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Adaptive Predictive Proportional Controller for IEEE 802.17

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ABSTRACT The Resilient Packet Ring (IEEE 802.17) fairness algorithm is simple, but exhibits some weaknesses. The bandwidth allocation severely oscillates when the traffic is unbalanced. Several algorithms have been proposed in recent years to overcome this issue. For example, the proportional controller is used for solving the fairness problem. The proportional controller is able to converge to the fair rates with no oscillations at the steady state. Unfortunately, the controller shows bandwidth oscillations and becomes unstable if the network delay is significant. In this paper, the impact of the delay is studied analytically and through simulation. Also, the Smith's principle is used to compensate the ring delay. Moreover, the controller gain is tuned using a fuzzy logic system. The performance is evaluated through simulation and the results show that the proposed adaptive predictive proportional controller assures fairness, stability and high bandwidth utilization even in ring network with large delay.

INDEX TERMS Fairness, fuzzy, RPR, predictive, proportional.

I. INTRODUCTION

The current technologies for metro access ring network have several limitations. For example, SONET ring assures fast protection at the expense of resource utilization where 50% of the available resources is reserved for protection. On the contrary, Gigabit Ethernet assures high bandwidth utilization at the expense of fairness and fast recovery from a failure. The Resilient Packet Ring Network (RPR) [1], [2] is described in the IEEE 802.17 as the integration of SONET and Ethernet advantages. It assures cost effectiveness, fast ring recovery, high utilization and fairness. RPR is consisting of two rings (Figure 1) and both rings are used to transfer data. The RPR technology supports the spatial reuse feature that enables deferent segment of the ring to carry deferent data traffic simultaneously for high bandwidth utilization. Also, RPR technology categorized data packets into three types, high quality traffic (class A), medium quality traffic (class B) and the best effort traffic (class C). The incoming traffic is either removed from the network if this switch is the destination or go through the transit buffer (Figure 2). The Primary Transit Queue (PTQ) for class A traffic and the Secondary Transit Queue (STQ) for class B and C traffics (Figure 3). The transit class A and B traffics have priority over the local traffic. The transit and local class A and B traffics have guaranteed bandwidth. The remaining bandwidth is for the best effort traffic and thus it is important to assure fairness. At the state of congestion, the backlogged node sends to the upstream nodes a control packet containing the fair rate according to its measurements and each node changes its rate accordingly.

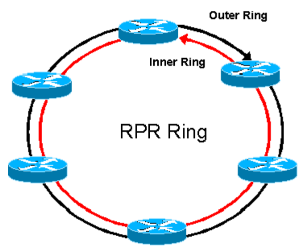

FIGURE 1. RPR network.

The rest of the paper is organized as follows: Section II debates fairness in RPR; Section III describes the proportional controller and the effect of the delay; Section IV illustrates the ring delay compensation by using the Smith predictor; Section V explains the controller's gain tuning done by using a fuzzy logic system; simulation results are shown in VI and conclusion in Section VII.

II. RELATED WORK

The standard fairness algorithm [3]–[5] is either aggressive or conservative. When the RPR switch is congested, it computes the fair rate as its transmitting rate namely *my-rate* if the

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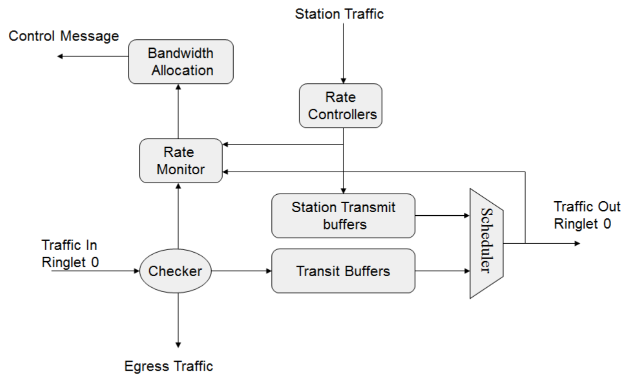


FIGURE 2. Architecture of RPR node.

