FLAG: A Fuzzy Local FairRate Generator for Resilient Packet Ring

Wen-Shiang Tang, Chung-Ju Chang, Po-Long Tien, and Wei-Chien Wang

***Abstract*—A local fairRate generator using fuzzy logic and the moving average technique is proposed for the resilient packet ring (RPR). The fuzzy local fairRate generator (FLAG) is designed to achieve both low convergence time and high system throughput, besides fairness. It contains three functional blocks, an adaptive fairRate calculator (AFC) to properly preproduce a local fairRate by the moving average technique, a fuzzy congestion detector (FCD) to intelligently estimate the congestion degree of the station, and a fuzzy fairRate generator (FFG) to precisely generate the local fairRate. Simulation results show that only the FLAG can stabilize all flows in parking lot scenarios with different finite traffic demands, compared with the conventional aggressive mode (AM) and distributed bandwidth allocation (DBA) fairness algorithms. Also, it attains a convergence time lower than the AM fairness algorithm by at least 7 times and the DBA fairness algorithm by at least 2 times in parking lot scenarios with greedy traffic demands.**

***Index Terms*—Resilient packet ring (RPR); Congestion control; Fairness algorithm; RIAS; Fuzzy logic.**

I. INTRODUCTION

The resilient packet ring (RPR) is a ring-based network for high-speed metropolitan area networks (MANs) [1]. It is a packet transport layer that can provide guaranteed quality-of-service parameters and support service monitoring including performance management and fault management [1,2]. In addition, the RPR has some notable properties such as spatial reuse, fair bandwidth allocation, and fast network failure recovery to eliminate the deficiencies of conventional high-speed Ethernet and a synchronous optical network (SONET) [3,4]. Therefore, the RPR can not only achieve high bandwidth utilization and fast network failure recovery but can also satisfy the requirements of MANs, such as reliability, flexibility, scalability, and large capacity [3–5]. The RPR is a superior candidate for MANs.

The spatial reuse allows a frame to be removed from the ring at its destination so that the bandwidth on the next links can be reused at the same time. Also, the fair bandwidth allocation avoids stations at upstream transmitting too many low-priority frames to cause stations at downstream system congestion. The RPR needs congestion control to enhance the fair bandwidth division in the congestion domain, which is defined in IEEE 802.17 [3,6]. The congestion control implemented in each station should periodically generate an advertised fairRate to advertise its upstream station for regulating the added fairness-eligible (FE) traffic flow defined in IEEE 802.17 [3,6]. The advertised fairRate should be determined referring to the local fairRate, the received fairRate, and the congestion degree of the station. The local fairRate is generated by a fairness algorithm, and the received fairRate is the advertised fairRate from the downstream station.

Two key factors affect performance of the fair bandwidth allocation: congestion detection and the fairness algorithm. If the congestion detection is too rough, it will lower the network's throughput or raise the frame loss. The fairness algorithm should consider the most important performance issues of FE traffic flows: stability, fairness, convergence time, and throughput loss caused by the FE traffic flow oscillation. The stability would avoid the oscillation of regulated FE traffic flows, which would cause the throughput loss. If a fairness algorithm referees a ring ingress aggregated with spatial reuse (RIAS) fairness, it has been proved that the algorithm will achieve high system utilization [7]. This is because the RIAS has two key properties. The first property is that an ingress-aggregated (IA) flow fairly shares the bandwidth on each link, relating to other IA flows on the same link, where an IA flow is the aggregate of all flows originating from a given ingress station. The second property is the maximal spatial reuse subjected to the first property. Thus, the bandwidth can be reclaimed by IA flows when it is unused. In summary, the RIAS is a max-min fairness with traffic granularity of the IA flow.

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The convergence time is the time interval between the start of the congestion and the instant that the amount of arriving specified traffic flow approaches the ideal fairRate that meets the the RIAS fairness. Therefore, a fairness algorithm should achieve not only high throughput based on the RIAS fairness but also low convergence time and flow oscillation.

The aggressive mode (AM) fairness algorithm has been proposed in IEEE 802.17. It would suffer from severe oscillations and bandwidth utilization degradation [3,6–8]. This is because the AM issues an unlimited fairRate, called the FullRate, as its advertised fairRate when the station is released from congestion. Several fairness algorithms were proposed to solve this problem and some of them were designed based on the RIAS fairness [7–14]. Gambiroza *et al.* proposed a distributed virtual-time scheduling in rings (DVSR) [7]. Unfortunately, it requires presource information and has a high computational complexity $O(N \log N)$, where N is the number of stations in the ring. Alharbi and Ansari proposed a distributed bandwidth allocation (DBA) fairness algorithm, which has almost the same performance as DVSR but has a low computational complexity $O(1)$ [8,10]. However, whenever the effect of propagation delay is severe, the DBA would not be a stable local fairRate algorithm. It is because the local fairRate generated by the DBA is related only with the amount of the arriving transit FE traffic flows measured during a short frame time. This short-term amount is easily influenced by the effect of the propagation delay, which starts from a station sending its advertised fairRate and ends the corresponding transit traffic flows arriving at the station. If the propagation delay is large, the short-term arriving transit FE traffic flows would be largely varied, making the generation of the local fairRate unstable (incorrect).

