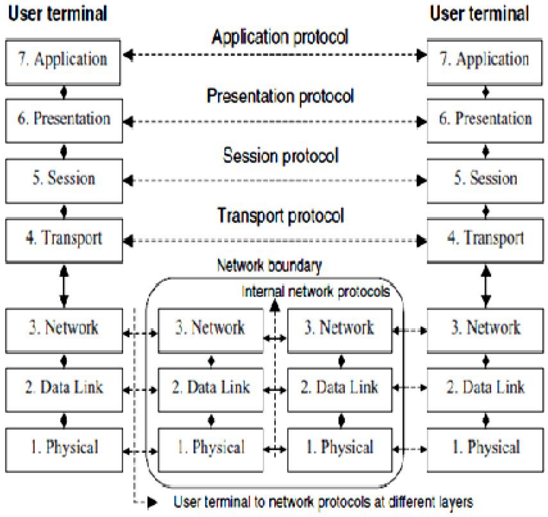

Figure 1: OSI/ISO seven-layer reference model [7],[8].

Description of the layers of the OSI Reference Model

The following are brief descriptions of each layer of the seven layer of the Open Systems Interconnection (OSI) reference model [8]:

Layer 1: The Physical layer specifies electrical interfaces and the physical transmission medium. In a satellite network, layer 1 consists of modulation and channel coding techniques which enable the bit stream to be transmitted in specific formats and allocated frequency bands. The radio links act as the physical transmission media.

Layer 2: The Data Link layer provides a line that appears free of undetected transmission errors to the network layer. A special sub-layer called Medium Access Control (MAC), deals with the sharing of the physical resource between communicating terminals. This is the subject of the multiple access techniques such as FDMA, TDMA, CDMA, etc. and Demand Assignment Multiple Access (DAMA). Broadcasting networks have additional issues in the data link layer, e.g. how to control access to the shared medium [8].

Layer 3: The Network layer routes packets from source to destination. The functions include network addressing, congestion control, accounting, disassembling and reassembling, coping with heterogeneous network protocols and technologies. In a broadcasting network, the routing problem is simple as the destination is the same for all packets. The routing protocol is often thin or even non-existent.

Layer 4: The Transport layer provides a reliable (error-free) data delivery service for processes utilizing the transmitted data at higher layers. It is the highest layer of the services associated with the provider of communication services, guaranteeing ordered delivery, error control, flow control and congestion control.

Layer 5: The Session layer provides the means for cooperating presentation entities to organize and synchronize their dialogue and to manage the data exchange.

Layer 6: The Presentation layer is concerned with data transformation, data formatting and data syntax.

Layer 7: The Application layer is the highest layer of the ISO architecture. It provides services to application processes.

When designing satellite networks, focus is primarily put on layers 1 to 4, but a good understanding of the upper layer processes and performances is also necessary, for the satellite network not to degrade the end-to-end quality of service of the communication [9]. To optimize the performance of the satellite communication system, we place more focus basically on issues of layer 4, which is the transport layer.

Satellite Transport Protocol

The Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) are the two common and basic transport layer protocols of the Internet Protocol (IP) reference model. The protocols originate at the end-points of bidirectional satellite communication flows, allowing for end-user terminal services and applications to send and receive data across the Internet [11]. UDP is connectionless oriented, no error check, no acknowledgement (ACK), less reliable but faster protocol. Its application therefore includes: VoIP, broadcasting, multicasting and gaming. TCP is a connection oriented protocol, capable of verifying the correct delivery of data between client and server using acknowledgement (ACK) technique. TCP recovers lost data by retransmitting data until the data is correctly and completely received. It ensures reliable service delivery and finds application in: web surfing- HTTP, HTTPs, files transfer- FTP, mails- SMTP[10]. Since the TCP provides more reliable user data transport but due to the processes involved in its ability to recover lost data and using acknowledgement scheme to deliver a more reliable data transfer, TCP has been accepted to be one of the most important satellite protocols that must be improved on.

RELATED WORKS

Basic TCP Mechanism

In the wired network, which TCP was originally designed for, the most common cause of packet loss is congestion thus; TCP treats packet loss as an indicator of network congestion. However, such an assumption is not applicable in wireless or satellite networks where packet loss is more likely caused by transmission errors. This happens automatically because that is the way it was originally designed and the sub-network need not know anything about IP or TCP. In such case, it simply drops packets whenever it must, though some packet-dropping strategies are fairer than others. TCP has two methods of recovering from packet loss. The most vital method is by the use of retransmission timeout which means that, if an ACK fails to arrive after a certain period of time, TCP retransmits the oldest unacknowledged packet. Assuming this as a hint that the network is congested, TCP waits for the retransmission to be acknowledged before it continues and it gradually increases the number of packets in flight as long as a timeout does not occur again. A retransmission timeout can inflict a significant performance consequence, as the sender waits during the timeout interval and restarts with a congestion window of one following the timeout which is referred to as slow start [12].

TCP Flow and Congestion Control

The TCP protocol uses its window size in controlling congestion as well as traffic. The window size is negotiated between the sender and receiver. The sender then sets its window size to a value less than the advertised receiver window (rwnd) size, to avoid overwhelming the receiver’s buffer as shown in figure 2. Thus, flow control is achieved. When the destination receives packet correctly, it returns an ACK to the sender, as shown in figure 3. When the sender receives the ACK, TCP increase its transmission window. However, if the sender does not receive an ACK for a packet within a certain timeout (TO) interval, TCP retransmits the packet and all subsequent packets in the window. This is known as retransmission timeout (RTO). Obviously, setting appropriate timeout is very relevant to ensuring fairness and maximizing throughput. Too short RTO result in unnecessary retransmissions and too long RTO causes undue time delay, waiting for ACKs. The computation of RTO is carried out based on the round trip time (RTT) between the sender and receiver. Congestion control is different from flow control. In flow control, the receiver attempts to prevent the sender from overflowing the receiver buffer.