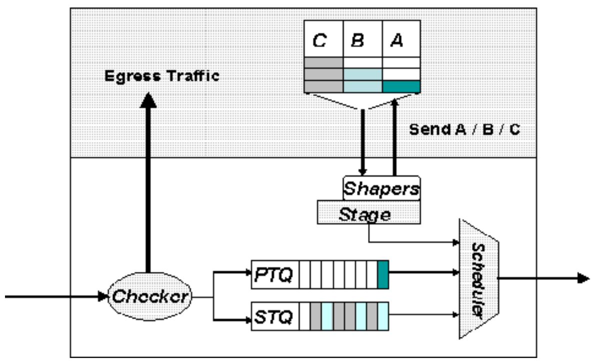


FIGURE 3. Dual buffers system.

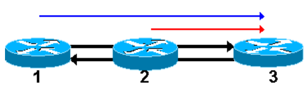


FIGURE 4. Simple scenario.

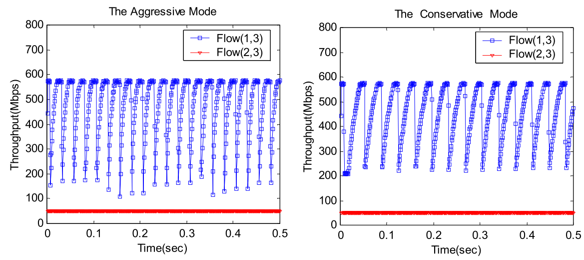
aggressive algorithm is adapted or the available bandwidth divided by the number of flows if the conservative mode is used. The fair rate is transmitted to upstream nodes to set their rates accordingly. When the congestion is cleared, upstream nodes are informed to increase their rates till the next congestion occurred and this process causes a repetitive oscillation.

Let's consider the scenario shown in Figure 4 [4]. Flow(2, 3) rate is 50 Mbps and flow(1, 3) rate is 622 Mbps. Each link has a capacity of 622Mbps and 0.1 ms propagation delay. At the state of congestion, node 2 transmits a fairness packet that includes its transmitting rate of 50 Mbps, thus node 1 regulates its transmitting rate to be 50 Mbps. On the other hand, node using the conservative transmits a fairness massage include the value of 311Mbps. After resolving the congestion, upstream nodes are notified to increase the rates. Node 1 increases its rate till the next congestion situation (figure 5) and these oscillations decrease the throughput.

Several alternative algorithms were proposed to resolve the fairness problem. For example, the distributed virtual-time scheduling in ring algorithm (DVSR) [4] requires per-source information and has a computational complexity of O(N log N), where N is the number of sources. Similarly, the distributed bandwidth allocation fairness algorithm [5] achieves similar performance like DVSR but with a low computational complexity of O(1). Moreover, the Virtual Queuing algorithm [6] has the same convergence as DVSR but requires per-source virtual queue at each switch. Alternatively, the fuzzy controller was designed to regulate the bandwidth allocation process by using the local information and compute the fair rate [7]. The fuzzy controller was shown to be simple and able to achieve fairness. Also, the control theory was applied by using the proportional integral controller [8] and the proportional controller [9] where the controllers demonstrated to achieve fairness with no oscillations and do not require per-source information.

The proportional controller is stable and simple to implement but if the network delay is large the closed loop system becomes unstable and the allocated bandwidth oscillates.

In this paper, two improvements are proposed to the proportional controller. First, the smith predictor is used for dead time compensation to get a delay free system and remove the influence of the network delay. Second, the proportional controller gain is tuned by a fuzzy logic controller to enhance the system performance and overcome the uncertainties of the system parameters.



(a) Agressive Mode (b) Conservative Mode

FIGURE 5. Performance of RPR fairness algorithm.

III. PROPORTIONAL CONTROLLER

Recently, a proportional controller proposed to monitor the congestion and compute the fair rate (Figure 6) [9]. At the bottlenecked link, the transit queue length $q(t)$ is

$$q(t) = \int_0^t \sum_{i=1}^{N} a_i(t - \tau_i^f)dt - \int_0^t D(t)dt, \tag{1}$$

where N is the number of sources, a_i is the rate of source i, τ_i^f is the forward delay experience by the data packets transmitted from source i to reach the congestion location and D is the available resources for class C.

At the reception of the fair rate, node i sets its data rate as follows

$$a_i(t) = f(t - \tau_i^b), \tag{2}$$

where τ_i^b is the backward delay.

