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Disturbance-Rejection Analysis of TCP-Based Wireless Networks in an Uncertain Channel using PID Control Techniques

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***Abstract* - Wireless networks experience some uncertainties which results from an unpredictable nature of wireless signals, interferences and signal propagation, leading to overall degradation of the entire system. The results lead to packet loss, fading, delays, reduced throughput and low latency. This paper is aimed at using PID Control Techniques to track network uncertainties in a TCP-based network and at the same time cancels it to enhanced the overall system performances. System performance measurement and analysis of the TCP- based network was performed with a link capacity of 3750, 4200 and 4500 packet/seconds respectively in three scenarios. The results showed that the PID control technique recorded sensitivity value of 0.0329dB, 0.0345dB and 0.0821dB. (all are less than 1dB), this means that it achieved good sensitivity levelto network disturbance for faster disturbance rejection capability and reduced sensitivity. I however recommend the PID control technique for wireless network improvement to attain enhanced performance, stability and good QoS.**

Keywords: Disturbance-Rejection, Congestion, PID Control, TCP.

1. Introduction

With recent improvement, emergence and service dependency of smart communication devices, there has been increasing demand for better quality of service (QoS) provisioning and experience (QoE) implementation at low operational cost (Capozzi et al, 2013). This necessitates the system resources for effective, resourceful, and optimized system performance and operational capability. The purpose of this research is to examine the effectiveness and efficiency of PID techniques in analyzing and improving network performance in TCP based wireless networks. TCP-based wireless networks operates under uncertain channel conditions. These uncertainties offer many challenges and restrictions including fluctuating signal strength, unnecessary interferences and varying network loads amongst others. All of this challenges and restrictions causes packet losses, delays and reduced throughput (Chen et al, 2019). Proportional-Integral-Derivative (PID) techniques have overtime, proven to be substantial in addressing the aforementioned limitations and improving network performance. PID control is a feedback mechanism that utilizes proportional, integral, and derivative actions to adjust the control parameters dynamically, based on the present network conditions, (Chen et al, 2019).

2. Literature Review

This section presents the review of existing literature on TCP-based wireless networks in an uncertain channel conditions. Wireless communication and its associated networks have become a critical and integral part of human existence. Communication ranges from line telephone and line telegraph, radio telephony and line telegraphy, radio broadcasting, point-to-point communication, radar communication, television broadcasting, radio telemetry, radio to navigation, radio aids to aircraft landing etc. This research is however centered on wireless communication which is the current trends in communication ecosystem.

2.1 Transmission Control Protocol (TCP) - Base Network

In Chen et al (2019), they examined the impact of uncertain channel conditions on TCP-based wireless networks. They however highlighted that fluctuating signal strength, interference, and varying network loads leads to packet losses, delays and reduced throughput. The study emphasized the need for efficient techniques to mitigate these limitations and as well optimize network performance. In their study, Zhang et al., (2017) focused on the effect of fading and shadowing in wireless channels. They investigated the impact of these channel impairments on TCP performance and proposed a channel estimation and prediction mechanism to improve the reliability and efficiency of TCP-based wireless networks. Their findings shed light and on the importance of considering channel conditions in network analysis and optimization. A

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study by Zheng et al., (2013), investigated the uncertain channel conditions on TCP-based wireless networks. They found that fluctuations in channel quality caused significant performance degradation in terms of throughput and latency. Huyng et al., (2017), conducted on extensive review of TCP congestion control mechanisms in wireless networks. As a result of challenges caused by uncertain channel conditions, they proposed adaptive approaches to mitigate them. A cross-layer approach that integrated network-layer feedback with TCP congestion control, leading to significant improvements in throughput and fairness in (Wang et al., 2015) in their work which focused on TCP performance optimization in the presence of uncertain channel conditions. Yang et al. (2018) explored the impact of different wireless channel models on TCP performance and compared the performance of various congestion control algorithms. Their findings indicated that considering the characteristics of uncertain channel conditions in TCP implementations in crucial for achieving efficient network performance.