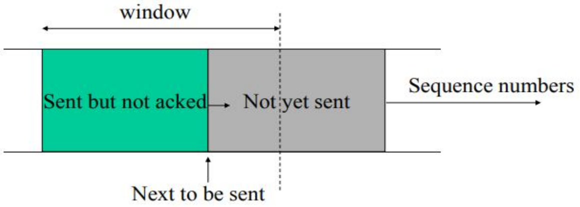

Figure 2: TCP window flow control: Send

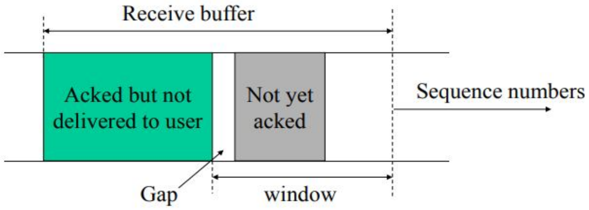

Figure 3: TCP window flow control: Receive

Congestion control is a congestion avoidance algorithm within the network. In addition to the general window, TCP also has a congestion window (cwnd) for each connection. The maximum number of allowed "on the flight" (or packets sent but not yet acked) packet is the minimum of the cwnd and the advertised rwnd size. TCP determines the cwnd based on the congestion it perceives in the network. As the congestion level increases, the congestion window decreases, similarly when the congestion level decreases, the congestion window increases. TCP assumes that all losses are due to congestion. Therefore, if a packet is lost, the congestion window is halved. If otherwise, the congestion window is incremented by one. This is known as the additive increase/multiplicative decrease (AIMD) [12]. The amount of data TCP transmits, but yet to be acknowledged constitutes the delay bandwidth (DB). The delay used in equation 2.1 is the round trip delay.

Time Delays in TCP over Satellite Channels

Each segment passing through a satellite network is subjected to 3 delays:

Transmission Delay: This is the time taken to transmit a segment on a network with the user-configured bandwidth.

Propagation Delay: This is the user-configurable amount of time it takes a segment to travel the length of the channel.

Queue Delay: This delay occurs when a segment arrives while another is being serviced. The new segment must be in the queue and await transmission. The length of the queue determines the queue delay [13].

Impact of TCP Delays on Satellite Networks

Long feedback loop: Due to the propagation delay with satellite transmission, it takes a significant time for a TCP sender to determine whether or not a packet has been successfully received at the final destination. This delay affects interactive applications such as Telnet, as well as some of the TCP congestion control algorithms.

Delayed ACKs: Normally TCP does not send an ACK directly following data reception. Instead, the ACK is delayed hoping to send it along with data going in the same direction, especially in the case of interactive applications.

Propagation delay: The end-to-end latency experienced by users includes transmission delay, queuing delay, and propagation delay. In satellite networks, the propagation delay is typically the largest component of the overall delay experienced. In geostationary (GEO) satellite networks, only round trip propagation delays, which is the delays aggregated from transmission of data and waiting for the receipt of an ACK, account for major delay. The bulk of the delay is associated with the uplink and downlink. However, links between satellite repeaters also add delay, typically on the order of a few milliseconds per link. The communication delay between two earth stations connected via satellite link is a major challenge to the performance of the highly interactive application like TCP. For GEO satellite communications systems, this latency is at least 250 milliseconds and sometimes can be as high as 300milliseconds. Other delays from framing, queuing, and on-board switching add extra delays, making the end-to-end delay as high as 400 milliseconds [27]. This delay represents more than 70% of total or end-to- end delay. These high round trip delays have a huge impact on the speed with which the TCP congestion window opens. Small file transfers may experience unnecessarily long delays due to the fact that it will take several RTTs before the congestion window opens up to a sufficiently large size.

The effect of these delays (in terms of RTT) on the throughput is made obvious from equation 2.1.

$$Throughput = \frac{Receiver\ Buffer\ Size}{RTT} \qquad (2.1)$$

The long delay channels require larger windows than what standard TCP offers and a more accurate Round Trip Time (RTT) evaluation. The TCP's receiving window size is critically relevant in satellite environment because, as evident from equation 2.1, the optimum throughput of TCP connection is dependent on the RTT [14], which is a function of time delay.

Effect of TCP Delays on Satellite Throughput

Satellite channel bandwidth ranges from 1.54Mbps for T1 channel to 622.08Mbps for OC-12 satellite channel [15]. Taking an instance of T1 satellite channel with bandwidth of 1.54Mbps and with reference to equation 2.1, the effect of delay on satellite TCP throughput can be appreciated. In applying this equation, we assume a loss-free network and a TCP that does not use any congestion control algorithms. Then, maximum throughput will occurs at minimum RTT and can be calculated.

$$Max.\ Throughput = \frac{Max.\ Receiver\ Buffer\ Size}{Min.\ RTT} \qquad (2.2)$$

The maximum TCP receive window over a satellite channel is 65,535 bytes. In this work, the minimum RTT is 582ms. Therefore, using (RTT of 582 ms)

$$Maximum\ Throughput = \frac{65535}{582} = 112.6 bytes/secs$$

Obviously, this upper limit on TCP throughput shows that TCP under utilizes the bandwidth or will be unable to exhaust the bandwidth provided by T1 satellite channels [14].