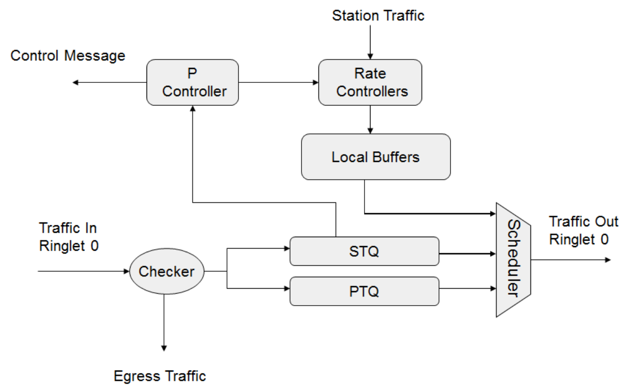


FIGURE 6. The proportional controller.

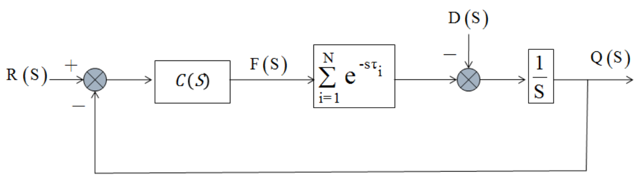


FIGURE 7. The control system.

Using Eq.(1) and Eq.(2), we get

$$q(t) = \int_0^t \sum_{i=1}^{N} f(t-\tau_i)dt - \int_0^t D(t)dt, \tag{3}$$

and

$$q''(t) = \sum_{i=1}^{N} f'(t-\tau_i), \tag{4}$$

where $\tau_i = \tau_i^b + \tau_i^f$ is the round trip delay.

Laplace transform of Eq. (4) is

$$Q(s) = \frac{\sum_{i=1}^{N} e^{-s\tau_i}}{s} F(s). \tag{5}$$

For ease, assume $\tau_i = \tau, \forall i \in N$ and τ is the maximum delay.

Thus, the process model $G(s) = \frac{Q(s)}{F(s)}$ is

$$G(s) = \frac{Ne^{-s\tau}}{S} \tag{6}$$

The proportional controller C(s) (Figure 7) calculates the fair rate as

$$f(t) = ke(t), \tag{7}$$

where $e(t) = r(t) - q(t)$, $r(t)$ is the set point and k is the controller gain.

The Laplace transform of Eq. (7) is

$$F(s) = kE(s), \tag{8}$$

and the system transfer function is

$$\frac{Q(s)}{R(s)} = \frac{kNe^{-s\tau}}{s + kNe^{-s\tau}} \tag{9}$$

The proportional controller is simple and suitable to guarantee stability, high utilization and fairness.

A. OFFSET ELIMINATION AND STABILITY

The process model is integrator plus dead time and due to the natural integrating action of the process it does not require integral control action to eliminate the offset [10]. The control system which is using the proportional controller satisfies the stability condition that $q(t) \leq r(t)$. So, let consider that the set point is a step function $r(t) = r^0 \cdot \mathrm{u(t)}$ and the system output in response to $r(t)$ is

$$Q(s) = \frac{kNe^{-s\tau}}{S + kNe^{-s\tau}} R(s) \tag{10}$$

The steady state queue level is $\lim_{t\to\infty} q(t) = \lim_{s\to 0} sQ(s)$, and we get

$$q(\infty) = r(\infty) = r^0 \tag{11}$$

It is clear that using a proportional controller to control a process with integrating action would assure stability and eliminate the offset that $\lim_{t\to\infty} q(t) = r(t)$, and $\lim_{t\to\infty} e(t) = 0$. So the proportional controller is suitable for bandwidth regulation at the high speed network due to its stability and simplicity.

B. ACHIEVING FAIRNESS

At the equilibrium point, the control system has

$$\lim_{t\to\infty} q(t) = r(t), \quad \lim_{t\to\infty} q'(t) = 0, \; and \; \lim_{t\to\infty} f(t) = f^*$$

therefore, Eq. (1) written as

$$\sum_{i=1}^{N} a_i^* = D. \tag{12}$$

Using Eq. (2) and Eq. (12), then obtain

$$\sum_{i=1}^{N} f^* = D, \tag{13}$$

and

$$f^* = \frac{D}{N}, \tag{14}$$

this assures that each flow attains no less than its fair share.

