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Design an Optimal Nonlinear Fractional Order PI Controller for Controlling Congestion in Network Routers

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ABSTRACT

Active Queue Management (AQM) is a mechanism adapted for notifying senders with network congestion traffics before any overflow happens in the queue which is led to loss data. AQM technique can be applicable in different network size in different fields like industrial systems, colleges and government. In this paper, a nonlinear Fractional Order proportional Integral (NLFOPI) controller is proposed for controlling the Active Queue Management (AQM) system in a stable and robust behavior. An intelligent optimization algorithm called Pelican Optimization algorithm (POA) has been chosen for attain optimal system desired response based on tuning the proposed controller gains for minimizing the error depending on the use of Integral time absolute Error as a fitness function to maintain the whole tuning process based on Matlab program. The proposed NLFOPI controller is regarded as one of the fractional order controllers that depend on using one fractional variable for the integral term only, due to this the tuning parameter will be three instead of two also the nonlinear term will give an enhanced robustness that reflected clearly on system performance. The evaluation analysis represented by settling time, peak time, rise time and overshoot value appeared in system response are done, based on comparison with different classical controllers (PI-PID-FOPI) to show the performance of the proposed controller in different scenarios and then a robustness analysis is adopted by varying the desired queue number values in different time period and also by disturbance rejection when add disturbances signals with values ± 100 packets to desired number of queue in two different periods (15-35) sec., the results reflect how does the system faces these tests done efficiently. Based on simulation results, the NLFOPI controller is regarded as the best controller based on its faster peak time value (tp=3.8 sec) with stable response and a smooth rise time value (tr=1.8 sec.) also a fast-settling time (ts=3.4 sec.) is achieved with un noticeable overshoot (0.2%) if it is compared to other controllers then its robust response is appeared by achieving a satisfied stability and robustness.

1. Introduction

The necessity of using different program and applications using internet network needs a higher speed transmission data and a flexible techniques for using these different applications, today due to higher increase in user numbers and the vast number of traffics led to a congestion issue, this issue is reflected on the network behavior in sending data which is either delayed or lose because of dropped data stored in packet [1]-[3], so for improve the quality of service(QoS) the congestion issue must fix by maintaining synchronization for data send and save all information from disappeared. The most important method used for solve saving data from lose is the Active Queue Management (AQM) which is regarded as a promising method. The AQM is utilized in the router of the network used for communication, which is improve the behavior of transformation of data and reduce the data lose during communication and achieve acceptable quality for service needed [4], [5].

The network organization is closely maintained by the TCP/IP protocols, its traffics and any delays happened are fixed using mechanisms of TCP/IP. Transport layer protocols arranges the rate of sent data based on network traffics, Fluid flow modeling analysis were suggested to adopt the organization of traffic paths in the network, and then AQM system provide the control of end-to-end congestion mechanism of TCP. The TCP/AQM is utilized for adjust and enhance the network efficiency. Previously, AQM system is suggested by Floyd and Jacobson in 1993 and they depend on Random Early Detection (RED) for fixing and maintaining the network congestion issues, the control of this issue in networks was translated as a nonlinear and complex problem which is varying with time continuously. For this reason a well-organized AQM system is become a demand for gaining acceptable network performance [6]-[10].

Various studies suggest many different ideas and schemes using different control technique to enhance congestion solving problem to achieve best network services, some researchers depend on different structure of PID controllers like using as shown in [5], [11], [12] a different smart tuning algorithm is adopted for tuning controller gains for maintaining the TCP flow behavior. In [13], [14] an intelligent and recent tuning algorithm is adopted with the aid of using a nonlinear formula with the controller, this combination reflects a stable behavior when the system response try to track the optimal and desired values. Other research proposes different structure of controllers that depend on fractional calculus by using fractional order controllers which is regarded as an expansion of the classical integer calculus mathematics, it has been used in various fields like industrial and scientific, in control engineering the fractional order controllers were significantly adopted and the advantages of these controllers types were extracted from its parameters named (λ, μ) which are a fractional values [15]-[17] with suitable dynamic properties if it is compared with integer values, in [18], [19] suggest a FOPID for maintain the TCP flow in different devices connected to the network routers by managing the AQM technique while in [20] an optimal FOPI controller is adopted with the aid of using a smart Gray Wolf Optimization (GWO) algorithm for choose the optimal values of controller gains that satisfy a robust system response with acceptable values in its transient analysis parameters. In [21]-[23] a fuzzy logic techniques is adopted for maintaining the AQM system to solve the congestion problem while in [24], [25] an adaptive integral backstepping controller are presented for solve congestion problem.

