A Fair Medium Access Protocol using Adaptive Flow-rate Control through Cooperative Negotiation among Contending flows in Ad hoc Wireless Network with Directional Antenna

Dola Saha[1], Siuli Roy[1], Somprakash Bandyopadhyay[1], Tetsuro Ueda[2], and Shinsuke Tanaka[2]

[1] Indian Institute of Management Calcutta,
Diamond Harbour Road, Joka, Kolkata – 700104
{dola, siuli, somprakash}@iimcal.ac.in
[2] ATR Adaptive Communication Research Laboratories,
2-2-2 Hikaridai, Seika-cho Soraku-gun, Kyoto 619-0288 Japan
{teueda, shinsuke}@atr.jp

Abstract. Medium Access Control protocols proposed in the context of ad hoc networks primarily aim to control the medium access among contending nodes using some contention resolution schemes. However, these protocols do not necessarily guarantee a fair allocation of wireless medium among contending flows. Our objective in this paper is to adaptively adjust the flow-rates of contending flows, so that each gets fair access to the medium. This adaptive adjustment will also ensure high packet delivery ratio and optimal utilization of wireless medium. We use a deterministic approach to adaptively improve the performance of the suffered flows in the network through mutual negotiation between contending flows. In this paper we have also suggested the use of directional antenna to further reduce the contention between the flows in the wireless medium. The proposed scheme is evaluated on QualNet network simulator to demonstrate that our scheme guarantees fairness to all contending flows.

1 Introduction

Fairness is one of the most important properties of a computer network: when network resources are unable to satisfy demand, they should be divided fairly between the clients of the network [1]. In ad hoc network environment, the wireless medium is a shared resource. Thus, the applications of ad hoc wireless networks raise the need to address a critical challenge: How to manage this shared resource in an efficient manner among the contending flows in the network, so that each flow gets fair chance to access the medium? MAC protocols proposed in the context of ad hoc networks aim to control the medium access among contending nodes using some contention resolution schemes [2]. However, these protocols do not necessarily guarantee a fair allocation of wireless medium among contending flows [3].

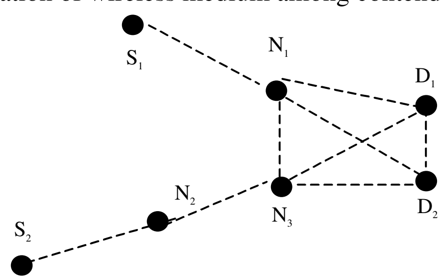

Figure 1: Flow (S_1-D_1) is disturbing Flow (S_2-D_2) because of route coupling. Dotted Lines show omni-directional connectivity among nodes

For example, in Figure 1, both N_3 and D_2 are aware of the communication between N_1-D_1 through exchange of RTS/CTS between N1 and D1. But, node N2, being unaware of this communication, sends an RTS packet for N_3 to reserve the channel. N3 cannot send a CTS packet in reply to that RTS, as it has heard of the communication N_1-D_1. So, N_2 backs off with increasing back-off time as a result of unsuccessful attempt to communicate with N_3. The data transmission between N_1 and D_1 may be over during this time. Since N_2 has chosen a larger back off, so, N_1-D_1 communication has higher chance to reserve the channel again than N_2-N_3 communication. Moreover, the source node S_2 of flow S_2-N_2-N_3-D_2, being unaware of the contention at the intermediate node N_3 on the flow, will continue injecting packets at a predefined rate. This will lead to an unnecessary packet drop at node $N_{2,}$ who is getting less chance to forward packets. As a result of that, the packet delivery ratio of that flow will suffer a lot. Our goal is to resolve the unfairness between contending flows rather than contending nodes, which is radically different from other existing approaches. In the situation shown in figure 1, if the flow-rate of S_1-N_1-D_1 can be optimally reduced, then the flow S_2-N_2-N_3-D_2 will get more chances to access the medium they share, which eventually reduces the congestion and improves the packet delivery ratio of both the flows. This, in turn, will also improve the overall network throughput.