Such an uncertain, complicated, and nonlinear bandwidth fairness control problem is not easy to formulate and find an optimal solution (allocation) to. Fortunately, fuzzy logic (inference) systems have been widely applied to nonlinear, time-varying, and well-defined traffic control systems [15,16]. The fuzzy logic system is an improved and intelligent design, which utilizes the mathematical formulation of classical control and mimics the expert knowledge [15], for traffic control systems. It can provide effective solutions with small computational complexity $O(N)$, where N is the number of the fuzzy inference rules [15]. Also, the fuzzy logic system can be implemented in a chip; this will greatly speed up the system computational time.

Therefore, in this paper, we propose an effective local fairRate generator based on fuzzy logic theory [15] and the moving average technique [17]. The effective local fairRate generator, called the fuzzy local fairRate generator (FLAG), can meet the RIAS fairness and reflect timely the congestion status of the station. The FLAG is sophisticatedly configured into three functional blocks: an adaptive fairRate calculator (AFC), a fuzzy congestion detector (FCD), and a fuzzy fairRate generator (FFG). It first preproduces a local fairRate to meet the RIAS fairness and diminish the effect of propagation delay by the AFC. Also, the FLAG evaluates the congestion degree of a station, denoting the forwarding capacity of added FE traffic flows at the station and buffering capacity of the secondary tranist queue (STQ) by the FCD. Finally, the FLAG generates a precise local fairRate by the FFG. The FFG finely adjusts the preproduced local fairRate from the AFC according to the congestion degree of the station from the FCD, using fuzzy logic based on the intelligence in domain knowledge. Simulation results show that the FLAG has better performance than the AM and DBA in various scenarios in the aspects of lower convergence time, more fairness, and higher throughput. Take a small parking lot scenario with a short propagation delay for instance. The FLAG improves the convergence time of traffic flows by more than 7 times over the AM and by 2 times over the DBA.

The rest of this paper is organized as follows. Section II introduces the RPR system model. Section III describes the proposed FLAG. Section IV shows simulation results and discussions. Finally, concluding remarks are given in Section V.

II. RPR SYSTEM MODEL

Assume that a RPR with N stations is constructed by two unidirectional, counterrotating ringlets, named ringlet-0 and ringlet-1. Each station has two pairs of input and output ports to communicate with neighbor stations. Station X (Y) is said to be an upstream (downstream) node of station Y (X) on ringlet-0 or ringlet-1 if the station Y (X) traffic becomes the received traffic of station X (Y) on the referenced ringlet. There are three classes of service for RPR. ClassA is used for real-time services, and it has subclassA0 for reserved bandwidth and subclassA1 for reclaimable bandwidth. ClassB is targeted for near real-time services, and it also has two subclasses: classB-CIR (committed information rate), which requires the bounded delay and guaranteed bandwidth, and classB-EIR (excess information rate), which does not guarantee bandwidth or delay bound. ClassC is intended for best-effort services and has the lowest priority. Each station only reserves bandwidth for subclassA0, and the remaining bandwidth is provided for other traffic classes according to the order of subclassA1, classB-CIR, classB-EIR, and classC. The latter two low-priority traffics are called the FE traffic and are controlled by a fairness algorithm [1–6].

Figure 1 shows the station structure for ringlet-0

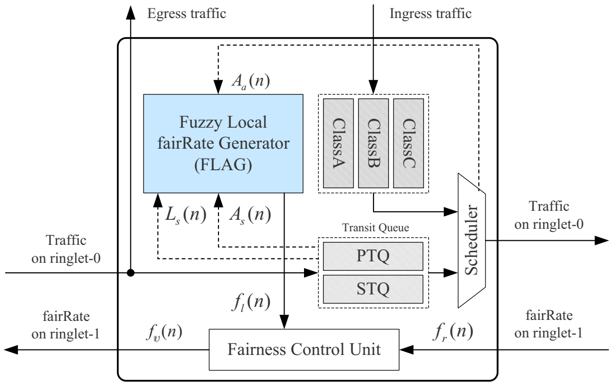


Fig. 1. (Color online) RPR station structure.