In this paper a NLFOPI controller is adopted to utilize the benefits of using the fractional calculus repressed by the fractional order PI controller and the nonlinear part suggested, this combination is used based on its effective behavior reflected on system stability, optimal system response is achieved and appeared clearly in selecting suitable gains values depending on the performance of the POA tuning algorithm which is realized outstanding convergence rates and efficient system performance compared to previous tuning methods in maintaining the AQM system and saving data from lose during traffic congestion in computer networks. The main contribution points of this study are:

1. The proposed NLFOPI structure with the POA tuning has used to show a satisfied response in tracking the efficient behavior for solving congestion problem.
2. A comparison with different tuned conventional controllers translates the efficient response of the proposed controller and reflects its superiority in settling time upon other selected controllers, its superior than PID and FOPI controllers by 25.6 % and 6.25 %.

3. For investigation of the system robustness in facing unwanted signals, disturbances signals are added to the AQM system, the proposed controller solved this matter efficiently in small period time; it needs just 15 sec. to return back the system to its desired.

This study is arranged as listed: Section 2 describes AQM system model. Section 3 presents the controller scheme used in this paper. Section 4, presents the POA algorithm, Section 5 demonstrates the simulation results and finally Section 6 explains the conclusions of this study.

2. AQM System Modeling

The system modeling is adopted based on [26], [27]. This part explains the fluid flow model for solve the bottleneck faced any router in TCP network connections, it will emphasis the TCP protocol dynamics that uses fluid flow model and stochastic differential relation formula. In this model, TCP timeout has been ignored and allows the average parameters values of the key network were obtained. A simplified differential relation was used by making expectations to the stochastic differential relations, these relations describe the real system behavior, the relations are as indicated on [26], [27]:

$$\dot{W}(t) = \frac{1}{R(t)} - \frac{W(t)W(t-R(t))}{2R\big(t-R(t)\big)}P(t-R(t)) \tag{1}$$

$$\dot{q}(t) = \frac{W(t)}{R(t)}N(t) - C \tag{2}$$

Where $C(t)$ is the network capacity (packets/seconds), $w(t)$ is the window size TCP predicted (packets), $q(t)$ is the queue length (packets); $R(t)$ is the full-trip path period (seconds), while $p(t)$ is the probability of packet (marking/dropping); and $N(t)$ is the number of TCP sessions. Fig. 1 explains the schematic graph for the formula appeared in Equations (1) & (2) which explains TCP window-control and queue dynamics.

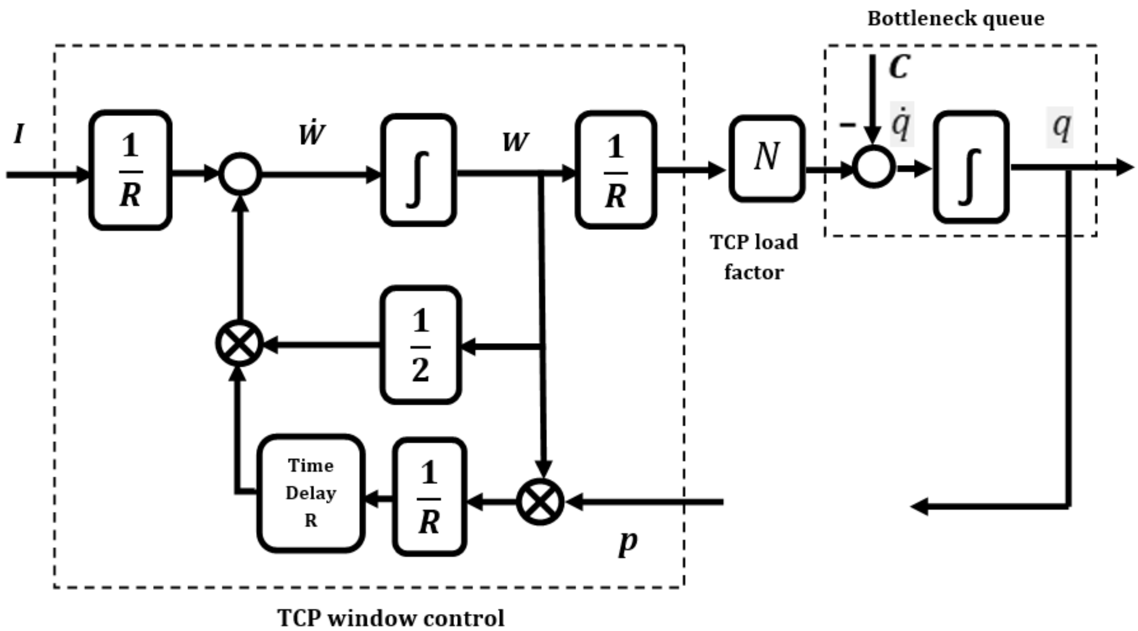


Fig. 1. AQM system flow control scheme [26]