Research Gap

From the review, there significant poor performance of the TCP over satellite network due to the features of the satellite channel that do not favor the mode of operation of the TCP which was originally designed for terrestrial network [16],[17]. The inherent characteristics of the long, end-to-end satellite channel path which include latency, delay bandwidth, packet loss, congestion, and losses due to transmission errors among others, contribute to delays as TCP mechanism tries to ensure reliability of data transfer and control of congestion between the user terminals [17].

SCOPE OF THE RESEARCH

This study is limited to the analysis of the existing satellite TCP model and the optimization of TCP Time delay using H-infinity technique. This analysis and the time delay optimization function were carried out in MATLAB simulation platform. An algorithm for improving the time delay was developed and converted into a computer program using MATLAB's H-Infinity syntax.

METHODOLOGY AND DISSCUSSION

Research Methodology

In line with the aim to optimize satellite system transport control protocol time delays for enhanced throughput and the objectives of this work, the methodology includes:

1. Study and analyzes the existing TCP model over satellite system in order to identify and establish the existence of research gaps.
2. Use Feedback Control Mechanism for TCP Compensation for the improvement of the satellite system performance by improving the time delay.
3. And develop the Compensator Design using H-Infinity synthesis syntax.

Existing TCP Model

The TCP model over the satellite communication system is modeled using the fluid flow approach [18], [19], [20], [21] and the TCP system is demonstrated as shown [22] in figure 4.

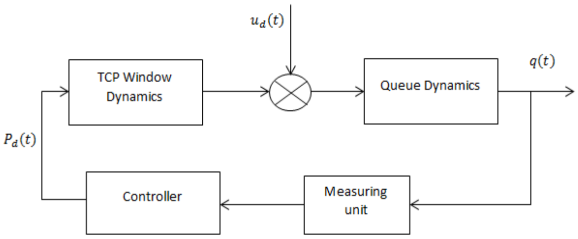

Figure 4: Block diagram of existing TCP model over satellite [22].

The existing TCP model is expressed in the equation model given in the time domain as shown in equation 4.1

$$\begin{cases} \dot{W}(t) = \dfrac{1}{R(t)} - \dfrac{W(t-R(t))}{R(t-R(t))} p(t-R(t)) \\ \dot{q}(t) = \dfrac{W(t)}{R(t)} N(t) - C \\ R(t) = \dfrac{q(t)}{C(t)} + T_p \end{cases} \tag{4.1}$$

where $\dot{W}(t)$ and $\dot{q}(t)$ represents the time-derivatives of $W(t)$ and $q(t)$, respectively. $W(t)$ means the TCP window size, $q(t)$ represents the queue length in the router. $p(t)$ denotes the probability packet marking/dropping. $R(t)$ signifies the round-trip time, $C(t)$ denotes the link capacity. T_p represents the propagation delay. $N(t)$ denotes the load factor or number of TCP sessions [22], [23].

Analysis of the Existing TCP Model

The first differential equation in equation (4.1) describes the TCP window control dynamic and the second equation models the bottleneck queue length. In this model, the congestion window *W*(*t*) increases linearly if no packet loss is detected; otherwise it halves.

Linearizing (4.1) about the operating point we obtain:

$$\begin{cases} \delta \dot{W}(t) = -\frac{N}{R_0^2 C}\left(\delta W(t) + \delta W(t - R_0)\right) - \frac{R_0 C^2}{2N^2}\delta p(t - R_0) \\ \delta \dot{q}(t) = \frac{N}{R_0}\delta W(t) - \frac{1}{R_0}\delta q(t) \end{cases} \quad (4.2)$$

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 [23],

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

$$\begin{cases} \delta \dot{W}(t) = -\frac{2N}{R_0^2 C}\delta W(t) - \frac{R_0 C^2}{2N^2}\delta P(t - R_0), \\ \delta \dot{q}(t) = \frac{N}{R_0}\delta W(t) - \frac{1}{R_0}\delta q(t) \end{cases} \quad (4.3)$$

Considering the following dynamics and performing Laplace transform on (4.3), we have equation (4.4)

$$\begin{cases} G_{TCP}(s) = \frac{\frac{R_0 C^2}{2N}}{\left(s + \frac{2N}{R_0^2 C}\right)} e^{-sR_0} \\ G_{queue}(s) = \frac{\frac{N}{R_0}}{\left(s + \frac{1}{R_0}\right)} \end{cases} \quad (4.4)$$

Equation 4.4 represents the frequency domain mathematical model of the existing TCP model over satellite. Where $G_{TCP}(s)$ is the TCP window dynamic and $G_{queue}(s)$ is the queue's dynamic.

Simplifying equation 4.4 yields:

$$\begin{cases} G_{TCP}(s) = \frac{R_0^3 C^3 e^{-sR_0}}{2NR_0^2 Cs + 4N^2} \\ G_{queu}(s) = \frac{N}{R_0 s + 1} \end{cases} \quad (4.5)$$

From equation 4.5, illustrates the simplified TCP model diagram in frequency domain as shown in figure 5.