2.2 Proportional-Integral-Derivative (PID) Control Technique

In their study, Guo et al, (2014) applied the PID control technique to optimize network traffic in software-defined networks (SDNs). They showed the effectiveness of PID controllers in adapting network parameters based on real-time traffic conditions. Liu et al, (2016) proposed a PID-based approach for network link congestion control. Their research showed that PID controllers could effectively defect and mitigate congestion in network links, leading to improved overall network performance. Haider et al, (2018) studied the application of PID control in wireless sensor networks (WSNs) for energy-efficient data gathering. They opined that PID controllers could optimize the transmission power and duty cycle of nodes in WSNs, enhancing network lifetime. Zhen et al, (2017) conducted a comprehensive survey of PID control techniques in network traffic management. They discussed the life of PID controllers for flow control, and quality of service (QoS) provisioning, highlighting their potential benefits in network optimization.PID control techniques have been studied extensively for network analysis and optimization. These techniques leverage feedback mechanisms to dynamically adjust control parameters based on the existing and current network conditions. Adnan et al, (2016) explored the application of PID control in wireless networks to adaptively adjust parameters such as congestion window size and timeout interval. Their study showed that PID-based congestion control algorithms can significantly improve network functionality and performance by reducing packet losses.

3. Research Gap

Most studies focus on either TCP-based wireless network on PID-based networks analysis individually, with few studies investigating the convergence of these two areas. Hence, there is need for research that bridges this gap and explores the potential advantages of incorporating PID techniques in TCP-based wireless networks for enhanced performance, stability and QoS.

4. Materials and Methods

4.1 Performance Measurement and Analysis of TCP over LTE Network Model

Wireless network system is designed to have a high speed for data communication propagation and requires a reliable data traffic congestion control method such as TCP. Since TCP has a significant limitation in data loss, it is slow due some uncertainties in the channel. Enhancing the performance is required to enable it withstand congestion disturbances will solve the problems of TCP.

In this work, TCP based network was considered and the focus here is to improve the performance of the TCP in terms of the following characteristics: data traffic congestion control speed, data transfer error and cross-over frequency ω_c; The cross-over frequency is proportionally inverse to the response time of the system, so it means that to get a faster system, ω_c must be as high as possible (Giglio, 2004).

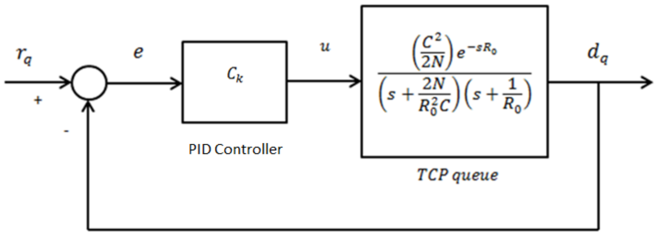

Figure 4.1: TCP plant with PID controller

Taking into consideration the following dynamics of the TCP queue system:

$$\begin{cases} G_W(s) = \dfrac{\frac{R_0 C^2}{2N}}{\left(s+\frac{2N}{R_0^2 C}\right)} \\ G_q(s) = \dfrac{\frac{N}{R_0}}{\left(s+\frac{1}{R_0}\right)} \end{cases} \tag{4.1}$$

Where $G_W(s)$represents the TCP's dynamic model without time delay and $G_q(s)$represents the queue dynamic model. These dynamic models are shown in Figure 4.1.

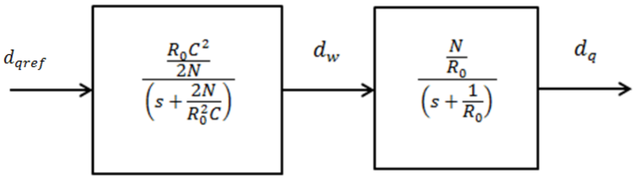

Figure 4.2: TCP queue model without time delay

The transfer function of the TCP queue without time delay becomes equation 4.2 and 4.3.

$$\frac{d_q}{d_{qref}} = G_W(s).G_q(s) \qquad (4.2)$$

$$\frac{d_q}{d_{qref}} = \frac{\frac{R_0C^2}{2N}}{\left(s+\frac{2N}{R_0^2C}\right)}.\frac{\frac{N}{R_0}}{\left(s+\frac{1}{R_0}\right)} \qquad (4.3)$$

Considering the AQM time delay shown in Figure 4.3, the TCP queue model becomes:

$$\begin{cases} G_W(s) = \dfrac{\frac{R_0C^2}{2N}}{\left(s+\frac{2N}{R_0^2C}\right)} e^{-sR_0} \\ G_q(s) = \dfrac{\frac{N}{R_0}}{\left(s+\frac{1}{R_0}\right)} \end{cases} \qquad (4.4)$$