For linearizing the model, it is supposed that the TCP sessions number and the capacity of the link are constant, and then the linearized model can be found using a small-signal linearization for the variables that represents the operating point (W_o, p_o, q_o). The linearized system modeling relations was used based on linearizing the nonlinear relations appeared in Equations (1) & (2) then using Laplace transform, the equations will be as indicated in Equations (3) & (4) [26], [27].

$$Ptcp\ (s) = \frac{W(s)}{P(s)} = \frac{\frac{RoC^2}{2N^2}}{s + \frac{2N}{Ro^2C}} \tag{3}$$

$$Pqueue\ (s) = \frac{q(s)}{W(s)} = \frac{\frac{N}{Ro}}{s + \frac{1}{Ro}} \tag{4}$$

The linearized AQM system is appeared in Fig. 2, where, $Ptcp(s)$ is the TCP transfer function, $Pqueue(s)$ is the queue transfer function.

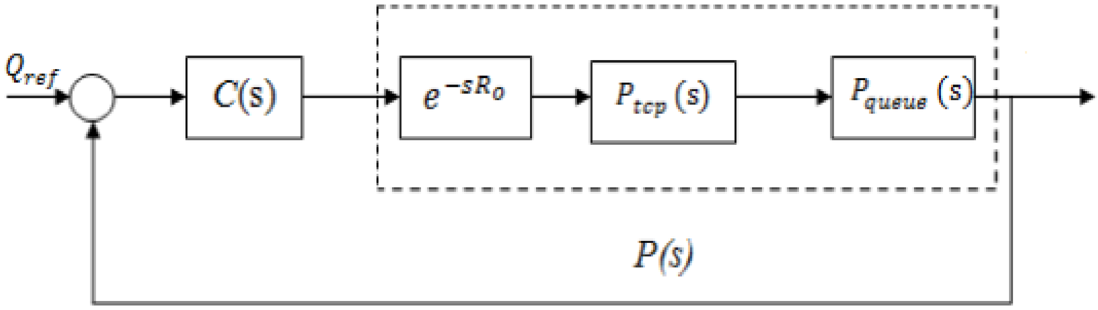


Fig. 2. Linearized AQM system

The system transfer function is:

$$P\ (s) = Ptcp\ (s).Pqueue\ (s).e^{-sRo} \tag{5}$$

Then based on equations explained the new transfer function model is as expressed in Equation (6)

$$G(s) = \frac{W(s)}{P(s)} = \frac{\frac{C^2}{2N}e^{-sRo}}{(s + \frac{2N}{Ro^2C})(s + \frac{1}{Ro})} \tag{6}$$

3. The Proposed Controller

Many traditional controllers are regarded as simple types of controllers and in many cases cannot improve system behavior, due to this, nowadays researchers modify these controllers like PID controller in different ideas to enhance system performance [28], one method of modification is by add an intelligent controller like merging neural with PID [29], [30] or change its structures based to achieve best results as in [31]-[33] or the use of fraction calculus for one of PID controller parts or together to enhance system output [34], other ideas is by use different nonlinear functions like hyperbolic relation [35], [36] to solve any undesired fluctuations may happen [37]-[39]. The Fractional Order Controllers (FOCS) attain more precise and efficient performances; it is divided into four controllers: CRONE, Tilt and Integral (TID), FOPID and lead-lag compensator. It has five important parameters: Normal PID gains (proportional, integral, and derivative) and the other two are fractional values for integral and derivative parts of PID controller. In this study a Nonlinear Fractional Order Proportional Integral (NLFOPI) controller is adopted to control congestion in which it is combine the fractional controller with a nonlinear hyperopic tanh function represented as a nonlinear value multiplied with the two gains of the proportional and the integral, its figure is shown in Fig. 3 and its equation is shown as:

$$Kn(e) = Tanh(e) = \frac{exp(k_0e) - exp(k_0e)}{exp(k_0e) + exp(k_0e)} \tag{7}$$

$$e = \begin{cases} e & |e| \le e_{max} \\ e_{max}.sign(e) & |e| > e_{max} \end{cases} \tag{8}$$

Where e is the error value and K_0 is a gain value with boundaries equal to [0-2] found its optimal value using the suggested tuning method POA.