transmisson, which contains an ingress queue with classA, classB, and classC queues, a transit queue with a primary transit queue (PTQ) and a STQ, a scheduler, the FLAG, and a fairness control unit. The classX queue (X=A, B, or C) stores the added classX traffic at the station. The PTQ (STQ) stores the transiting classA and classB-CIR (classB-EIR and classC) frames. The scheduler decides the transmitting order. If the STQ occupancy is less than the *stqHighthreshold* defined in IEEE 802.17 [1], the order is PTQ, classA, classB, classC, and STQ; otherwise, it is PTQ, classA, classB, STQ, and classC. The FLAG generates a local fairRate at every time nT, denoted by $f_l(n)$, where n is a positive integer and T is the duration of an agingInterval. Notice that f_l is also generated per agingInterval in the DBA but is generated only when the station is in congestion in the AM. The fairness control unit usually refers to both $f_l(n)$ and the received fairRate from the downstream node, denoted by $f_r(n)$, to determine an advertised fairRate, denoted by $f_v(n)$, and then sends $f_v(n)$ to upstream stations to regulate traffic flows, at every agingInterval time nT.

The advertised fairRates generated by the fairness control unit are described as follows. The f_v would be set to f_l if f_r is smaller than f_l and larger than the bandwidth rate of the transit FE traffic flows that will pass through the originally congested station. Otherwise, it is set to be $\min(f_l,f_r)$. Here we also describe the advertised fairRate generated by the AM below. When the station is congestion free, the f_v is set to be the FullRate if the f_r is larger than the bandwidth rate of the transit FE traffic flows that will pass through the originally congested station and to be f_r otherwise. The FullRate is a specially advertised fairRate to indicate that the station does not need to limit its added FE traffic flow. When the station is in congestion, f_v is set to be f_l if f_r is the FullRate and to be $\min(f_l,f_r)$ otherwise. Note that congestion occurs at a station for the AM if the STQ occupancy of the station is larger than the *stqLowthreshold*, defined in IEEE 802.17 [1]. Also, the originally congested station is known to the observation station since the message of the advertised fairRate contains a field to record it [1]; f_l is the FE traffic flow rate added to the network.

III. FUZZY LOCAL FAIRRATE GENERATOR

The proposed FLAG, shown in Fig. 2, is composed of an AFC, a FCD, and a FFG. During the nth agingInterval, which is from time $(n-1)T$ to time nT, the FLAG determines $f_l(n)$ by referring to the FE traffic flows arriving at the STQ, denoted as $A_s(n)$; the added FE traffic flow to the network, denoted as $A_a(n)$; and the STQ occupancy, denoted as $L_s(n)$. The AFC pregenerates a local fairRate, called p-fairRate and denoted by $f_p(n)$, which satisfies the RIAS fairness. Its design imitates the DBA's generation of the local fairRate, but it would overcome the unstable (incorrect) local fairRate generation by the DBA when the propagation delay is significant. Instead of using the short-term arriving transit FE traffic flows, it calculates a proper average of the arriving transit FE traffic flows by the moving average technique to mitigate the effect of the propagation delay. The FCD appraises the congestion status of the station using fuzzy logic. Its design can softly detect the congestion degree of the station in each agingInterval n, denoted by $D_c(n)$, considering not only the STQ occupancy but also the amount of the arriving transit FE traffic flows at the queue. The latter term denotes the change rate of the STQ occupancy that would play an important role in the congestion detection. Finally, the FFG generates a precise local fairRate by fine-tuning the p-fairRate from the AFC, referring to the congestion degree from FCD, and further using domain knowledge designed by fuzzy logic. The FLAG would avoid serious regulating of FE traffic flows to decrease the throughput or excessive relaxing of the traffic flows to increase the frame losses.

A. Adaptive FairRate Calculator

The AFC adopts the moving average technique [17] on the short-term arriving FE traffic flows, trying to mitigate the effect of propagation delay on the generation of the local fairRate by the DBA [8]. During the nth agingInterval, the AFC first takes the moving av-

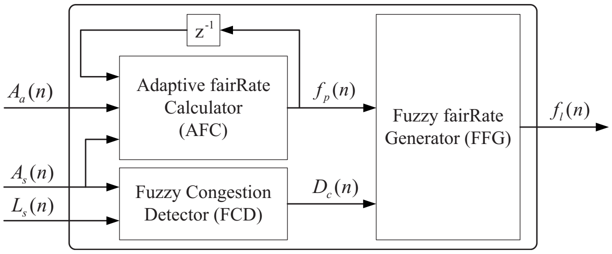


Fig. 2. Functional blocks of the FLAG.

erage of arriving transit FE traffic flows to the STQ, $A_s(n)$. The average is denoted by $\widetilde{A}_s(n)$ and given by

$$\widetilde{A_s}(n) = \Sigma_{i=n-k+1}^{n} A_s(i)/k, \tag{1}$$

where k is the size of the observation window and the sum of two kinds of the data frame trip time: one is the time from the furthest source to this observation station, and the other is the time from this station to the originally congested station. This is because the FE traffic flow of a station in this interval would be regulated by an advertised fairRate that is sent out from one of the stations in the interval. The $\widetilde{A}_s(n)$ will not vary too much and become more stable.