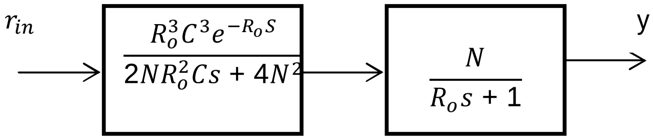

Figure 5: Simplify TCP model block diagram in frequency domain

$Let\ \rho_{(s)} represnts\ the\ TCP\ window\ dynamics\ and\ \partial(s), the\ queue\ dynamics.$
Then computing for the output, y

$$y = \rho_{(s)} \times \partial(s) r_{in} \qquad (4.6)$$

The transfer function, G(s) becomes:

$$G(s) = \frac{y}{r_{in}} = \rho_{(s)} \times \partial(s) \qquad (4.7)$$

Where:

$$\rho_{(s)} = \frac{R_0^3 C^3 e^{-sR_0}}{2NR_0^2 Cs + 4N^2} \qquad (4.8)$$

$$\partial(s) = \frac{N}{R_0 s + 1} \qquad (4.9)$$

As the network parameter {*N*, *C*, *R*₀} are positive, where *R*₀ > 0 is the time delay, N is the number of TCP sessions and *C* (*s*) is the link capacity.

$$G(s) = G_{TCP}(s) G_{queue}(s) \qquad (4.10)$$

$$G(s) = \frac{y(s)}{r_{in}(s)} \qquad (4.11)$$

$$G(s) = \rho_{(s)} \times \partial(s) \qquad (4.12)$$

Substituting for $\rho_{(s)}$ and $\partial(s)$ in 4.12 and simplifying, the existing TCP model equation becomes thus:

$$G(s) = \frac{R_0^3 C^3 e^{-sR_0}}{2NR_0^2 Cs + 4N^2} \times \frac{N}{R_0 s + 1}$$

$$G(s) = \frac{\frac{C^2}{2}}{\left(s + \frac{2N}{R_0^2 C}\right)\left(s + \frac{1}{R_0}\right)} e^{-R_0 s} \qquad (4.13)$$

Equation 4.13 is the equation describing the existing TCP model over satellite. For the ease of circuit synthesis, further simplification of equation 4.13 gives:

$$G(s) = \frac{R_0^3 C^3 e^{-R_0 s}}{2R_0^3 Cs^2 + 2R_0^2 Cs + 4R_0 Ns + 4N} \qquad (4.14)$$

Where: $R_0\ is\ the\ round\ trip\ time, RTT;\ C\ is\ the\ link\ capacity$
$and\ N\ is\ Number\ of\ TCP\ sessions$S$(i.e\ the\ load\ factor)$.
Equation 4.14 is the simplified transfer function representing the performance of the existing TCP model over satellite system.

Time Delay Analysis of Existing TCP Model

The performance and time delay analyses of the existing TCP model over satellite communication system involve the use of Step Function Technique**.** This is a graphical time domain analytical method that computes the damping time, the percentage overshoot and the steady state error through the use of the system model. The damping time of the TCP model over the satellite shows the speed the system or how fast the system can bounce back to its equilibrium when disturbance occurs in the system. This means that low damping time shows higher speed for the system output. The percentage overshoot depicts the percentage difference in height the system trajectory in time can go beyond its equilibrium height before settling down. This means that low percentage overshoot shows better system output behavior.

Feedback Control for TCP Compensation

This method involves the application of feedback control measure and the design of a compensator for the performance improvement of the TCP model over satellite communication system as shown in figure 6. G(s) represents the TCP model; K(s) represents the compensator, while the e(s) represents the error which is the difference between the reference input R_{ref} and the actual output y of the system. The u represents the control law which guides the improvement of the TCP model.

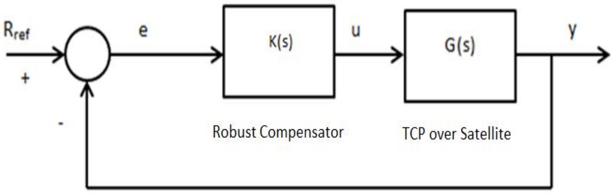

Figure 6: The improved TCP model with feedback and compensation

In order to model the improved TCP system, a closed loop control technique was applied to figure 4.3.

$$T = \frac{GK}{1+GK} \qquad (4.15)$$

Substituting for G(s) into equation 4.15, we have:

$$T = \frac{\left(\frac{R_0^3 C^3 e^{-R_0 s}}{2R_0^3 Cs^2+2R_0^2 Cs+4R_0 Ns+4N}\right)K}{1+\left(\frac{R_0^3 C^3 e^{-R_0 s}}{2R_0^3 Cs^2+2R_0^2 Cs+4R_0 Ns+4N}\right)K} \qquad (4.16)$$

Simplifying completely, the equation becomes:

$$T = \frac{R_0^3 C^3 K e^{-R_0 s}}{2R_0^3 C s^2 + 2R_0^2 C s + 4R_0 N s + 4N + R_0^3 C^3 K e^{-R_0 s}} \qquad (4.17)$$

Where: T is the modified TCP model over satellite communication system.

Equation 4.17 represents the H-infinity controlled TCP over satellite for improve satellite communication performance.

To achieve the TCP over satellite communication system performance improvement, the robust compensator was designed using H-Infinity synthesis. This method applies adjustable weights at the error signal, the control signal and the actual output of the system in order to achieve the desired improved throughput by loop shaping.

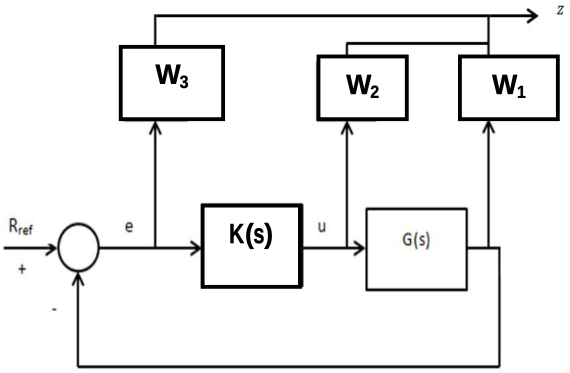

Figure 7: TCP model feedback control with the weights

The robust compensator design for the TCP over satellite communication system was based on the computation and analysis of the following functions:

Complementary sensitivity (T), Sensitivity (S) and Open loop gain (L) [25].