We use a deterministic approach rather than a probabilistic approach to adaptively improve the performance of the suffered flows in the network through mutual negotiation between contending flows. Each node continuously monitors the packet arrival rate of other flows in its vicinity. As soon as a node belonging to, say flow 1, senses that another flow, say flow 2, in its vicinity has a lower flow-rate than its own flow-rate, indicating that flow 2 is not getting fair access, then flow 1 will decide to reduce its flow rate adaptively so that flow 2 can get chance to access the medium and uniform performance can be achieved by each flow. The scheme is based on mutual cooperation between contending flows. In other words, *our objective is to adaptively adjust the flow-rates of contending flows, so that each gets fair access to the medium. This adaptive adjustment will also ensure optimal utilization of wireless medium.*

For example, let us assume that flow 1 is operating at a flow-rate p and flow 2 at flow-rate q where p>q. Flow 1 detects flow-rate of flow 2 and decides to reduce its flow-rate p to accommodate higher flow-rate of flow 2. Flow 2 in turn detects the flow-rate of flow 1 and decides to increase its flow-rate in anticipation that Flow 1 will reduce its flow-rate to accommodate higher flow-rate of flow 2. This control-action will continue till flow-rate of flow 1 becomes less than that of flow 2(p<q). Then, the same process is repeated with reversed control-action i.e. flow 1 will now increase its flow-rate and flow 2 will reduce its flow-rate. Eventually both of them will settle down to a common flow-rate. Figure 2 shows the flow control decision of Flow 1. This simulation is done in QualNet network simulator, as will be detailed in section 5.

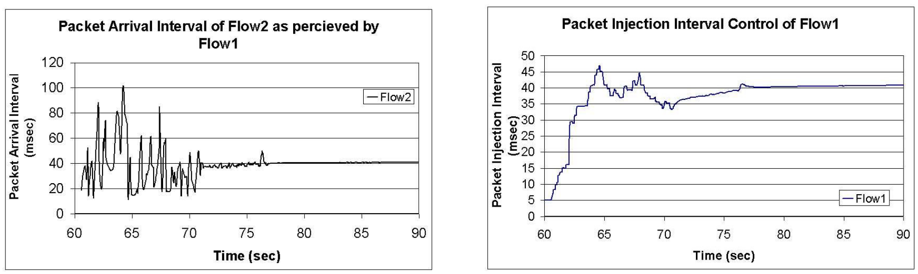

Figure 2. Flow Control by Flow1 on detection of Flow 2 in the vicinity

2 Related Work

A number of fair-scheduling algorithms have been proposed to address the fairness issues in wireless network. An online scheduling policy for providing fair allocation of bandwidth is described in [10]. The policy can detect whether the traffic demand of a flow is consistently less than its fair share, and in such cases distribute the excess bandwidth among other flows. A centralized packet-scheduling algorithm that achieves optimal channel utilization and fairness for each flow is designed in [11]. It uses some kind of predictions about maximum achievable channel utilization, which provide essential guidelines during the design of new fairness-aware scheduling protocols. Much research has been performed on “fair queuing" algorithms for achieving a fair allocation of bandwidth on a shared link. By design, these fair queuing algorithms are centralized, since they are executed on a single node which has access to all information about the flows. It has been observed that fairness achieved by these algorithms may suffer in presence of location-dependent errors [14]. Many approaches for improving fairness in presence of location-dependent errors have been developed [15, 16]. These approaches are centralized and require the base station to coordinate access to the wireless channel to “compensate" hosts whose packets are corrupted due to the presence of location-dependent errors.

In [17], a Distributed Fair Scheduling (DFS) approach is proposed for wireless LAN, by modifying the Distributed Coordination Function (DCF) in IEEE 802.11 standard. This protocol allocates bandwidth in proportion to the weights of the flows sharing the channel. In [18], a general mechanism is presented for translating a given fairness model into a corresponding contention resolution algorithm. Using this, a back-off algorithm is derived for achieving proportional fairness in shared wireless channel.

Our proposal of adaptive flow rate control through cooperative negotiation among contending flows in the context of fairness is radically different from the earlier proposals in the sense that, it deals with the two major issues discussed above: i) Flow-wise fairness and ii) Unproductive congestion due to packet-drop. The key features of our proposed scheme are:

- it is *deterministic,* not probabilistic;
  - ¬ The degradation of performance of each flow found in the vicinity of a flow is detected and measured.
  - ¬ Depending on the measured value of degradation, proper rate control decision is taken by the source node of privileged flows so that the suffered flow may get more access to the medium through reduction in flow rate of privileged flow.
  - ¬ The situation is getting monitored continuously, the information about any degradation in performance of a flow as perceived by each of the other contending flows in its vicinity is propagated back to their respective sources and the flow-rates are regulated accordingly. So, whenever a privileged flow will sense that a flow, which was suffering earlier, has improved substantially then it will automatically increase its flow rate so that *all the flows can be operated uniformly with full utilization of the medium.*
- *Continuous mutual negotiation and collaboration* between flows helps to achieve fairness in the truest sense of the term.
- Since the contention-information is back-propagated at the source node who will regulate the flow, the packet delivery ratio of the entire flow improves substantially, resulting in less congestion in the medium due to packets that are going to be lost anyway.
- Use of directional antenna will improve the individual throughput and fair medium access further, when the traffic density is high.

3 Implementation of flow control scheme

In order to illustrate our scheme, let us refer back to the example shown in figure 1. There are basically three parts in this scheme: i) Contention detection and measurement at each node of a flow, ii) Back propagation of the knowledge of contention to source node, and iii) Adaptive regulation of flow rate at source using the knowledge of contention. Part i) and ii) i.e., contention detection, measurement and back propagation of the knowledge of contention to source node are implemented with the help of traditional RTS and CTS exchange scheme, with a minor change in the format of existing RTS, CTS packets. From the RTS transmitted by N_1 and CTS transmitted by D_1, both N_3 and D_2 detect the presence of flow S_1-D_1 in their neighborhood. This remains unknown to the source S_2, which is far away from the flow S_1-D_1. So, with the help of CTS packet, D_2 transmits the knowledge to N_3. When N_3 has to send a CTS packet to N_2, it combines its own detection of contention with the received knowledge from D_2 and considers the maximum contention in the flow and transmits it with the CTS packet. N_2 lastly sends this information back to S_2 through a CTS packet. The source node, S_2, then considers the contention in the medium of the flow and adaptively takes a decision of adjusting its packet injection rate. Hence, with no extra packet, the information of contention in the medium as perceived by a flow is transmitted to the source node, which adaptively controls the packet injection rate.

To implement the above scheme, we assumed that each flow in the network is identified by a unique communication-id and we have introduced a special type of RTS and CTS packets. An extra field is attached to the original format of RTS packet, which denotes the *communication-id* of the flow for which the current RTS is being sent. Similarly, CTS packet has got two extra fields now. The first field is exactly similar to the extra-field of RTS packet, and is required to convey the *communication-id* of the flow for which the current CTS is being sent. The second field contains *the packet-arrival-interval of the most suffered flow* among the flows contending for the medium in the neighborhood of the flow for which current CTS is being sent. So, in presence of more than one contending flow in the neighborhood of a flow, back-propagation of the maximum packet arrival interval of the flows is done. This indicates that the privileged flow can adaptively adjust itself repeatedly, so that the suffered flows can get maximum chance to the medium and their packet arrival interval at the region of contention is improved. A control theoretic approach is adopted in this context to adjust the flow-rate at the source node according to the feedback of contention acquired from the affected nodes on a flow. The adaptive flow-rate control scheme, suggested in this paper, is based on conventional Proportional-Integral-Derivative (PID) Control mechanism. The control mechanism will be explained elaborately in the subsequent section.

3.1 Use of Directional Antenna

So far, we have considered omni-directional neighbors using omni-directional antenna. But, to modify the scheme using directional antenna, we have to consider a directional MAC and its directional neighbors. We have used a receiver-oriented rotational-sector based directional MAC protocol [19, 20], and a network-aware, directional routing protocol [8] to implement the proposed scheme. Here, each node is aware of its directional neighbors and this information is recorded in its Angle-Signal Table (AST). RTS and CTS packets are omni-directional, whereas data and acknowledgement packets are directional. Use of directional antenna in the context of ad hoc wireless networks can largely reduce

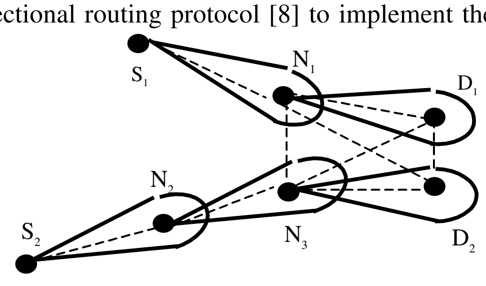

Figure 3: Using directional antenna flow S_2-D_2 can coexist with flow S_1-D_1.