C. GAIN SELECTION

The characteristic equation of the control model is

$$s + kNe^{-s\tau} = 0. \tag{15}$$

and the controller's gain computed as follows

By $s = j\omega$ and $e^{-j\omega\tau} = \cos(\omega\tau) - j\sin(\omega\tau)$, we have

$$kN\cos(\omega\tau) - jkN\sin(\omega\tau) = -j\omega. \tag{16}$$

and the stability condition is

$$0 < k < \frac{\pi}{2N\tau}. \tag{17}$$

this result is similar to one reported by Ziegler and Nichols tuning method [11]–[13]

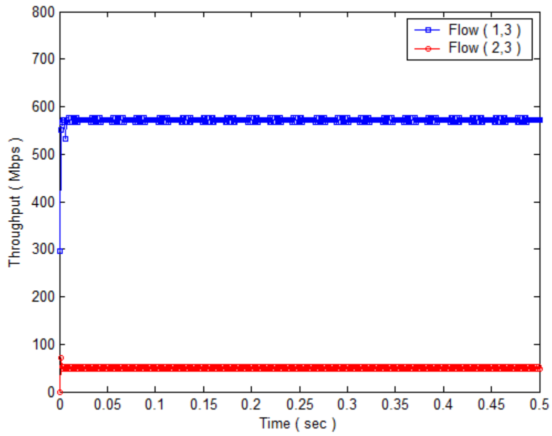


FIGURE 8. Proportional controller performance (low link delay).

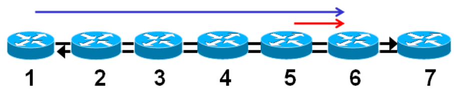


FIGURE 9. Large delay scenario.

D. FULL LINK UTILIZATION

The control system assures full link utilization by keeping the following condition that $q(t) > 0$.

The system output in response to r(t) and d(t) is

$$Q(s) = \frac{kNe^{-s\tau}}{S + kNe^{-s\tau}} R(s) - \frac{1}{S + kNe^{-s\tau}} D(s) \tag{18}$$

and final queue level is

$$\begin{aligned} q(\infty) &= r(\infty) - \left(\frac{1}{kN}\right) d(\infty) \\ &= r^0 - \left(\frac{1}{kN}\right) d_\infty \end{aligned} \tag{19}$$

The compulsory condition to assure full link utilization is maintain the following

$$r^0 > \left(\frac{1}{kN}\right) d(t)$$

E. PERFORMANCE EVALUATION

Now, the simple scenario (Figure 4) is used to evaluate the proportional controller. The oscillation is reduced as shown in Figure 8 and flow(1, 6) claim the available bandwidth of 571Mbps. The proportional controller attains its objectives of fairness, stability and high bandwidth utilization.

Unfortunately, the system is very sensitive to the ring delay. For instance, the congestion point is made farther from node 1 and the link's propagation delay is increased to1ms as shown at Figure 9. Flow (1, 6) oscillates as shown in Figure 10 due to large network delay and this causes bandwidth loss.

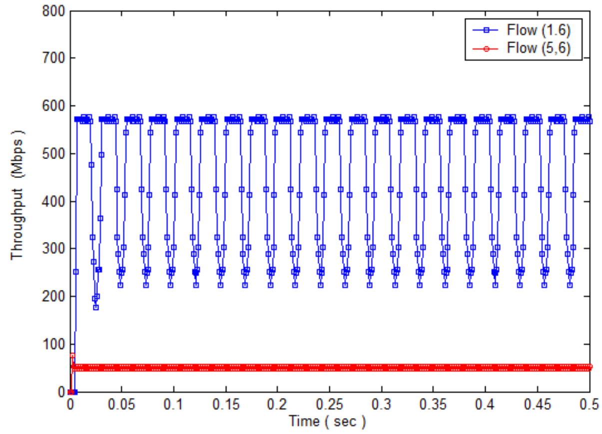


FIGURE 10. Proportional controller (large delay).

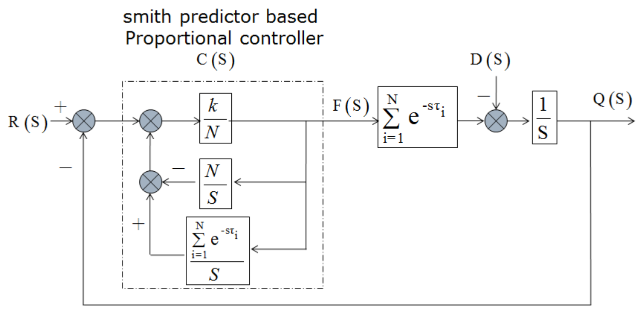


FIGURE 11. The predictive control model.