H-Infinity Compensator Design

The H-Infinity controller design method here involves the control of the TCP model with the adjustable weights W1 and W2 during the simulation based on the TCP model parameters. The weight parameters are varied in order to improve the iteration results. The weighting functions have been chosen according to industrial performance specifications [26]:

W1: the inverse of the weighting function Wp(s) is used to impose a performance specification in terms of the sensitivity function S. Wp is chosen:

$$W_1(s) = \frac{{}^{s}/_{M_s} + wb}{s + w_b * A_s} \qquad (4.18)$$

where M_s is to introduce a margin of robustness on the peak of S, w_b helps to have a sensible attenuation of disturbances and A_s helps to reduce the steady-state position error.

W2: the control output u is weighted according to the actuator limitations. Wu(s) is set to:

$$W_2(s) = \frac{s + {}^{\omega_{bc}}/_{Mu}}{s * \varepsilon + \omega_{bc}} \qquad (4.19)$$

Where, M_u helps to impose limitations on the maximum value of the controller output signal, w_{bc} helps to limit the effect of measurement noise and plant uncertainties at high frequencies, and ε helps to ensure a high-frequency controller gain.

Proposed H-Infinity Algorithm

i. Bearing in mind that the equation of the existing model as represented by equation 4.14, thus:

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

ii. Apply weight W1 to control the TCP model sensitivity to disturbance

iii. Apply restrained control W2 on the control signal u

iv. Ignore the closed loop system (T) control by applying no control, W3=0

v. Augment or connect the plant *G*(*s*) with weighting functions *W*1(*s*), W2(s) and *W*3(*s*) (design specifications) to form an “augmented plant” *P*(*s*)

vi. Apply H-Infinity synthesis for loop shaping and generate the compensator K

vii. Compute the loop gain (L) = K*P

viii. Compute the system sensitivity function $S = (1+L)^{-1}$

ix. Compute the complementary sensitivity function T=(1-S)

x. Analyze L, S and T for performance and robustness of the controlled system

This technique allows very precise loop shaping via suitable weighting strategies and thereby achieves robust control. Augmenting the TCP model with frequency dependent weights *W*1, W2 and *W*3, the Matlab script hinfsyn will find a compensator that ”shapes” the signals to the inverse of these weights. The Matlab function augw (or connect) forms the augmented TCP model plant function. H-Infinity synthesis technique does not require simulation turning, rather it is achieved in computation using Matlab program codes and the results were noted as the weights were varied. This algorithm was designed to use control weights or gains to generate a compensator or modified TCP model based network which is represented mathematically by the TCP transfer function through simulation. The proposed algorithm is converted to a MATLAB syntax program codes in an m-file and executed in MATLAB application software platform. The controller which is realized in state space can be achieved physically using microcontroller or analog devices.

Specific Objective of H-Infinity Technique

The objectives of this robust control system here is to help to reduce the damping time of the TCP model over satellite system because this will help to improve the speed with which the TCP cancels the effect of disturbances from congestion or delay in ACK reception and hence, improve the throughput of the communication system.

Round Trip Time (RTT) Measurement

The RTT measurement for the TCP over satellite communication was carried out in a service provider facility using Wireshark Network Analyzer application software through the VSAT connection. The Wireshark network analyzer application software is a versatile software tool that runs in a computer system, especially in servers connected to the network to monitor the behavior of the packets of information as they are transmitted and received. It also monitors the network protocols such as the transport protocols, application protocols etc. The service provider facility was chosen for the TCP over satellite RTT measurement because they have a connection into the internet through the satellite communication network. The purpose of choosing Wireshark network analyzer application system is that it is very fast in monitoring, computing the monitored data and it has a friendly user interface which makes it easy to be operated by the users. The results of the RTT measurements were carefully observed and recorded as shown in Table 4.2. These results were further analyzed to obtain the minimum, mean and maximum values of RTT, as shown in Table 4.3.

Table 4.1: Simulation Parameters

Parameter	**Value**
Link Capacity, C	4000 packets/s
Bandwidth of Server link	100Mbps
Load Factor, N	60
Window Size	64 Kbytes
Simulation Time	10 sec

Table 4. 2: Round Trip Time Measurement

SN	RTT (milliseconds)	RTT (seconds)
1	600	0.600
2	603	0.603
3	599	0.599
4	596	0.596
5	600	0.600
6	605	0.605
7	609	0.609
8	603	0.603
9	606	0.606
10	610	0.610
11	618	0.618
12	609	0.609
13	605	0.605
14	620	0.620
15	616	0.616
16	611	0.611
17	615	0.615
18	609	0.609
19	609	0.609
20	611	0.611
21	618	0.618
22	582	0.582
23	592	0.592
24	601	0.601

Total RTT = 14547
Frequency = 24
Minimum RTT = 582ms
Mean RTT = 606ms
Maximum RTT = 620ms

Table 4.3: Summary of the RTT results for simulation

RTT	Value (ms)	Value (s)
Minimum	582	0.582
Mean	606	0.606
Maximum	620	0.620

RESULTS

This section presents and explains data and the findings as analyzed, for the existing TCP over satellite system and then, for the improved TCP over satellite system.

Existing TCP over Satellite Results and Analysis

Step response for minimum RTT

The step response simulation for Minimum RTT was carried out to find out the settling time of the existing system. The result of this simulation is shown in figure 8. From the result, the system achieved settling time of 386 seconds. This means that it takes the system 386 seconds to get back to its equilibrium after encountering disturbance. It also achieved 0% overshoot which indicates that the system can perform very well when there is no significant disturbance.