Then the AFC computes the effective number of IA flows during the nth agingInterval, denoted by $M(n)$, which is obtained by

$$M(n) = \frac{\widetilde{A_s}(n) + A_a(n)}{f_p(n-1)}. \tag{2}$$

The AFC fairly allocates the remaining bandwidth to these effective IA flows, which would be $1/M(n)\{C-[A_s(n)+A_a(n)]\}$. Finally, the AFC calculates the $f_p(n)$ by adding up the previous p-fairRate, $f_p(n-1)$, and the fairly shared bandwidth. The $f_p(n)$ is given by

$$f_p(n) = \mathrm{mim}\left(C, f_p(n-1) + \frac{1}{M(n)}\{C - [A_s(n) + A_a(n)]\}\right), \tag{3}$$

where C is the unreserved bandwidth for FE traffic flows per agingInterval used to denote the upper bound of the local fairRate.

B. Fuzzy Congestion Detector

The FCD refers not only to the occupancy of the STQ, $L_s(n)$, as defined in the IEEE 802.17 [1], but also to the arriving FE traffic flows to the STQ, $A_s(n)$, to determine the congestion degree, $D_c(n)$. The $A_s(n)$ can be viewed as the change rate of the STQ, which is also an important variable in the detection of congestion degree. We define the term set for $L_s(n)$ as $T[L_s(n)] = \{\text{Short } (S), \text{Long } (L)\}$, for $A_s(n)$ as $T[A_s(n)] = \{\text{Low } (L), \text{Medium } (M), \text{High } (H)\}$, and for $D_c(n)$ as $T[D_c(n)] = \{\text{Very Low } (VL), \text{ Low } (L), \text{ Medium } (M), \text{ High } (H), \text{Very High } (VH)\}$.

Here, the triangular function $f(x;x_0,a_0,a_1)$ and the trapezoidal function $g(x;x_0,x_1,a_0,a_1)$ are used to define the membership functions for the terms in the term set. These two functions are given by

$$f(x;x_0,a_0,a_1) = \begin{cases} \dfrac{x-x_0}{a_0}+1, & \text{for } x_0-a_0 < x \leqslant x_0, \\ \dfrac{x_0-x}{a_1}+1, & \text{for } x_0 < x < x_0+a_1, \\ 0, & \text{otherwise}, \end{cases} \tag{4}$$

$$g(x;x_0,x_1,a_0,a_1) = \begin{cases} \dfrac{x-x_0}{a_0}+1, & \text{for } x_0-a_0 < x \leqslant x_0, \\ 1, & \text{for } x_0 < x \leqslant x_1, \\ \dfrac{x_1-x}{a_1}+1, & \text{for } x_1 < x < x_1+a_1, \\ 0, & \text{otherwise}, \end{cases} \tag{5}$$

where x_0 in $f(\cdot)$ is the center of the triangular function, $x_0(x_1)$ in $g(\cdot)$ is the left (right) edge of the trapezoidal function, and $a_0(a_1)$ is the left (right) width of the triangular or the trapezoidal function.

The corresponding membership functions of S and L in $T[L_s(n)]$ are denoted by $\mu_S[L_s(n)]=g[L_s(n);0,0.125Q,0,0.25Q]$ and $\mu_L[L_s(n)]=g[L_s(n);0.35Q,Q,0.25Q,0]$, where Q is the size of the STQ. As defined in the IEEE 802.17 [1] standard, we take 0.125 of the STQ size as the *stqLowthreshold* to judge the light congestion degree and 0.25 of the STQ size as the *stqHighthreshold* to judge the heavy congestion degree. The corresponding membership functions of L, M, and H in $T[A_s(n)]$ are denoted by $\mu_L[A_s(n)]=g[L_s(n);0,0.125C,0,0.375C]$, $\mu_M[A_s(n)]=f[A_s(n);0.5C,0.25C,0.25C]$, and $\mu_H[A_s(n)]=g[A_s(n);0.875C,C,0.375C,0]$, respectively. Here, we note that the medium value for $A_s(n)$ is 0.5 and the low and high values for $A_s(n)$ are 0.125 and 0.875, respectively, which are symmetrical to 0.5. Thus we have the center, edge, and width values for the membership functions of $A_s(n)$.