The typical approach to overcome this problem is to use dead time compensator [14]–[19] and it has been shown that the Smith predictor is successful for system with large delay.

IV. DEAD TIME COMPENSATION

In this section, the proposed control system (Figure 11) is designed after Smith's predictor [20]–[22] for dead time compensation.

The control system is enhanced by the Smith predictor to compensate the time delay and remove its effect on the system stability. The proposed controller (Figure 11) consists of the proportional controller and smith predictor. The predictor is composed of the process model without dead time $\frac{N}{S}$ and the process model with the dead time $\frac{\sum_{i=1}^{N} e^{-s\tau_i}}{s}$.

The objectives of the control system are to obtain a free delay system, stability and full link utilization. These goals are detailed through the following proposition:

Proposition 1: The proposed system is a delay free.

Proof: The transfer function is

$$\frac{Q(s)}{R(s)} = \frac{\dfrac{\frac{k}{N} \times \frac{1}{s} \sum_{i=1}^{N} e^{-s\tau_i}}{1 + \frac{k}{N} \times \frac{1}{s}\left(N - \sum_{i=1}^{N} e^{-s\tau_i}\right)}}{1 + \dfrac{\frac{k}{N} \times \frac{1}{s} \sum_{i=1}^{N} e^{-s\tau_i}}{1 + \frac{k}{N} \times \frac{1}{s}\left(N - \sum_{i=1}^{N} e^{-s\tau_i}\right)}} \tag{20}$$

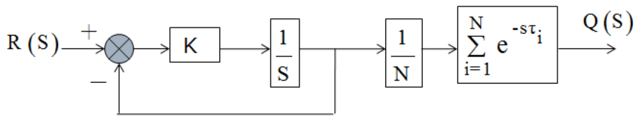


FIGURE 12. The desired control model.

Eq.(20) is simplified to

$$\frac{Q(s)}{R(s)} = \left(\frac{\frac{k}{s}}{1+\frac{k}{s}}\right)\left(\frac{1}{N}\right)\left(\sum_{i=1}^{N} e^{-s\tau_i}\right) \tag{21}$$

The system is first order closed loop system followed by sum of delays (Figure 12).

Proposition 2: The proposed system satisfies the stability condition $q(t) \leq r(t)$.

Proof: The system output in response to r(t) is

$$Q(s) = \frac{\frac{k}{N}\sum_{i=1}^{N} e^{-s\tau_i}}{s+k} R(s) \tag{22}$$

and the final queue level is

$$q(\infty) = r(\infty) = r^0 \tag{23}$$

and the proof is complete.

Proposition 3: The proposed system assures full link utilization, that $q(t) > 0$

Proof: The system output in response to r(t) and d(t) is

$$Q(s) = \frac{\frac{k}{N}\sum_{i=1}^{N} e^{-s\tau_i}}{s+k} R(s) - \frac{1+\frac{k}{s}-\frac{k}{N}\times\frac{1}{s}\sum_{i=1}^{N} e^{-s\tau_i}}{s+k} D(s) \tag{24}$$

and the final queue level is

$$q(\infty) = r(\infty) - \left(\frac{1}{k}+\frac{1}{N}\sum_{i=1}^{N}\tau_i\right) d(\infty)$$
$$= r^0 - \left(\frac{1}{k}+\frac{1}{N}\sum_{i=1}^{N}\tau_i\right) d_\infty \tag{25}$$

and the required condition for full utilization is

$$r^0 > \left(\frac{1}{k}+\frac{1}{N}\sum_{i=1}^{N}\tau_i\right) d(t)$$

and this completes the proof.

The predictive proportional controller C(s) calculates f(t) as

$$f(t) = \frac{k}{N}\left(r(t) - q(t) - N\int_0^t f(t)dt + \sum_{i=1}^{N}\int_0^{t-\tau_i} f(t)dt\right)$$
$$= \frac{k}{N}\left(r(t) - q(t) - \sum_{i=1}^{N}\int_{t-\tau_i}^{t} f(t)dt\right) \tag{26}$$

The fair rate $f(t)$ is proportional to the available queue space $r(t) - q(t)$ decreased by the sum of packets that are injected in the ring through the time $(t - \tau_i \rightarrow t)$.