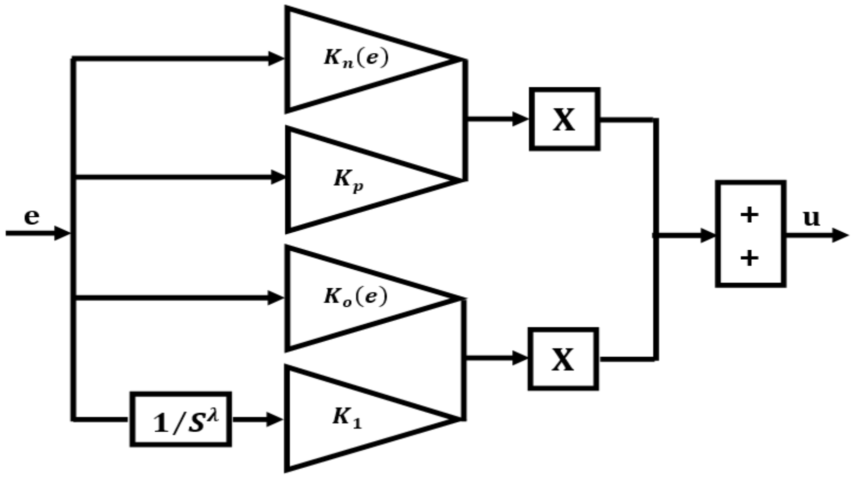


Fig. 3. NLFOPI proposed controller

4. Pelican Optimization Algorithm

Swarm optimization algorithms become ideal methods for tuning system parameters, its mimic real live styles for any nature swarm to fix complex tuning issues. These methods takes its procedures from different physical and biological phenomena, one of these methods is the Pelican Optimization Algorithm (POA)which is adopted as a swarm based cooperating team based on hunting process in encircling then catching small fishes. The way of performing the hunting phase can be expressed in two points [40], [41]:

i. Specifying the prey (exploration phase).

ii. Flying on a specific area (exploitation phase)

4.1. Specifying the Prey (Exploration Phase)

In this stage the pelicans search for a prey then move near its place. Testing the search field and the chosen POA's ability for exploration in finding different places until reach best modeling for the pelican's process. The randomly obtained places for the prey's places I within region boundaries is very important to POA. This enhances POA's ability to find the solution exactly for any problem fixing issue. Equation (9) expresses the mathematical relations for specifying tactic for finding the prey's place.

$$X_{i,j}P_1 = \begin{cases} x_{i,j} + rand \cdot (P_j - I \cdot x_{i,j}), F_p < F_i \\ x_{i,j} + rand \cdot (x_{i,j} - P_j), else, \end{cases} \tag{9}$$

where P_j is the prey's place in the jth domain, F_p is the cost function, and $X_{i,j}P_1$ is the ith pelican's next value in the domain of j, and i is a random parameter [1], [2]. For each pelican and iteration, a randomly chosen value is generated. This variables' value with make two causes in which one pelican must be displaced, in which it can help in discover new places in the hunting field for this reason, i variable will effect on the POA's capability to find new space precisely.

If the value of the function that expresses the objective aim is amended in the new pelican place, then the location is admitted. This type of updating is regarded as an efficient updating, saves the method from moving towards in a not suitable direction. Equation (10) will translate this step:

$$X_i = \begin{cases} X_i P_1, & F_i P_1 < F_i \\ X_i, & else, \end{cases} \tag{10}$$

where $F_i P_1$ is the cost function value calculated in the exploration phase and $X_i P_1$ is its new record.

4.2. Flying on a Specific Area (Exploitation Phase)

In this stage pelicans will be near the surface of the water, and then move their wings to move the fish up and then collect their food in its neck pouch. This behavior makes the pelicans collect more seafood in the specific area. In this step the chosen POA reaches to suitable places inside the specified area. This stage enhances the exploitation and the performance of local paths. Then for reach near to the optimal decision, it must search within the areas nearby the pelican location. Equation (11) translates the pelicans hunting formula:

$$x_{i,j} P_2 = x_{i,j} + R \cdot (1 - t/T) \cdot (2 \cdot rand - 1) \cdot x_{i,j}, \tag{11}$$

Where R is a constant value, equal to 0.2, $x_{i,j} P_2$ is the ith values of second stage, finds the next location of pelicans in the second space, t is the period of the recurrence clock, and T explain the maximum iterations number. The nearby area dimension $x_{i,j}$ is refer to $R \cdot (1 - t/T)$. The circumference of the swarm specified area for finding any pelican far from the swarm to move towards a best decision is expressed by the formula "$R \cdot (1 - t/T)$". This formula performs perfectly on the exploitation power of the POA to reach fastly to find the optimal decision.