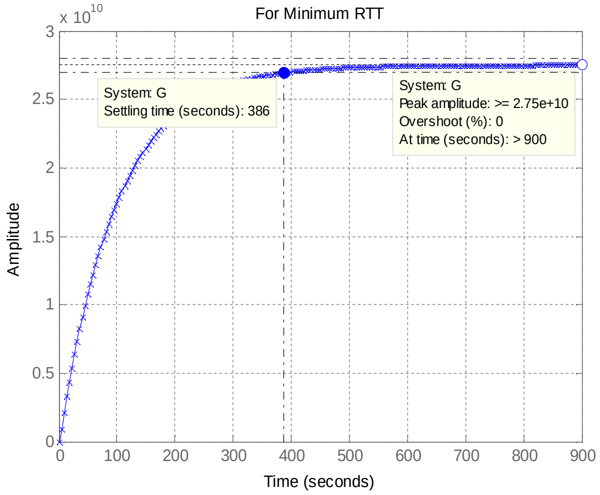

Figure 8: TCP step response for minimum RTT

TCP step response for mean RTT

The simulation of step response for the mean RTT was also carried out and the result is displayed in figure 9. From the graphical results shown in figure 9, it is clear that the existing TCP over satellite model with mean RTT achieved settling time of 356 seconds. That is, it takes the system 356 seconds to get back to its equilibrium after encountering disturbance. It also achieved 0% overshoot which also indicates that the system can perform very well when there is no significant disturbance.

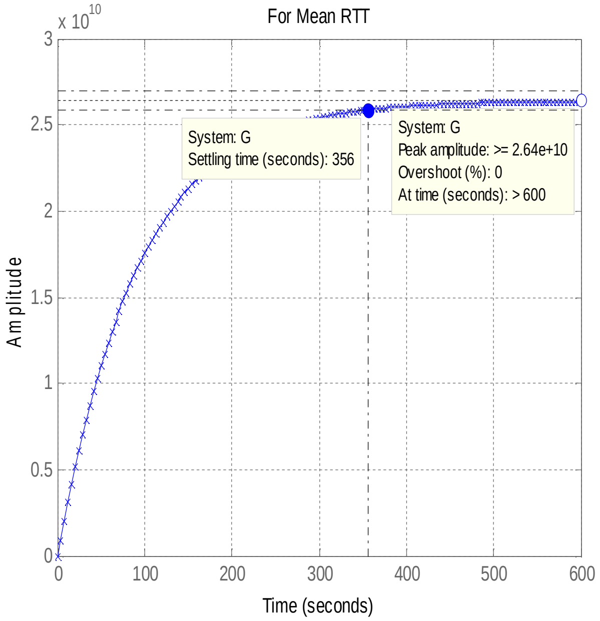

Figure 9: TCP step response for mean RTT.

TCP step response for maximum RTT

Considering, the maximum value of RTT, the simulation for the step response was also conducted and the result is as shown in figure 10. The result shows that the TCP over satellite system recorded a settling time of 340 seconds. That is, it takes the system 340 seconds to get back to its normal function after disturbance. It also recorded 0% overshoot which indicates that the system can perform very well when there is no significant disturbance. These findings are displayed in figure 10.

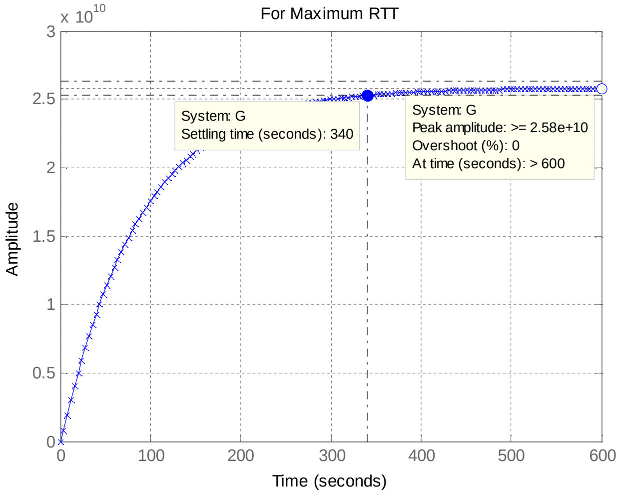

Figure 10: TCP step response for maximum RTT.

The results of all the simulations done on the existing TCP over satellite model, for minimum, mean and maximum values of RTT were displayed together in a tabular form for easy comparison and are shown in table 5.1.

Table 5.1: Summary performance of the existing TCP over satellite model analysis

RTT	Settling Time (seconds)	Overshoot (%)
Minimum	386	0
Mean	356	0
Maximum	340	0

In summary, the results in table 5.1 show that the existing system recorded very high settling time indicating significant time delays in the system which varied significantly due to lack of system robustness.

H-Infinity Controlled TCP over Satellite System Results and Analysis

This section is designed for the simulation results and analysis of the H-Infinity controlled TCP over satellite system. The designed controller K for the improvement of the TCP over satellite model is as represented in state space model as follows:

$x = ax + bu$

$y = cx + du$ (5.1)

H-Infinity controlled TCP step response for minimum RTT

The result for the H-Infinity step response for minimum RTT shows that the H-infinity controlled TCP over satellite model recorded a settling time of 0.0394 seconds and overshot of 0%. This means that the system achieved significant improvement in performance due to the reduced and very low settling time recorded. This is shown in figure 11.