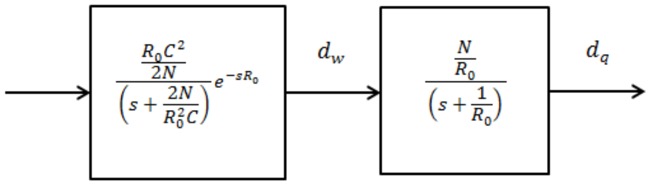

Figure 4.3: TCP queue model with time delay

The transfer function becomes:

$$\frac{d_q}{d_{qref}} = \frac{\frac{R_0C^2}{2N}}{\left(s+\frac{2N}{R_0^2C}\right)} e^{-sR_0}.\frac{\frac{N}{R_0}}{\left(s+\frac{1}{R_0}\right)} \qquad (4.5)$$

Solving the differential equation for the function, Gp(s) and Gq(s) becomes plant transfer function and queue dynamics. The TCP behavior dynamics is (Ptcp(s)), the following equation was obtained:

$$G_p(s) = \frac{\left(\frac{C^2}{2N}\right)e^{-sR_0}}{\left(s+\frac{2N}{R_0^2C}\right)\left(s+\frac{1}{R_0}\right)} \qquad (4.6)$$

The demonstration of TCP/AQM dynamic model transfer function is shown in Figure 4.4.

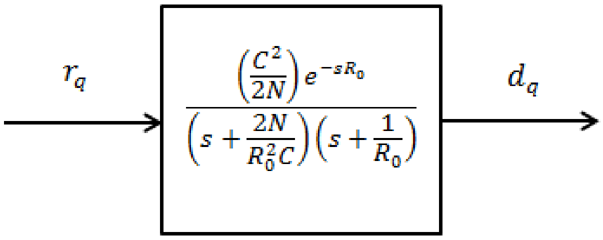

Figure 4.4: The TCP/AQM model plant

Where r_q is the input signal (reference input) into the TCP/AQM system.

4.2 Performance Analysis of the TCP model based on the LTE network

The performance analyses of the TCP system model were carried out based on loop control without external control technique. The purpose of carrying out these analyses was to study the behavior of the system in order to ascertain the need for an external control technique. The analyses were carried out in two domains, namely: time and frequency domains. These methods of analyses reveal most of the characteristics of the TCP model and provide most needed features to enable better description of the system characteristics.

4.2.1 Performance Analysis in Time Domain

The performance analysis of the TCP controlled queue length output characteristics were determined by the trajectory of the queue length graph in time domain. The time-domain graph plots its amplitudes as a function of time. The TCP model performance analysis was based on determining Steady state error and Settling time of the system output. The value of the steady state error determines the level of error existing in the data transfer. This relates to the amount of data loss and other forms of disturbances existing in the network. The steady state error is deduced from the time domain graph of the TCP/AQM model queue length output trajectory. Steady-State Error is the difference between the input and output of a system after the natural response has decayed to zero (Dukkipati, 2006; Agbaraji, 2015 and Philip-Kpae, et al. 2022) as shown in Figure 4.5. This means that minimizing the steady state error value will help to improve the performance of the TCP/AQM system. Hence, the steady state error becomes one of the critical characteristics of the TCP/AQM system when the LTE network is the area of its application which must be considered during the design stage of the system. On the other hand, the settling time is another critical characteristic of the TCP model when its application is focused on the speed of the LTE network systems. The settling time is the time required for the system output to settle within a certain percentage of the input amplitude. This means that the settling time determine the speed of the network during the data transfer and data traffic congestion control of the system.

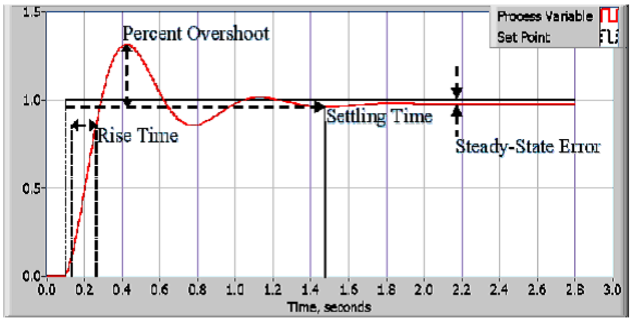

Figure 4.5: Step reference tracking response (Agbaraji, 2015)

4.2.2 Frequency Domain Performance Analysis

The frequency-domain performance analysis examines the behavioral attributes of the system output response in frequency against magnitude (in decibel (dB)). Generally, it plots each sine wave peak's amplitude against its frequency. The frequency domain analysis reveals the hidden or real internal behavior of the system. When a system satisfies the desired frequency analysis characteristics, it is said to be well designed. This is because a system may seem to achieve good performance in time domain but achieves poor performance in frequency domain analysis. Thus, a good system design must include the frequency analysis in other to examine the real-time behavior attributes of the system. In this work, the tracking error is analyzed in the frequency domain trajectory. It can be explained more as the ability of the system actual output to track the desired output characteristics. The target of most design works is to achieve a 0dB error, which shows that the system actual output has no difference with the desired output characteristics.