In the initial iterations this variable value will be high, each pelican near at this period of time it will be notified and will be in the consideration. The formula "$R \cdot (1 - t/T)$" reduces when these steps are repeated more, each neighborhood pelican will have a smaller radius. For this reason, more precious steps must be done by look at the space encircling for every pelican in the swarm, this will make the pelican very near to the choices that are closer to the universal optimal depending on the understanding of usage. Equation (12) calculates the updated selected pelican locations.

$$X_i = \begin{cases} X_i P_2, & F_i P_2 < F_i, \\ X_i, & else, \end{cases} \tag{12}$$

where $F_i P_2$ is the member's cost function calculated in the second step and $X_i P_2$ is its next value. The more suitable decision till this point will have a new value when each pelican in the swarm has a new value different from the initial and the other stages, the population's new record, and the variables values of the goal function. Finally, a virtually response is presented based on the efficient decision taken during the iterations specified to complete the algorithm.

For tracking and monitoring system response efficiently a fitness function ITAE [42]-[44] is adopted for check continuously the deviation between desired output and the actual output obtained [45]-[47] its equation is:

$$ITAE = \int_0^\infty t|e|\,dt \tag{13}$$

Algorithm 1 lists the essential steps of POA and demonstrates the pseudocode of the algorithm. The algorithm starts by the initialization of essential parameters, like the pelican number, places and the global best decision, the pseudocode appeared in Algorithm 1 translates the steps of the algorithmic way of implementation, providing the optimal solutions. The flowchart of POA method is demonstrated in Fig. 4.

5. Simulation Results

The simulation results and analysis is demonstrated in this section, maintaining AQM system is controlled by a NLFOPI controller and all controllers' gains are founded by using POA algorithm, all

POA parameter is listed in Table 1 and the system block diagram is shown in Fig. 6, In simulation analysis network parameter is taken with values (N=60, C=3750 packets and R0=0.253), these values is adopted based on several previous studies that study controlling AQM based on different control schemes.

Algorithm 1. POA pseudocode

```
Initialize the population number of pelican (N) and the iterations maximum value (T).
Find the places of pelicans and obtain the fitness function.
For t = 1:X
Find the prey place randomly.
For I = 1: Y
Phase 1: Specify prey path then move to it (exploration phase).
For j = 1: Z
Update the jth dimension based on Equation (9).
End.
Update the ith pelican member based on Equation (10).
Phase 2: Winging on the surface of the water (exploitation phase).
For j = 1: Q.
Update the jth dimension based on Equation (11).
End.
Find the new ith pelican based on Equation (12).
End.
Find the best candidate decision.
End.
Final optimal solution obtained by POA.
```

Table 1. POA parameters

Description	Value
Pelican Swarm Number	50
Tuned variables	4
Maximum number of iterations	30

Then to confirm the controller performance in achieving optimal response, a performance metric represented by an ITAE formulae are utilized for monitoring system behavior based on its error value between desired and actual response during simulation continuously as indicated in Fig. 5, and the AQM system based on POA is shown in Fig. 6.

The system response based on these parameters is indicated in Fig. 7. Then to test controller efficiency in controlling AQM system and show its superiority in achieving a stable behavior a comparative analysis is utilized with different classical controller (PI, PID, FOPI), all controllers gains are tuned using POA tuning method, the system behavior with all controllers are appeared in Fig. 8. And the tuned gains are shown in Table 2.

Table 2. The gains of all controllers based on POA algorithm

	K_p	K_I	K_D	λ	K_0
PI	0.0000321	0.000026	-	-	-
PID	0.0000142	0.0000105	0.0000051	-	-
FOPI	0.0000633	0.0000129	-	0.723	
NLFOPI	0.00001488	0.00000866	-	0.901	1.477

The evolution parameters for analyze system performance is listed in Table 3, as shown from result The classical PI controller is faster than other controller but it is suffer from high overshoot percentage (21.16%) and this value is not acceptable and become a problem when the system work in long period and with large number of users packets due to this issue other controller (PID, FOPI) are appeared better than PI controller but still they suffer from the same overshoot problem but with moderate values but also not acceptable when using network in long period. As shown from result the

NLFOPI gives the best results in fast reaching to desired value with very small overshoot percentage (0.2%).