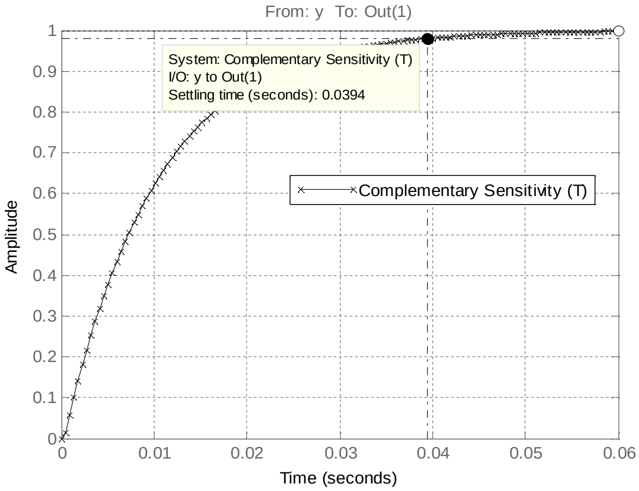

Figure 11: H-infinity controlled TCP step response for minimum RTT

H-Infinity controlled TCP step response for mean RTT

The result for the H-Infinity step response for mean RTT shows that the H-infinity controlled TCP over satellite model for the mean RTT also recorded a settling time of 0.0394 seconds and overshot of 0% as shown in figure 5.5. This also means that the H-infinity controlled system achieved significant improvement in performance due to the reduced and very low settling time recorded. This is detailed in figure 12.

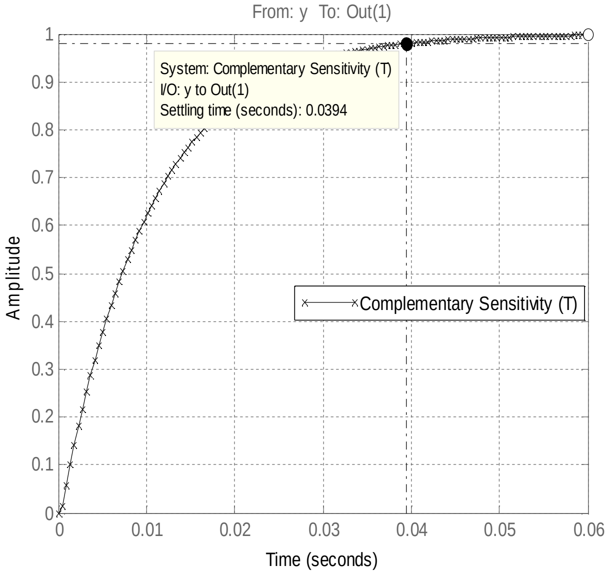

Figure 12: H-infinity controlled TCP step response for mean RTT

H-Infinity controlled TCP step response for maximum RTT

The result for the H-Infinity step response for maximum RTT shows that the H-infinity controlled TCP over satellite model for the mean RTT also recorded a settling time of 0.0394 seconds and overshot of 0% as shown in figure 5.6. This also means that the H-infinity controlled system achieved significant improvement in performance due to the reduced and very low settling time recorded. The results also indicate that the H-infinity controlled TCP over satellite model maintain same settling time and overshoot as the RTT varied. This is made obvious in figure 13.

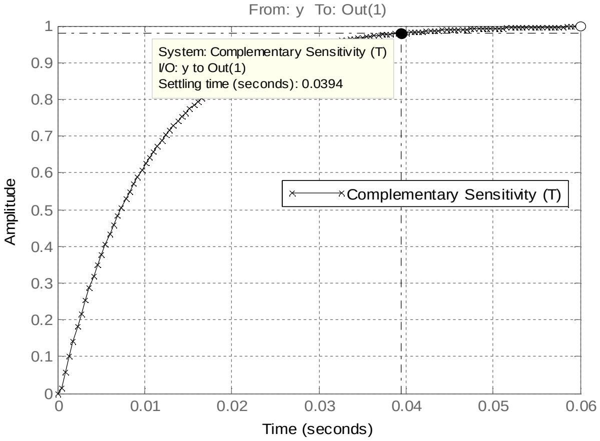

Figure 13: H-infinity controlled TCP step response for maximum RTT

In table 5.2, the results of all the simulations carried out on the H-infinity controlled TCP over satellite model, for minimum, mean and maximum values of RTT were put together in a tabular form for easy comparison.

Table 5.2: Summary of the H-infinity controlled TCP over satellite model analysis

RTT	**Settling Time (second)**	**Overshoot (%)**
Minimum	0.0394	0
Mean	0.0394	0
Maximum	0.0394	0

The results in table 5.2 show the summary of the H-infinity controlled TCP over satellite model for the varied RTT. The results indicate that the H-infinity controlled TCP over satellite model recorded a reduced and very low settling time of 0.0394 seconds and sustained this throughout the variations in the RTT. This means that it will take the system as fast as 0.0394 seconds to regain its normal function in the face of any form of disturbance. Thereby reducing the delays and improving the TCP general performance and consequently, the satellite communication throughput.

CONCLUSIONS

This work therefore concludes that the existing proportional controlled TCP over satellite recorded very high settling times which vary with RTTs. This shows significant level of time delays and thus poor performance for the different variations of the RTT. It also concludes that the H-infinity controlled TCP over satellite model achieved very good performance with low settling time for the variations of the RTT. The time it takes the TCP over satellite system bounce back to its normal function after encountering disturbance was improved by the H- infinity synthesis method from 356 seconds, for mean RTT to a consistent value of 0.0394 seconds, despite variations in RTT. This represents 99.9% improvement of the settling time. Therefore, the H-infinity controlled TCP over satellite shows robustness and ability to cushion the effect of delays and enhances the system throughput.