For the reason of simplicity in the computation of defuzzification, the corresponding membership functions of VL, L, M, H, and VH in $T[D_c(n)]$ are defined as singleton functions given by $\mu_{VL}[D_c(n)]=f[D_c(n);0,0,0]$, $\mu_L[D_c(n)]=f[D_c(n);0.25,0,0]$, $\mu_M[D_c(n)]=f[D_c(n);0.5,0,0]$, $\mu_H[D_c(n)]=f[D_c(n);0.75,0,0]$, and $\mu_{VH}[D_c(n)]=f[D_c(n);1,0,0]$, respectively. Since these five terms in $T[D_c(n)]$ from VL to VH demonstrate a linear congestion increment for $D_c(n)$, the effective values for membership functions of VL, L, M, H, and VH are assumed to be uniformly distributed over [0, 1].

There are six fuzzy rules for FCD. As shown in Table I, the order of significance of the input linguistic

TABLE I
THE RULE BASE OF THE FCD

Rule	$L_s(n)$	$A_s(n)$	$D_c(n)$
1	*S*	*L*	*VL*
2	*S*	*M*	*VL*
3	*S*	*H*	*L*
4	*L*	*L*	*M*
5	*L*	*M*	*H*
6	*L*	*H*	*VH*

variables is $L_s(n)$ then $A_s(n)$. The station with high occupancy of the STQ would be at a high congestion degree, and it would be at a higher (medium) congestion degree if the arriving FE traffic flows to the STQ were also high (low).

The fuzzy congestion detector adopts the max-min inference method for the inference engine because it is suitable for real-time operation [18]. To explain the max-min inference method, we take rule 1 and rule 2, which have the same control action "$D_c(n)$ is *VL*," as an example. Applying the min operator, we obtain the membership function values of the control action "$D_c(n)$ is *VL*" of rule 1 and rule 2, denoted by $m_1(n)$ and $m_2(n)$, respectively, by

$$m_1(n) = \min\{\mu_S[L_s(n)], \mu_L[A_s(n)]\}, \quad (6)$$

$$m_2(n) = \min\{\mu_S[L_s(n)], \mu_M[A_s(n)]\}. \quad (7)$$

Subsequently, applying the max operator yields the overall membership function value of the control action "$D_c(n)$ is *VL*," denoted by $w_{VL}(n)$, by

$$w_{VL}(n) = \max\{m_1(n), m_2(n)\}. \quad (8)$$

The fuzzy inference results of the output indication *L*, *M*, *H*, and *VH*, denoted by $w_L(n)$, $w_M(n)$, $w_H(n)$, and $w_{VH}(n)$, respectively, can be obtained in the same way. Finally, the fuzzy inference results are to be defuzzified to become usable values. The defuzzification method adopted is the center of area defuzzification method [15,18], and a crisp value of the congestion degree $D_c(n)$, denoted by z_0, can obtained by

$$D_c(n) = z_0 = \frac{0.0 \cdot w_{VL}(n) + 0.25 \cdot w_L(n) + 0.5 \cdot w_M(n) + 0.75 \cdot w_H(n) + 1.0 \cdot w_{VH}(n)}{w_{VL}(n) + w_L(n) + w_M(n) + w_H(n) + w_{VH}(n)}. \quad (9)$$

C. Fuzzy FairRate Generator

The FFG refers to the *p*-fairRate, $f_p(n)$, and the congestion degree, $D_c(n)$, as the input variables to generate a proper and robust local fairRate, $f_l(n)$. Since the fairness control unit shown in Fig. 1 finally determines the advertised fairRate by the simple logic of referring to $f_r(n)$ and $f_l(n)$, which has been given before in Section II, the FFG does not consider the received fairRate, $f_r(n)$, as the input variable. This local fairRate $f_l(n)$ affects the fairness performance and the bandwidth utilization.

Define the term set with 6 terms for $f_p(n)$ as $T[f_p(n)]$ = {Extremely Low (*EL*), Pretty Low (*PL*), Slightly Low (*SL*), Slightly High (*SH*), Pretty High (*PH*), Extremely High (*EH*)}, the term set with 3 terms for $D_c(n)$ as $T[D_c(n)]$={Low (*L*), Medium (*M*), High (*H*)}, and the term set with 11 terms for $f_l(n)$ as $T[f_l(n)]$={Extremely Low (*EL*), Very Low (*VL*), Pretty Low (*PL*), Low (*L*), Slightly Low (*SL*), Medium (*M*), Slightly High (*SH*), High (*H*), Pretty High (*PH*), Very High (*VH*), Extremely High (*EH*)}. Note that the number of terms in $T[f_l(n)]$ would be larger than that of $T[f_p(n)]$ for better performance.