In Table 4, a comparison with studies using various controllers is demonstrated depending on different response analysis parameters (settling time, rise time and overshot values), as appeared from the NLFOPI controller analysis is faster than studies in [21], [48], fuzzy PI, but it is slower than Fuzzy and optimized PID controllers appeared in [49], [50], but these controllers suffer from high overshoot level if compared with proposed controller suggested, these improvements done are due to the POA smart tuning POA to find the best optimal values to achieve robust and efficient response.

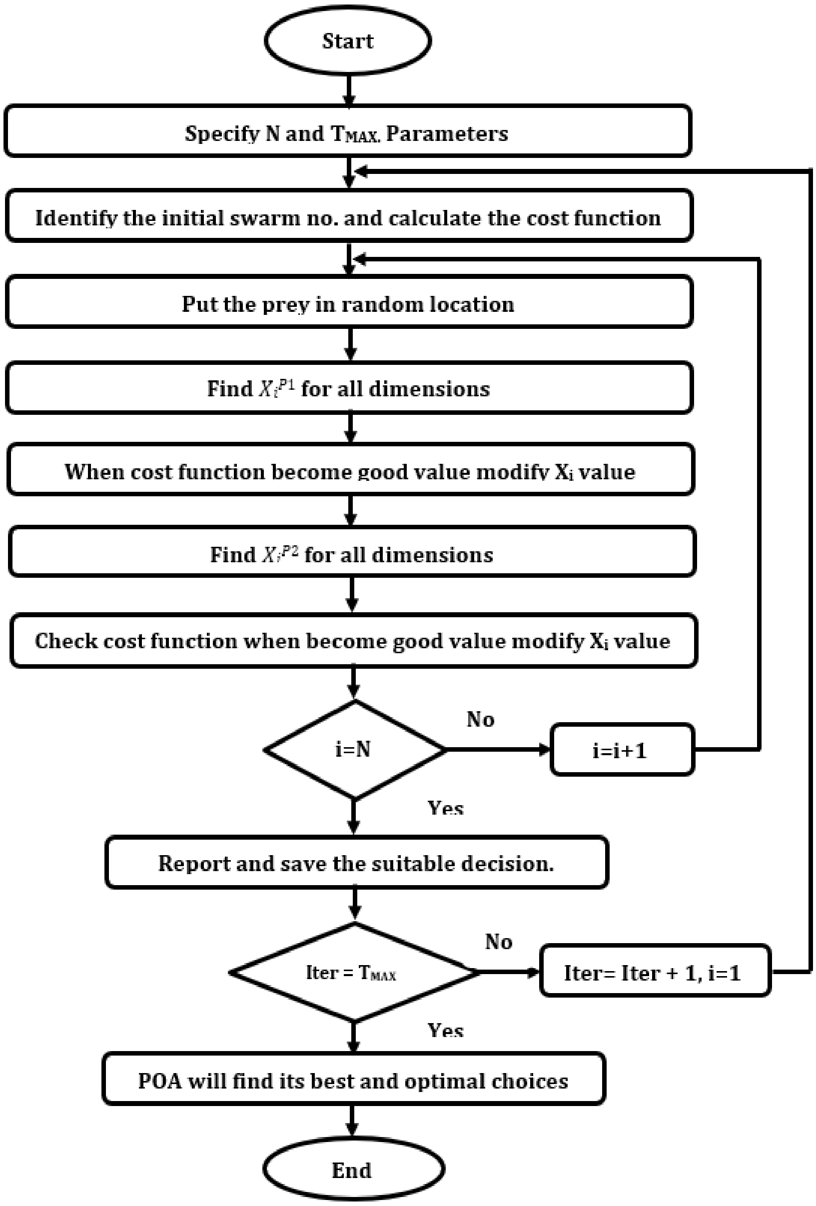


Fig. 4. Flowchart of POA

Table 3. Evaluation results for all adopted controllers

Controller	Peak time (sec.)	Rise Time (s)	Settling Time (s)	M_p (%)
PI	2.65	0.94	1.7	21.16
PID	6.25	2.7	4.02	8.083
FOPI	4.7	1.97	3.4	3
NLFOPI	3.8	1.8	3.2	0.2