4.2.3 Simulation Parameters

The simulation parameters for the LTE network congestion improvement is as shown in the table 4.2.

Table 4.2: Simulation parameters for the LTE network (Abed et al, 2011)

Parameter	Value
Link Capacity, C	3750 or 4200 or 4500 packets/s
Round Trip Time, R	0.25s
Bandwidth of Server link	100Mbps
Load Factor, N	60
Packet Size	1500 Bytes
Window Size	48 Kb
Simulation Time	30 seconds

Substituting the parameters of the TCP based LTE network in table into the system transfer function G:

For link capacity C=3750, the plant model been:

$$G = \frac{25310000000}{s^2+4.002s+0.008} \qquad (4.7)$$

For link capacity C=4200, the plant model been:

$$G = \frac{31750000000}{s^2+4.002s+0.007143} \qquad (4.8)$$

4.2.4 Improved TCP Model

In order to achieve the TCP model performance improvement a feedback method of control was employed. The feedback system is roughly made of two parts: the plant that describes the system dynamics, and a controller, which must ensure that the system performs robustly with good time-response to the inputs (Giglio, 2004). The feedback system provides the means to minimize the system error, and improve the time response of the system. In this feedback mechanism, the TCP output is measured and compared with the reference input into the system to produce an error as shown in Figure 4.6. This error requires a controller and the output of the controller u as demonstrated in Figure 4.7 is fed into the TCP/AQM plant in order to produce an improved output signal.

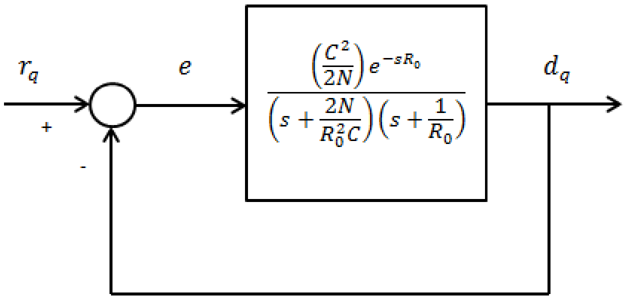

Figure 4.6: Feedback mechanism for the plant

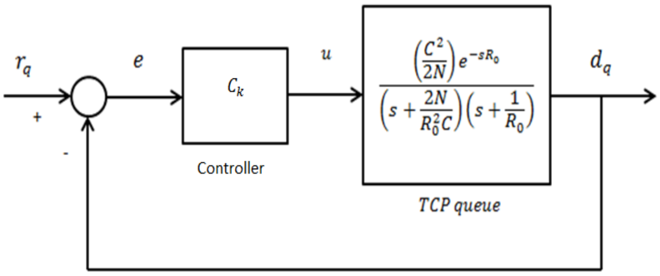

Figure 4.7: Feedback mechanism with a compensator for the plant

$$\frac{C^2}{2N} = x \qquad (4.9)$$

$$\frac{2N}{R_0^2 C} = n \qquad (4.10)$$

$$\frac{1}{R_0} = m \qquad (4.11)$$

Substituting the equations 4.9, 4.10 and 4.11 into equation 4.6, TCP transfer function is:

$$G_P = \frac{xe^{-sR_0}}{(s+n)(s+m)} \qquad (4.12)$$

For close loop model, transfer function of feedback system is give as follows:

$$\frac{d_q}{r_d} = \frac{G_P C_k}{1+GC_k} \qquad (4.13)$$

Substituting the equations 4.12 into equation 4.13 gives the following:

$$\frac{\frac{C_k xe^{-sR_0}}{(s+n)(s+m)}}{1+\frac{C_k xe^{-sR_0}}{(s+n)(s+m)}} \qquad (4.14)$$

$$\frac{\frac{C_k xe^{-sR_0}}{(s+n)(s+m)}}{\frac{(s+n)(s+m)+C_k xe^{-sR_0}}{(s+n)(s+m)}} \qquad (4.15)$$

$$\frac{C_k xe^{-sR_0}}{(s+n)(s+m)} \times \frac{(s+n)(s+m)}{(s+n)(s+m)+C_k xe^{-sR_0}} \qquad (4.16)$$

$$\partial(s) = \frac{C_k xe^{-sR_0}}{(s+n)(s+m)+C_k xe^{-sR_0}} \qquad (4.17)$$

Where $\partial(s)$ is the modified TCP based LTE system transfer function.