radio interference, thereby improving the utilization of wireless medium [8,19,20]. This property of directional antenna is utilized to improve the efficiency of our protocol. This is shown in Figure 3, where S_1-D_1 and S_2-D_2 flows of figure 1, can co-exist without disturbing each other, using directional antenna, which would not have been possible using omni-directional antenna (Figure 1). So, with directional antenna, it is not necessary to control the packet injection rate of S_2-D_2 even in presence of S_1-D_1. Using directional antenna, the detection of contention in medium is also directional in the sense, that even if there are multiple contending flows in the vicinity, only the contention from communication in the direction of flow is considered. MAC detects the directional contention in medium consulting its AST. Since directional antenna improves SDMA (Space Division Multiple Access) efficiency, it enhances the packet injection rate of suffered flow with minimally disturbing other flows in the medium and hence leads to increased throughput of all the flows in the network. At the same time, chance of multiple flows getting coupled is reduced, leading to improved network performance.

3.2 Contention Detection and Measurement of flow-rates by other flows

When a flow is initiated, packets are sent through multiple hops to the destination and at MAC layer, the packet delivery at each intermediate node is ensured by RTS/CTS/DATA/ACK exchange. These RTS and CTS packets are utilized to detect and back-propagate the flow-related information on which packet injection rate control decision is taken at source nodes. In the context of directional transmission, two flows will interfere with each other, only if the direction of flows overlaps. In figure 3, although N_1 and N_3 are within the omni-directional transmission range of each other, the flow from N_1 to D_1 will not interfere with the flow from N_3 to D_2 during directional data communication. In order to detect the contention faced by a flow using directional antenna, it is imperative that each node in that flow should sense whether its directional transmission zone in the direction of flow contains any node handling any other flow. If it does, it implies that a contention is expected to occur at that node during directional data communication. So it is necessary to control the flow-rate of the flow that has detected the contention to protect the flow rate of the other contending flow.

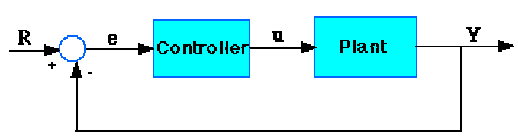

Figure 4. Basic Feedback Controller

3.3 Flow-Control Mechanism

A feedback controller is designed to generate an output u that causes some corrective effort to be applied to a process so as to drive a measurable process variable Y towards a desired value R known as the set-point (Figure 4). The controller uses an actuator to affect the process and a sensor to measure the results. Virtually all feedback controllers determine their output by observing the error e between the set-point (R) and a measurement of the process variable (Y). Errors occur when a disturbance or a load on the process changes the process variable. The controller's mission is to eliminate the error automatically [21]. Earlier feedback control devices implicitly or explicitly used the idea of proportional, integral and derivative (PID) actions in their control structure. The general form of the PID control algorithm is:

$$u = K_P e + K_I \int e\,dt + K_D \frac{de}{dt}$$

The variable (e) represents the tracking error, the difference between the desired input value (R) and the actual output (Y). This error signal (e) will be sent to the PID controller, and the controller computes both the derivative and the integral of this error signal. The signal (u) just past the controller is now equal to the proportional gain (K_p) times the magnitude of the error plus the integral gain (K_i) times the integral of the error plus the derivative gain (K_d) times the derivative of the error. Proportional gain (K_p) will have the effect of reducing the rise time and will reduce, but never eliminate, the steady-state error. An integral gain (K_i) will have the effect of eliminating the steady-state error, but it may make the transient response worse. A derivative gain (K_d) will have the effect of increasing the stability of the system, reducing the overshoot, and improving the transient response. The above equation is a continuous representation of the controller and it must be converted to a discrete representation. There are several methods for doing this, the simplest being to use first-order finite differences. So the discrete representation of the equation is:

$$m(n) = k_p * e(n) + k_i * \sum_{k=n-w}^{n} e(k) * \Delta t + k_d * \frac{[e(n) - e(n-1)]}{\Delta t}$$

Thus it will be necessary to find the current error, the sum of the errors, and the recent change in error in order to calculate desired output.