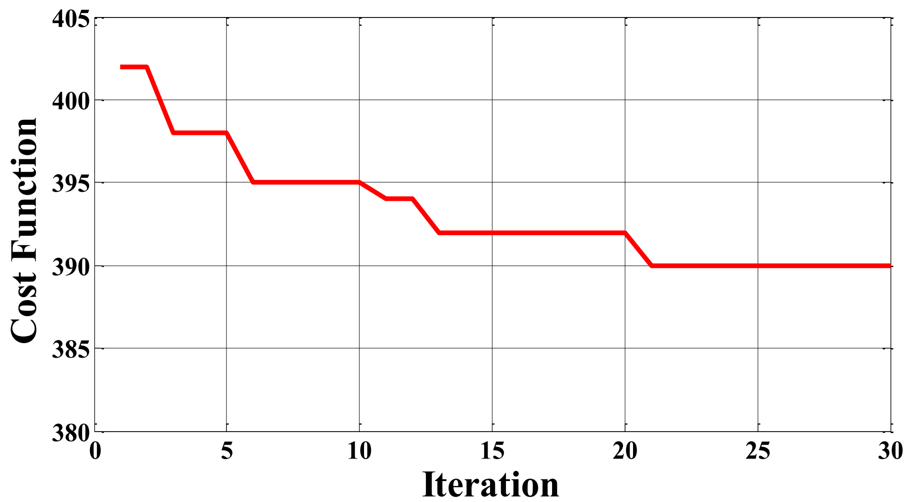


Fig. 5. ITAE index behavior for AQM system based on POA

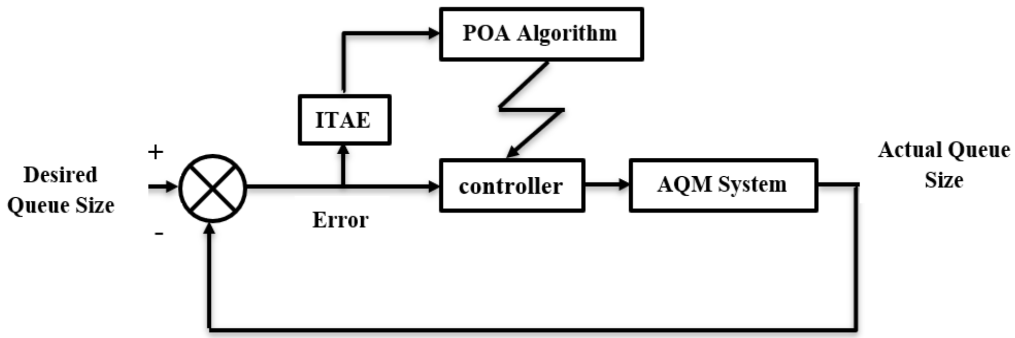


Fig. 6. AQM system based on POA

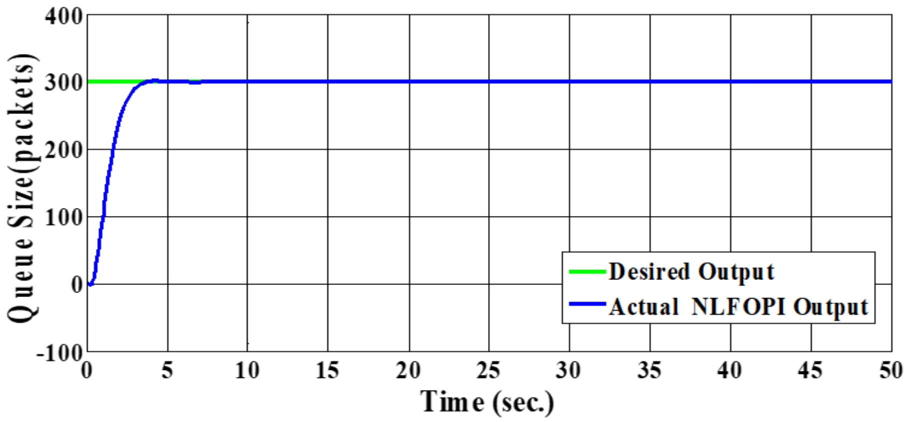


Fig. 7. System response based POA algorithm

6. Robustness Analysis

The robustness analysis is done in two steps the first one is by changing the queue size (No. of packets) during simulation time into different values (200-300-400) packets in different time duration, this test translate what happen in the real networking process since the users requirements differ from time to time, as shown in Fig. 9 (a) the AQM system is follow these changes without any oscillations or delay in its response, the other test is done by apply signals to system during simulation time which is regarded as a disturbances signal, these signals represent the increasing values of packets that may increase or decrease suddenly as shown in Fig. 9 (b) without any predefined acknowledge from network system, it is taken in two different time periods (15sec.- 35 sec.) with a value equal to ± 100 packets. In the two tests the system fixes these two tests robustly and gives a stable response after a short time as shown in Fig. 9.