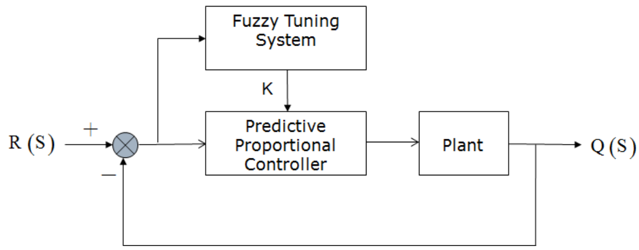


FIGURE 13. The adaptive predictive proportional controller.

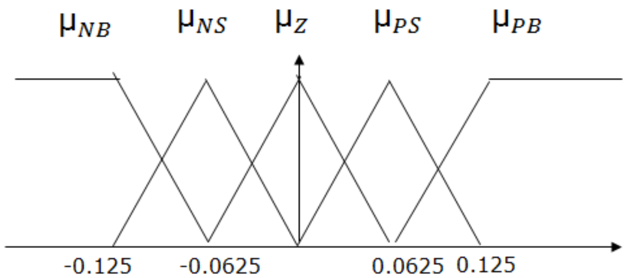


FIGURE 14. Functions of $e(k)$ and $\Delta e(k)$.

TABLE 1. The rule base for K.

$e(k)$ \ $\Delta e(k)$	NB	NS	Z	PS	PB
NB	0.5	0.4	0.05	0.4	0.5
NS	0.5	0.4	0.05	0.4	0.5
Z	0.4	0.3	0.1	0.3	0.4
PS	0.5	0.4	0.2	0.4	0.5
PB	0.5	0.5	0.2	0.5	0.5

V. CONTROLLER GAIN TUNING

The proposed predictive proportional controller involves many uncertainties such as the process model and the controller parameters that may affect the performance of the control system. Thus, an adaptive gain tuning method is proposed using the fuzzy logic [23]–[27] to dynamically adjust the controller gain k. The proposed system is illustrated at Figure 13.

The error $e(t)$ and the differential error $\Delta e(k)$ are the inputs to the fuzzy system. These inputs are normalized with respect to the secondary transit queue size and then fed to the fuzzification process. These inputs are mapped into linguistic values Positive Big (PB), Positive Small (PS), Zero (Z), Negative Big (NB) and Negative Small (NS) through their corresponding membership functions μ_{PB}, μ_{PS}, μ_Z, μ_{NB} and μ_{NS} respectively (Figure 14). Triangular membership functions are selected because of their simplicity, easy to implement and provide good performance in control systems [28]–[32]. The rule-based fuzzy system is used for the inference process.

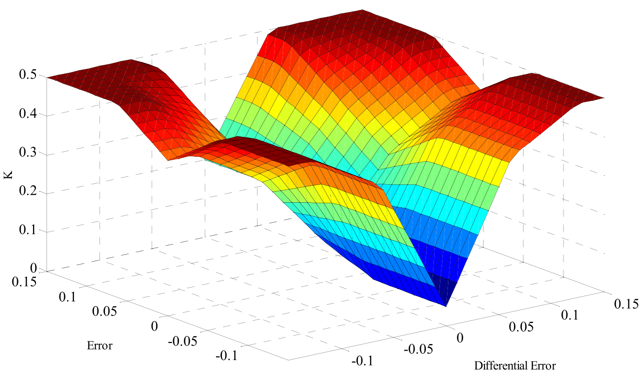


FIGURE 15. The controller gain *k*.

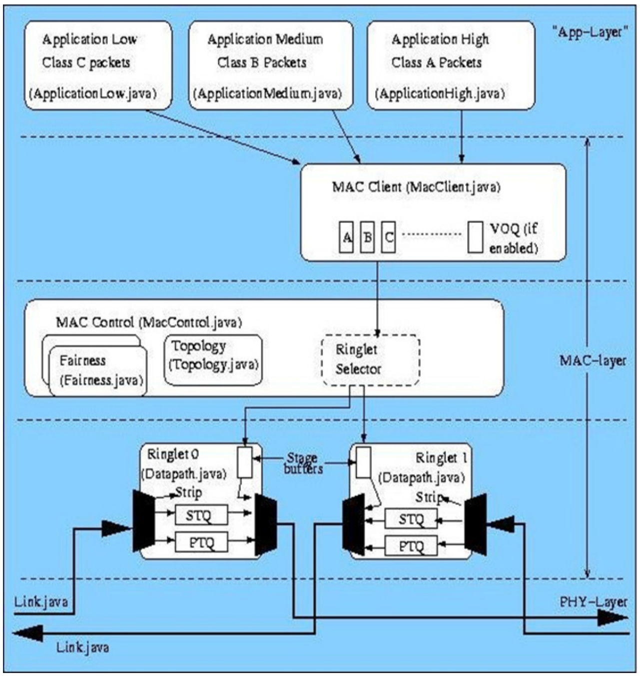


FIGURE 16. The RPR simulation model.