The membership functions for terms *EL*, *PL*, *SL*, *SH*, *PH*, and *EH* in $T[f_p(n)]$ are defined as $\mu_{EL}[f_p(n)]$ $=f[f_p(n);0,0,0.3C]$, $\mu_{PL}[f_p(n)]=f[f_p(n);0.2C,0.2C,0.2C]$, $\mu_{SL}[f_p(n)]=f[f_p(n);0.4C,0.2C,0.2C]$, $\mu_{SH}[f_p(n)]$ $=f[f_p(n);0.6C,0.2C,0.2C]$, $\mu_{PH}[f_p(n)]=f[f_p(n);0.8C,0.2C,0.2C]$, and $\mu_{EH}[f_p(n)]=f[f_p(n);C,0.3C,0]$, respectively. The membership functions for terms *L*, *M*, and *H* in $T[D_c(n)]$ are defined as $\mu_L[D_c(n)]$ $=g[D_c(n);0,0.125,0,0.375]$, $\mu_M[D_c(n)]=f[D_c(n);0.5,0.25,0.25]$, $\mu_H[D_c(n)]=g[D_c(n);0.875,1,0.375,0]$, respectively. The membership functions for terms in $T[f_l(n)]$ are defined as fuzzy singletons, denoted by $\mu_T[f_l(n)]=f[f_l(n);x_T,0,0]$, where T=*EL*, *VL*, *PL*, *L*, *SL*, *M*, *SH*, *H*, *PH*, *VH*, or *EH*, and $x_{EL}=0$, $x_{VL}=0.1C$, $x_{PL}=0.2C$, $x_L=0.3C$, $x_{SL}=0.4C$, $x_M=0.5C$, $x_{SH}=0.6C$, $x_H=0.7C$, $x_{PH}=0.8C$, $x_{VH}=0.9C$, or $x_{EH}=C$. Notice that similar to the reason given for the setting of parameter values of $D_c(n)$, the parameter values for membership functions of $f_l(n)$ are generally set over [0, 1] uniformly. Also, the center value of the triangular membership function f of each term for $f_p(n)$ is the same as the center value of the singleton function f of the same term for $f_l(n)$, where these terms are *EL*, *PL*, *SL*, *SH*, *PH*, and *EH*.

There are 18 fuzzy rules for FFG. As shown in Table II, the order of significance of the input linguistic variables is $f_p(n)$ then $D_c(n)$. These fuzzy rules are set in such a way that the generation of $f_l(n)$ mainly refers

TABLE II
THE RULE BASE OF THE FFG

Rule	$f_p(n)$	$D_c(n)$	$f_l(n)$	Rule	$f_p(n)$	$D_c(n)$	$f_l(n)$	Rule	$f_p(n)$	$D_c(n)$	$f_l(n)$
1	*EL*	*L*	*PL*	7	*SL*	*L*	*M*	13	*PH*	*L*	*VH*
2	*EL*	*M*	*VL*	8	*SL*	*M*	*SL*	14	*PH*	*M*	*PH*
3	*EL*	*H*	*EL*	9	*SL*	*H*	*L*	15	*PH*	*H*	*H*
4	*PL*	*L*	*SL*	10	*SH*	*L*	*H*	16	*EH*	*L*	*EH*
5	*PL*	*M*	*L*	11	*SH*	*M*	*SH*	17	*EH*	*M*	*VH*
6	*PL*	*H*	*PL*	12	*SH*	*H*	*M*	18	*EH*	*H*	*PH*

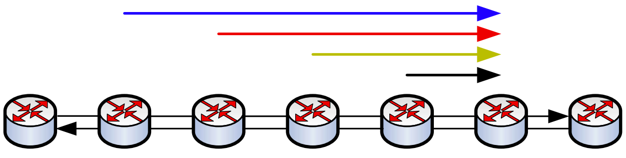
to $f_p(n)$ but slightly adjusted by $D_c(n)$ so as to achieve lower convergence time and thus higher throughput. When $f_p(n)$ is *EL* or *PL*, $f_l(n)$ is designed to raise two levels more than $f_p(n)$ ($EL \rightarrow PL$ or $PL \rightarrow SL$) if $D_c(n)$ is *L* and $f_l(n)$ remains unchanged if $D_c(n)$ is *H*. This tends to increase the throughput. When $f_p(n)$ is *SL*, *SH*, or *PH*, $f_l(n)$ decreases one level less than $f_p(n)$ if $D_c(n)$ is *H* and $f_l(n)$ increases one level larger than $f_p(n)$ if $D_c(n)$ is *L*. When $f_p(n)$ is *EH*, $f_l(n)$ should be decreased two levels less than $f_p(n)$ ($EH \rightarrow PH$) if $D_c(n)$ is *H* and $f_l(n)$ remains unchanged if $D_c(n)$ is *L*. This tends to achieve RIAS fairness. Finally, the inference engine uses the min-max method and the defuzzifier uses the center of the area method, mentioned in Subsection III.B, to generate a crisp-valued local fairRate.