Substituting the equations for 4.9, 4.10 and 4.11 into Equation 4.17, gives:

$$\partial(s) = \frac{C_k \cdot \frac{c^2}{2N} \cdot e^{-sR_0}}{\left(s+\frac{2N}{R_0^2 C}\right)\left(s+\frac{1}{R_0}\right)+C_k \cdot \frac{c^2}{2N} \cdot e^{-sR_0}} \qquad (4.18)$$

$$\partial(s) = \frac{\frac{c^2 C_k e^{-sR_0}}{2N}}{\left(s+\frac{2N}{R_0^2 C}\right)\left(s+\frac{1}{R_0}\right)+\frac{c^2 C_k e^{-sR_0}}{2N}} \qquad (4.19)$$

Equation 4.19 becomes the controlled TCP queue system transfer function. Where C_k is the controller that can improve the system speed and also enhance its performance by reducing or cancelling the reference tracking error.

4.3 TCP Performance with PID Control

The PID control transfer function can be expressed as follows:

$$\boldsymbol{C_{kPID}(s) = K_p + \frac{K_i}{s} + K_d s} \qquad (3.58)$$

4.3.1 The PID control algorithm is expressed as follows

Apply the TCP queue system transfer function:

$$G_p(s) = \frac{\left(\frac{c^2}{2N}\right)e^{-sR_0}}{\left(s+\frac{2N}{R_0^2 C}\right)\left(s+\frac{1}{R_0}\right)} \qquad (4.20)$$

Formulate the improved TCP queue system model

$$\partial(s) = \frac{\frac{c^2 C_k e^{-sR_0}}{2N}}{\left(s+\frac{2N}{R_0^2 C}\right)\left(s+\frac{1}{R_0}\right)+\frac{c^2 C_k e^{-sR_0}}{2N}} \qquad (4.21)$$

Find the controller C_k using PID control design method through MATLAB simulation that can improve the output of the system and satisfy the desired characteristics.

Formulate the loop gain:

$$L = C_k G_p = \frac{C_k \cdot \left(\frac{c^2}{2N}\right)e^{-sR_0}}{\left(s+\frac{2N}{R_0^2 C}\right)\left(s+\frac{1}{R_0}\right)} \qquad (4.22)$$

Plot a time graph for the improved LTE system function $\partial(s)$ to determine the settling-time, overshoot and steady-state error.

Plot of a frequency graph for improved LTE system function $\partial(s)$ to determine the tracking error.

The algorithm for the controller design using PID technique is implemented in MATLAB m-file for the TCP queue performance improvement and analysis.

5. Results and Analysis

5.1 TCP Performance using PID Control

TCP performance improvement using PID control technique was carried out in three scenarios: when the link capacity is 3750 packets/seconds, 4200 packets/seconds and 4500 packets/seconds.

5.1.1 First Scenario - when C=3750 packets/seconds

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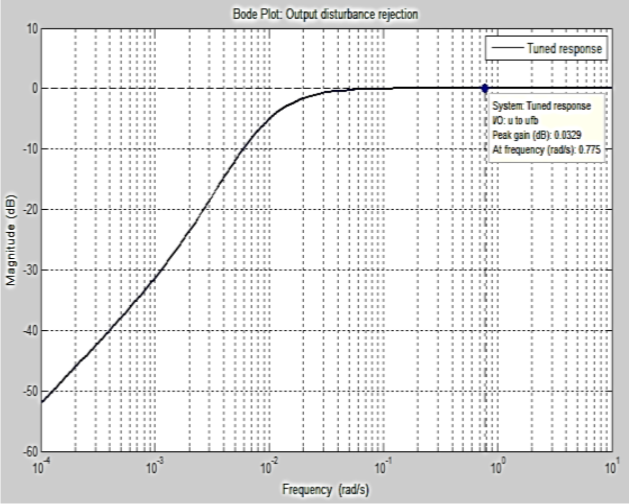

Figure 5.1: Sensitivity plot of the TCP-PID based network when C=3750 packets/seconds