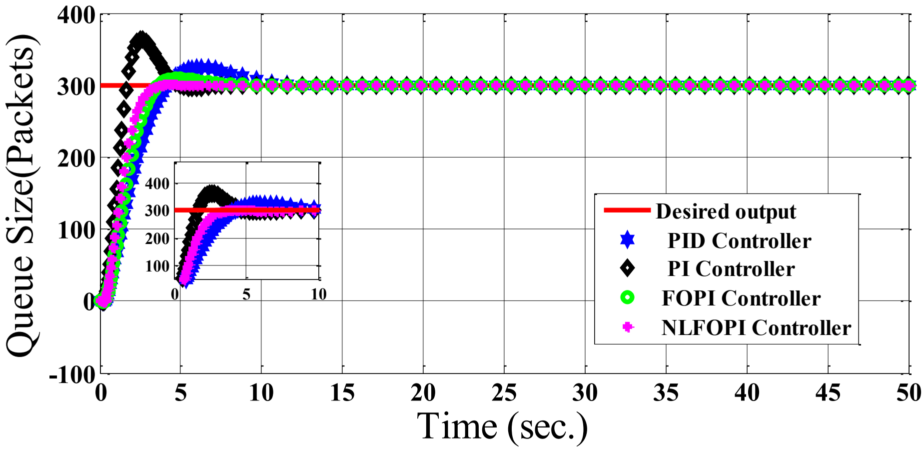
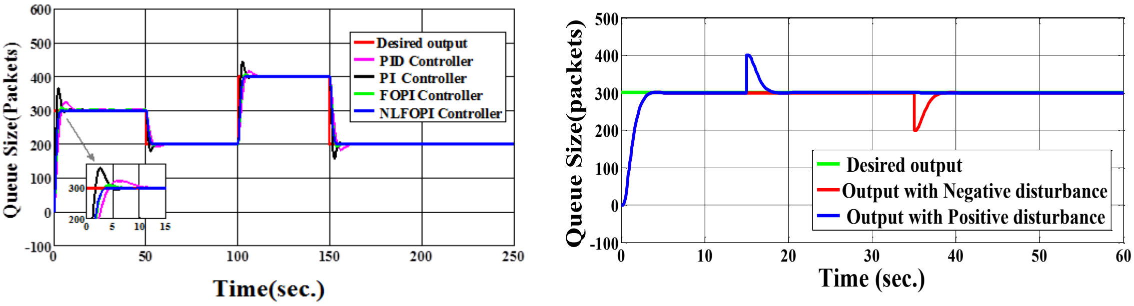


Fig. 8. The system behavior for all tuned controllers

Table 4. Comparison with other previous studies

Optimization-Controller [Ref.]	Settling Time (Sec.)	Rise Time (Sec.)	Overshoot (%)
SOA-PI [13]	3.4	2.95	0
PI [48]	36	3.3	33
LQ-SERVO [48]	8	2.4	-
PSO/LQ-SERVO [48]	4	0.83	-
PID-ACO [49]	2.0865	0.6732	2.1571
PID-GA [49]	2.1873	0.6297	4.1763
Fuzzy-PID [50]	2.65	1.32	10
PSO-PID [50]	2.64	0.56	27.7
ACO-PID [50]	1.84	1.065	3.09
Proposed NLFOPI	3.2	1.8	0.2



(a) (b)

Fig. 9. AQM system response: (a) when varying desired queue size (200-300-400) packets. (b) Adding disturbances signals to ± 100 packets

7. Conclusion

In this study a nonlinear FOPI controller is suggested for maintain congestion issue in internet networks due to huge users, the controller gains are tuned using an intelligent POA algorithm for achieve a robust desired system response efficiently. A comparative analysis with various classical controllers (PI-PID-FOPI) is utilized for test controller performance, it can be seen that the best behavior is of NLFOPI controller is reflected clearly on its evaluation values, in reach to its fast settling time its superior than PID and FOPI controllers by 25.6 % and 6.25 % respectively while PI controller is faster than NLFOPI controller by 88.2% but its suffer from high overshoot value which is not acceptable and undesired level when working also it can be seen that the same case is appeared in rise time and peak time values, due to these evaluation parameters and its stable response its regarded as the suitable controller that can maintain the AQM system with the aid of the optimal gains selected by POA. Two robustness tests is used and applied to the suggested NLFOPI controller, one of them is adopted by changing the number of the packets used from user into different values to see the system response based on this change and the other test is done by applying two disturbance signals in two different periods of time in both positive and negative values, in all tests done the controller fix these tests in a robustly and resist all tests applied during simulation time and finally reach to its desired response in un noticeable period of time. For future work could extend to the integration of real-world testing or implement the suggested system in embedded systems like FPGA by using hardware-in-loop validation or may use multi-agent POA for distributed congestion control.

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