IV. SIMULATION RESULTS AND DISCUSSIONS

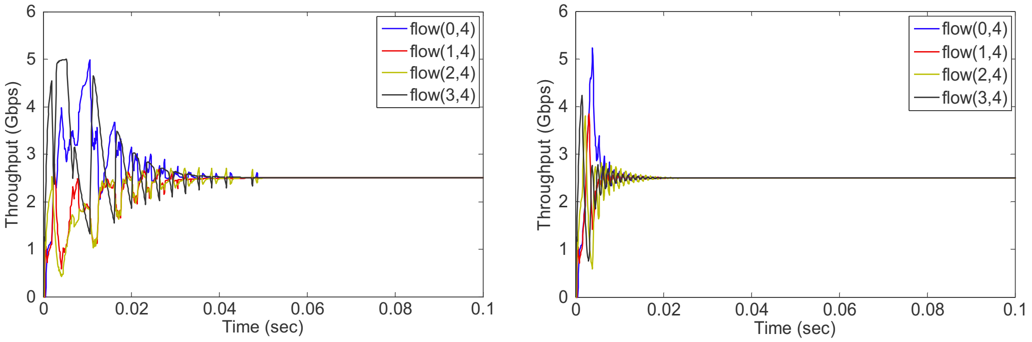
In the simulations, settings for the environment include 10 Gbps link capacity, 100 μs propagation delay between stations, 4 Mbytes STQ size, and 100 μs agingInterval. The value of the *stqHighthreshold* is 1 Mbyte and the value of the *stqLowthreshold* is 0.5 Mbyte. Simulations for the proposed FLAG, the proposed AFC only, the DBA [8], and the AM [6] are conducted for performance comparison. Simulation results are recorded per agingInterval. Also, assume that the reserved bandwidth is zero and only FE traffic flow is considered.

Figure 3(a) shows a small parking lot scenario where there are 5 (0–4) greedy stations, and Figs. 3(b)–3(e) present the throughput of each flow by the AM, DBA, AFC, and FLAG, respectively. This small parking lot scenario assumes that flows are generated from station 0, 1, 2, and 3 but terminated at station 4. The propagation delay is small. It can be seen that the FE flows of the AM, DBA, AFC, and FLAG take 49, 14, 13.5, and 7 ms to reach steady state (stabilize), respectively. Thus the FLAG improves the convergence time of traffic flows by 7 times over the AM and by 2 times over the DBA. The reasons are given as follows. The fuzzy logic provides a robust mathematical method to solve problems that are complicated to find a proper mathematical model for them. In particular, the FLAG contains sophisticated functional blocks that combine advantages of the AM and DBA. It finetunes the so-called *p*-fairRate generated by the AFC according to the congestion degree softly determined by the FCD using the fuzzy logic and the effective fuzzy rules designed in the FFG by expert's domain knowledge. On the other hand, the DBA and AFC generate the local fairRate depending only on the short-term (average) arriving FE traffic flow, or equivalently the change rate of the STQ, without considering the STQ occupancy, which is usually used to determine the congestion degree of the station given in [1]. This would incorrectly limit the amount of the passing transit FE traffic flow to the next station and cause the DBA to make an error decision. For example, if the amount of the short-term arriving transit FE traffic flow is large but the STQ occupancy of a station is short, the station should not seriously regulate the FE traffic flow of its upstream stations. Also, the AM generates a local fairRate that is equal to the added FE traffic flow rate of the station to regulate the flow when the station is in congestion. The AM immediately sets the advertised fairRate as the FullRate to allow the upstream stations to unlimitedly send traffic flow when the congestion is released. This excess variation of the advertised fairRate would cause the station congestion again and thus make the flow of the AM damping the longest. It can also be observed that, at steady state, the throughputs of all flows are the same as required, thus achieving fairness.