The results in Figure 5.1 show that, the system using PID control technique recorded sensitivity peak of 0.0329dB. This means that the system can reject disturbances very well with reduced sensitivity. The parameters of the developed compensator Ck using PID control technique for the first scenario with link capacity of 3750 packets/seconds is expressed in Table 5.1 as follows:

Table 5.1: The PID controller parameters

PID Parameter	Value
K_p	1.5357e-10
K_i	7.6607e-13
K_d	0

5.1.2 Second Scenario - when C=4200 packets/seconds

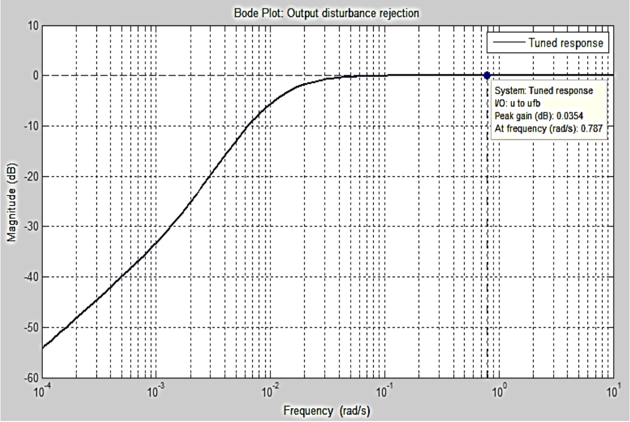

Figure 5.2: Sensitivity plot of the TCP-PID based when C=4200 packets/seconds

The results in Figure 5.2 show that, the modified system using PID control technique recorded sensitivity peak of 0.0354dB. This means that the system has good disturbance rejection capability with reduced sensitivity. Table 5.2 shows the parameters of the developed compensator Ck using PID control technique for the second scenario with link capacity of 4200 packets/seconds.

Table 5.2: The PID controller values for second scenario

PID Parameter	Value
K_p	1.3177e-10
K_i	7.004e-13
K_d	0

5.1.3 Third Scenario for the PID Control when C = 4500 packets/seconds

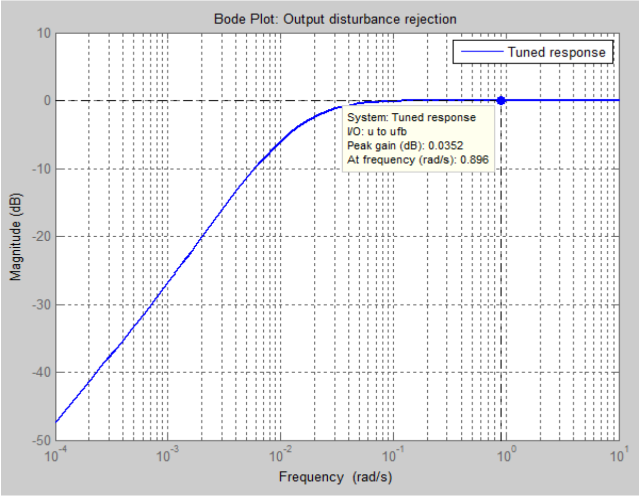

Figure 5.3: Sensitivity plot of the TCP-PID based network when C=4500 packets/seconds

The results in Figure 5.3 shows that, the modified system using PID control technique recorded sensitivity peak of 0.0352dB at frequency of 0.896 rad/sec in the frequency domain. This means that the system can reject disturbances well with reduced sensitivity much lesser than 1dB.

Table 5.3: The PID controller parameters for Experiment III

PID Parameter	Value
K_p	1.1645e-10
K_i	451.697
K_d	0

Table 5.4: Summary of performance using PID control technique

Parameter	First Scenario	Second Scenario	Third Scenario
Sensitivity to Disturbance (dB)	0.0329	0.0345	0.0821

6. Conclusion

The PID control technique recorded sensitivity value of 0.0329dB, 0.0345dB and 0.0821dB when the link capacity is 3750 packets/seconds, 4200 packets/seconds and 4500 packets/seconds respectively. This technique used in this work has a better capability to perform traffic congestion cancellation, reduced data transfer error and better disturbance rejection functionality in a wireless network.

Contribution to Knowledge

The PID control technique is adjudge to perform well for having high sensitive to disturbances in the present of uncertainty. From the result, it actually enhances congestion control, faster packet delivery, reduced packet loss and improve QoS and system stability.

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