In order to provide fairness to all the contending flows in the network, each flow, on detecting contention in the medium, is adaptively changing its flow-rate u at its source using PID control strategy. According to our control strategy, a flow will detect error in other flows in terms of reduction in flow-rate and accordingly adjust its own flow-rate to allow an improved flow-rate for the deprived flows. This kind of requirement is absent in conventional PID control and, therefore, our approach is a derivative of conventional PID control, which we will illustrate subsequently. In subsequent discussion, we have considered Packet Injection Interval (PII) at source node as a measure to controlling flow-rate. The Packet Injection Rate (PIR) of flow (in packets/sec) at a source node is computed at: PIR = 1/ PII. In order to take any control decision, first we have to compute the *error* term in PID controller.

Error e at any flow F_i at its source node S = (PII^{Fi} - $PAI(S)^{Fi}$),

where PII^{Fi} is the Packet Injection Interval of the flow F_i and $PAI(S)^{Fi}$ is the maximum packet-arrival-interval of other contending flows in the neighborhood of F_i , detected by nodes in F_i and propagated back to the source node S of F_i.

Once the error e(n) and the time interval between two successive error •t is calculated, the PII of F_i (S) is calculated as

$$\mathrm{PII}(new) = \mathrm{PII}(old) - [k_p * e(n) + k_i * \sum_{k=n-w}^{n} e(k) * \Delta t + k_d * \frac{[e(n) - e(n-1)]}{\Delta t}]$$

The value of k_p, k_i and k_d needs to be tuned for optimal performance. The performance of the controller is shown in the next section. The value of kp, ki, kd and w has been chosen to 0.2, 0.08, 0.08 and 5 respectively in the simulation.

4 Performance Evaluation

We have evaluated the performance of our proposed scheme on QualNet simulator [9]. We have considered IEEE 802.11 based directional MAC [19] and implemented the proposed protocol with directional antenna only. We have simulated ESPAR antenna [20] in the form of a *quasi-switched beam antenna*, which is steered discretely at an angle of 30 degree, covering a span of 360 degree. We have done the necessary changes in QualNet simulator to implement the proposed protocol. The set of parameters used is listed in Table I.

Table I. Parameters used in Simulation

Parameters	**Value**
Transmission Power	15 dBm
Receiving Threshold	-81.0 dBm
Sensing Threshold	-91.0 dBm
Data Rate	2Mbps
Packet Size	512 bytes
Simulation Time	5 minutes

4.1 Performance in Static Scenario

We have used static routes in order to avoid the effects of routing protocols to clearly illustrate the gain obtained in our proposed protocol. When two flows are coupled with each other and contend to access the shared medium, unfair medium access may result in variable performance of the coupled flows. In this situation, our proposed protocol of packet injection rate control is required for fair medium access. So, in all the static topology, instead of random selection of source destination pair, we have chosen the source destination pairs in such a way, that they are coupled with each other to artificially create a situation so that we can demonstrate the effect of Packet Injection Interval Control. We have evaluated the performance in string topology and under three settings of grid topology. We have compared our proposed protocol, captioned as "Fair Media Access" with the scheme, where no fairness scheme is applied, captioned as "Unfair Media Access".

4.1.1 String Topology

Our initial string topology, with 'Flow1" and 'Flow2" using directional antenna is shown in Figure 5(a). Without any fairness mechanism, the throughput (Figure 5(b)) of Flow1 is even less than one-third of the throughput of Flow2. This is the effect of unfair medium access. With the introduction of fair medium access, the throughput of the two flows nearly becomes equal and the throughput of each flow is even more than that of Flow2 without any fairness scheme. So, the average throughput doubles in our proposed protocol than it was without any fairness scheme. Without any fairness scheme, Flow2 gets most chance to the medium and Flow1 suffers. Also, the contention of the two flows is not in a single node, rather all the links of the two flows are tightly coupled with each other. Due to this strong coupling, even the best-performed flow has lesser throughput without any fairness scheme than that of each flow after introduction of packet injection rate control.

4.1.2 Grid Topology

We have evaluated the packet injection rate control algorithm for fair media access in the following grid topology setting: six flows crossing each other along three horizontal rows and three vertical columns of a grid as shown in Figure 6(a). The transmission zone of each flow is similar to that shown with fig. 5(a). All the flows selected are 4 hop. Flows are captioned as 'Flow1" to 'Flow6". Our proposed fairness scheme yields improved uniform throughput, as evident from Figure 6(b).