In specific, the Sugeno method [33]–[36] is applied and the rules are in the form of

IF antecedent THEN consequent

where the antecedent is based on the fuzzy sets, while the rule consequent is a crisp function and the controller gain has 25 rules. The rules for the proportional controller has the form

$$R^j: \text{ IF } e(t) \text{ is } X_e \text{ and } \Delta e(k) \text{ is } X_{\Delta e} \text{ Then } k \text{ is } b_j$$

where R^j is the jth rule, $e(t)$ and $\Delta e(k)$ are the Controller's inputs with their linguistic values X_e and $X_{\Delta e}$, respectively, and k is the output which takes the value of b_j as tabulated in Table.1. The result of each rule is a crisp output. Thus, the weighted average defuzzification method is used to obtain the controller gain k. The objective of using the triangular membership function for fuzzification process, the Sugeno method for inference process and the weighted average defuzzification is to simplify the computation process of the gain tuning system and make it suitable for the high speed network application. The surface of the controller gain is shown in Figure 15 as a function of the inputs $e(t)$ and $\Delta e(k)$.

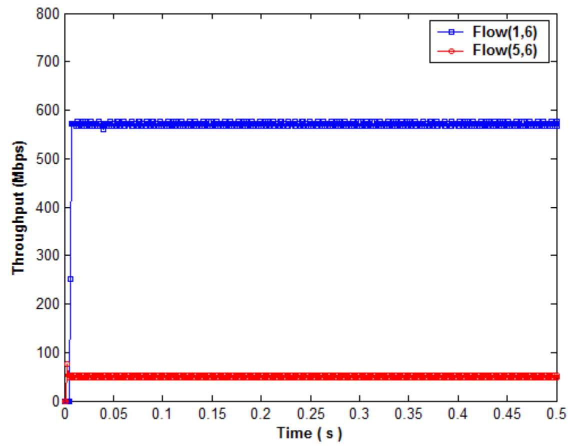


FIGURE 17. Adaptive predictive proportional controller performance.

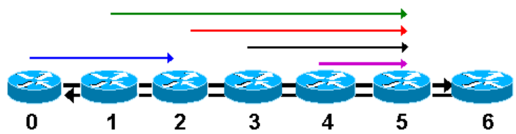


FIGURE 18. Re-claim available bandwidth scenario.

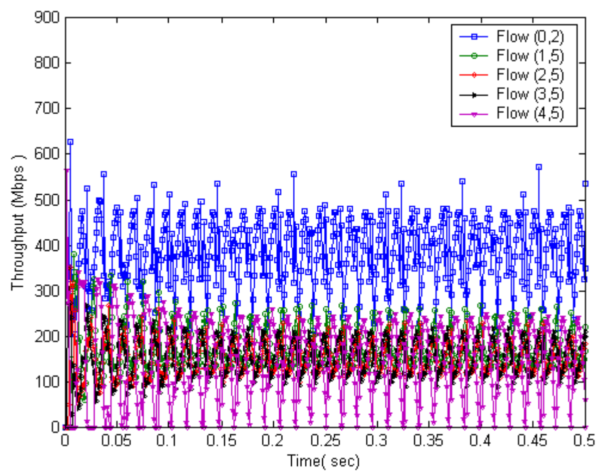


FIGURE 19. RPR-AM.

VI. SIMULATION RESULTS

The Simula RPR simulator is used for evaluating the fairness algorithms [37]. The Simulator structure is described at Figure 16 where the simulation software is written in Java and each class relates to a switch's entity. For example, the fairness algorithm is implemented in the fairness java class as a part of the MAC control.