REFERENCES

[1] Oueslati-Boulahia S, Serhrouchni A, Tohme S, Baier S. & Berrada M. (2014): TCP Over Satellite Links: Problems and Solutions, *ENST-Paris*, pp.1-12

[2] Abdelrahman A.M, Abdalla M.S, Ali B.M, Prakash V and Sabudin R.K.Z. (2002). Improving the performance of TCP over LEO satellite Environment. *Pakistan Journal of Information and Technology* (ITJ'2002) 1 (3), pp. 250-254
x

[3] Allman M., Dawkins S., Glover D., Griner J., Tran D., and Henderson T., (2000). Ongoing TCP Research Related to Satellites, Internet RFC 2760

[4] Huston G. **(2000):** The Future for Transport Control Protocol (TCP)**,** *The Internet Protocol Journal***,** vol. 3, no. 3

[5] Maini A.K. and Agrawal V., (2014): Satellite Technology Principles and Applications, 3rd Ed John Wiley and Sons Ltd.

[6] Dennis Roddy (2018). Satellite communications, 4th edition, Mc. Graw Hill Publication (online) retrieved 18/01/2022

[7] Roseti C., (2007). Enhancing Transport Layer in Satellite Systems: Design and Development of an Emulation Platform, *Universita di Roma*, pp. 1-201

[8] Maral G. and Bousquet M, (2009): Satellite Communications Systems, Techniques and Technology, 5TH Ed, John Wiley and Sons Ltd.

[9] Giridhar, M and Jersey, L (2012) Third-Generation CDMA Systems for Enhanced Data Services, *The academic press series on communication, Networking and multimedia, Academic Press:* An Elsevier Science company, California 92101-4495, USA, pp. 112-147

[10] Criscuolo, Keith Hogie and Ron Parise(2019). Transport Protocols and Applications for Internet Use in Space Ed, Computer Sciences Corp 7700 Hubble Dr. Lanham-Seabrook MD 20706 (301) 794-4072 Ed.Criscuolo@gsfc.nasa.gov

[11] Stevens W., (1994). Transport Control Protocol/Internet Protocol Illustrated", Vol. 1, Ed. Addison Wesley, Reading, UK

[12] Sonia, Jain,(2003). Enhancing the performance of TCP over satellite link, Master thesis Department of electrical engineering and computer science, MIT

[13] Mark Allman, (1997). Improving TCP performance over satellite channel, Master Thesis, Ohio University, Athens OH 45701.

[14] Neglia, G., Mancuso, V. Saitta, F and Tinnirello, I, (2018). A Simulation Study of TCP Performance Over Satellite Channels, Department of electrical engineering, university of palermo viale delle scienze 9, 90128 palermo, Italy.

[15] Optical carrier transmission rate, Wikipedia, *en.m.wikipedia.org*.

[16] Khudhair, A. A., Jabbar, S. Q., Sulttan, M. Q., & Wang, D., (2016), Wireless indoor localization systems and techniques: survey and comparative study, *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 3, no. 2, pp. 392-409, doi: 10.11591/ijeecs.v3.i2.pp392-409.

[17] Sultan Q.M, (2019). Enhancement of K-Best Sphere Detection algorithm Performance in MIMO Systems, *IOP Conference Series: Materials Science and Engineering*, vol. 518, no. 5, IOP Publishing.

[18] Cao, J. and Stefanovic, M. (2009). Switching congestion control for satellite TCP/AQM networks, *American Control Conference*, Pp.4842-4847

[19] Sheikhan, M., Shahnazi, R.& Hemmati, E. (2010), *"PSO-RBF Based control Scheme for Adaptive Active Queue Management in TCP Networks, Faculty of Engineering, Islamic Azad University"*, South Tehran Branch, Tehran, Iran

[20] Misra V., Gong W. and Towsley D. (2000): Fluid-based Analysis of Network of AQM Routers Supporting TCP Flows with an Application to RED, In Proc. of ACM/SIGCOMM

[21] Labit, Y., Ariba, Y. and Gouaisbaut, F. (2007): Design of Lyapunov based controllers as TCP AQM, Research gate.

[22] Testouri, S., Saadaoui, K. and Benrejeb, M. (2012). Analytical Design Of First-Order Controllers For The TCP/AQM Systems with Time Delay*, International Journal of Information Technology", Control and Automation (IJITCA)* Vol.2, No.3, pp. 27-37

[23] Vishal Misra, Wei-Bo Gong and Don Towsley (2019). Stochastic Differential Equation Modeling and Analysis of TCP-Window size Behavior, Department of Computer Science University of Massachusetts, Amherst, MA 01003

[24] Hollot, C. V., Misra, V., Towsley, D. and Gong, W. (2002): Analysis and Design of Controllers for AQM Routers Supporting TCP Flows, *IEEE Transactions on Automatic Control*, Vol. 47, No. 6, pp. 945-959

[25] Agbaraji, C.E., Udeani, U.H., Inyiama, H.C. and Okezie, C.C. (2020). Robust Control for a 3DOF Articulated Robotic Manipulator Joint Torque under Uncertainties, *Journal of Engineering Research and Reports*, Vol. 9, No. 4, pp. 1-13

[26] Filardi, G, Oliver Sename, Alina Voda & Schroeder, H, J (2015). Robust H-Infinity control of DVD Drive under Parametric Uncertainties, pp 2715-2720

[27] Yongguang Zhang, Dante De Lucia, Bo Ryu and Son K. Dao(2021). Satellite Communications in the Global Internet: Issues, Pitfalls, and Potential, Hughes Research Laboratories, USA. https://www.isoc.org/inet97/proceedings/F5/F5_1.HTM