4.2 Performance under Mobility

We have evaluated the proposed protocol under average mobility of 0-10mps with 6 flows in 100 nodes in a bounded region of 1500×1500 sq. m. area. Mobility of nodes indulges each flow to operate at various scenarios at different point of time. The scenarios may be 1) operating alone, when there is no requirement of fair media access, 2) operating just beside another flow and contend with that flow to get access to the shared media, where flow-rate controlling is necessary, and 3) operating just beside multiple flows and contend with those flows to get access to the shared media, where drastic flow-rate controlling is done to give fairness to each contending flow. In each scenario, the throughput of any flow is widely different from other scenarios. Fair media access is ensured only between the contending flows during the contention. So, we do not show throughput of the flows under mobility. Packet delivery ratio and average end-to-end delay of the 6 flows is shown in Figure 7(a) and 7(b) respectively. With the implementation of our proposed protocol, packet delivery ratio of each flow increases two to three times more than its value without any fairness scheme. As shown, end-to-end delay of each flow with flow control is nearly one-third to one-fifth than that without flow control. Also, the variation of end-to-end delay among the contending flows is diminished after the implementation of flow-rate control scheme. All these indicate that the flow-rate control scheme gives a fair access of the shared medium to all the contending flows.

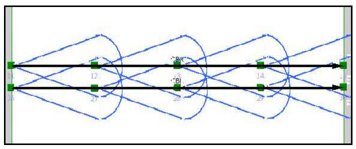

Figure 5(a). String Topology

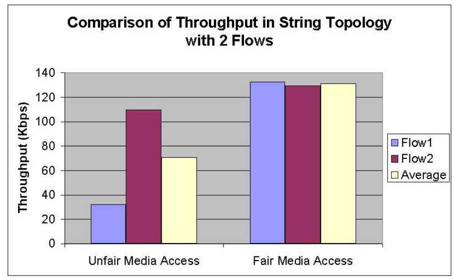

Figure 5(b). Comparison of Throughput

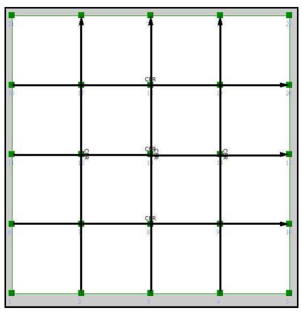

Figure 6(a). Grid Topology

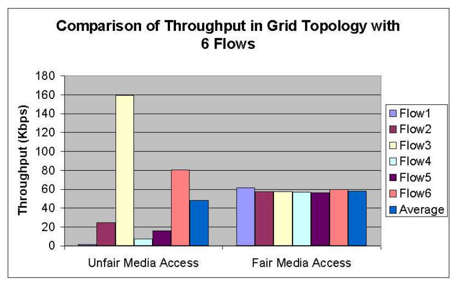

Figure 6(b). Comparison of Throughput

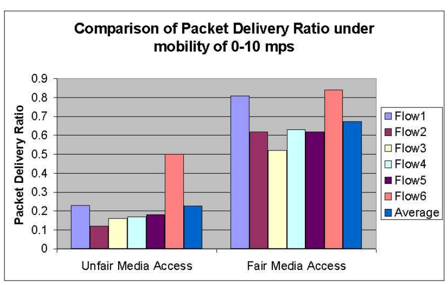

Figure 7(a). Comparison of Packet Delivery Ratio under mobility

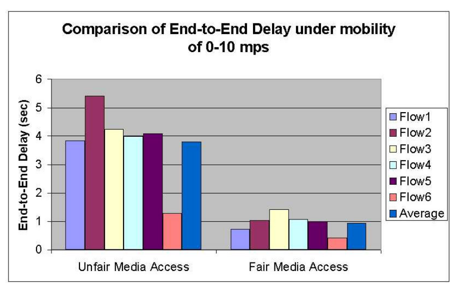

Figure 7(b). Comparison of End-to-End Delay under mobility

5 Conclusion

In this paper, we adaptively adjust the flow-rates of the contending flows, so that each flow gets fair access to the medium. Flow rates are adjusted in anticipation that other contending flows will also adjust their flow-rates accordingly. Thus, continuous mutual negotiation and collaboration between flows helps to achieve fairness in the truest sense of the term. We have tuned the K_p, K_i and K_d values in different scenarios, and the values have great impact on improving the fairness scheme. Currently, we are trying to adjust the K_p, K_i and K_d values dynamically according to the application scenarios.

Acknowledgements

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