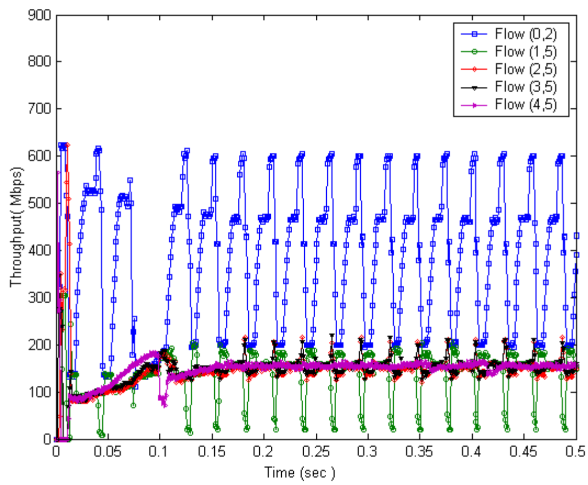


FIGURE 20. RPR-CM.

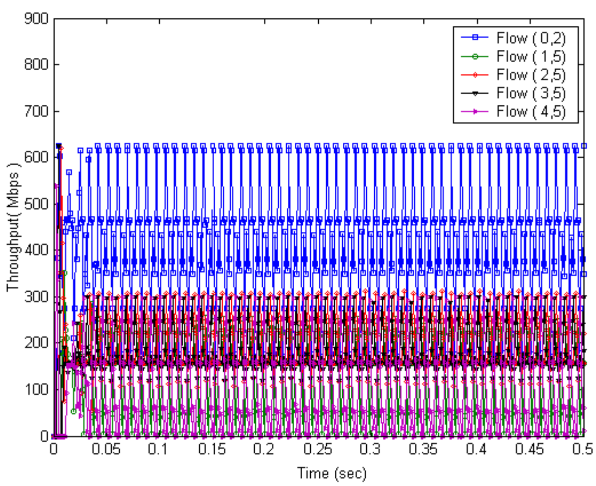


FIGURE 21. Proportional controller performance.

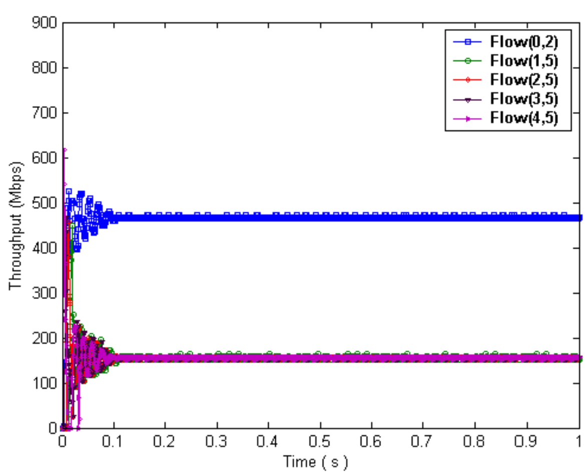


FIGURE 22. Adaptive predictive proportional controller performance.

The proposed system is tested for the large delay scenario illustrated in Figure 9. The proposed controller's performance is shown in Figure 17. Flow(5, 6) gets its rate of 50Mbps and Flow(1, 6) gets the rest of the available resources and sends data at rate of 572Mbps with no oscillations. This proves the advantage of the adaptive predictive proportional controller to dynamically tune the controller gain and eliminate the delay impact.

In the second experiment (Figure 18) [4], [5], links have 622Mbps bandwidth and 1ms delay. All flows have rates of 622Mbps and start at time t = 0. The standard algorithm is evaluated and the performance is shown in Figures 19-20, where the algorithm exhibits permanent oscillation. The proportional controller's performance is shown in Figure 21, where the allocated bandwidth severely socialites due to the large ring delay. In contrast, the proposed system is able to converge to the fair rates with no oscillation as shown in Figure 22. Flows traversing link 4-5 achieve fair rate of 155 Mbps. Moreover, flow (0, 2) claims the leftover resources at link 1-2.

VII. CONCLUSION

The standard RPR algorithm exhibits oscillations resulting in a bandwidth loss. Recently, a proportional controller was designed to allocate bandwidth fairly. The proportional controller works well when the ring delay is small. But, the proportional controller exhibits oscillation if the delay is large. In this paper, the delay impact is investigated and the proportional controller is improved by using the Smith predictor to compensate the dead time and the fuzzy logic to tune the controller gain. The simulation results demonstrate that the proposed adaptive predictive proportional controller achieves its objectives of fairness, stability and high ring utilization.

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