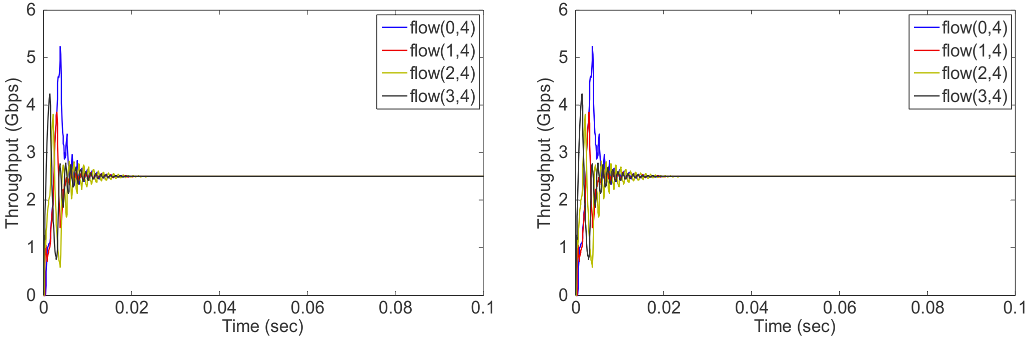
Figure 4(a) shows a large parking lot scenario containing 8 (0–7) greedy stations, and Figs. 4(b)–4(e) present the throughput of flow(0, 7), flow(2, 7), flow(4, 7), and flow(6, 7) at station 7 by the AM, DBA, AFC, and FLAG, respectively. This scenario differs from the previous one of Fig. 3 in that the propagation delay would be large. It can be seen that the FLAG and the AM take 11 and 27 ms to stabilize the flows, respectively; unfortunately, the DBA and AFC take quite a long time to make the flows reach steady state. This is because the DBA computes the number of effective IA flows referring to both the short aggregating traffic (per agingInterval) and the previous local fairRate to generate the current local fairRate. However, due to



(a) Small parking lot scenario with greedy traffic



(b) AM (c) DBA

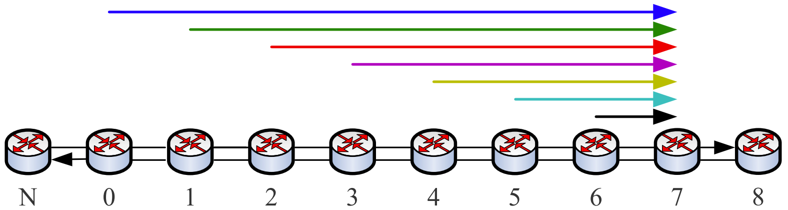


(d) AFC (e) FLAG

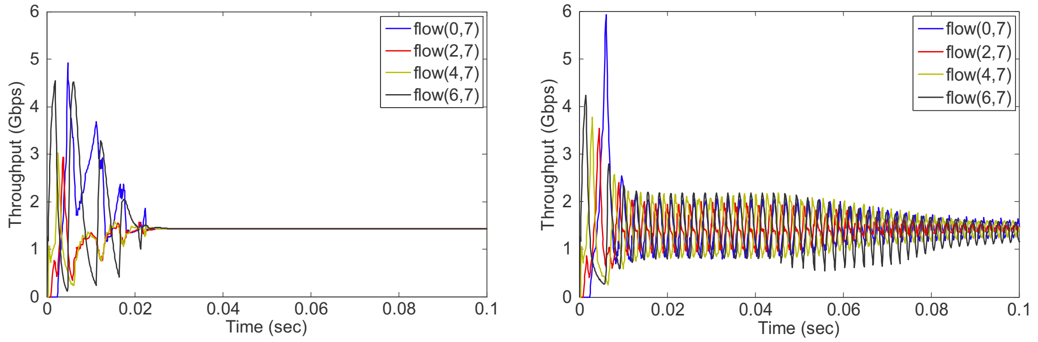
Fig. 3. (Color online) (a) Small parking lot scenario with greedy traffic, and the throughput of the (b) AM, (c) DBA, (d) AFC, and (e) FLAG.

the large propagation delay, the correlation between the short aggregating traffic and the previous local fairRate becomes low. Therefore, the DBA cannot generate a correct local fairRate to regulate flows. Thus the flows oscillate and converge slowly; the convergence time takes about 0.15 s, which is not shown here. The AFC uses the moving average technique to lessen the effect of propagation delay. The flow oscillation of the AFC is half smaller than the DBA but still exists. Since the STQ occupancy is not considered for the congestion degree of the station, the AFC incorrectly limits the amount of the passing transit FE traffic flow to the next station. On the other hand, the FLAG can correctly generate the p-fairRate to meet the RIAS fairness and diminish the effect of the propagation delay to some extent. Also, the FLAG finely adjusts the p-fairRate to a precise local fairRate according to both the congestion degree and the effective fuzzy rules well designed by domain knowledge. The main reason that the AM in this scenario takes less time to stabilize all flows than the AM in the previous scenario shown in Fig. 3(b) is given below. Since, here in Fig. 4(a), there are more stations with greedy traffic, more aggregated traffic per agingInterval will be caused. This more aggregated traffic and the larger propagation delay would make the station congestion always occur earlier. Afterwards, the station would not have the chance to set the advertised fairRate as the FullRate. Thus the convergence time is shorter.

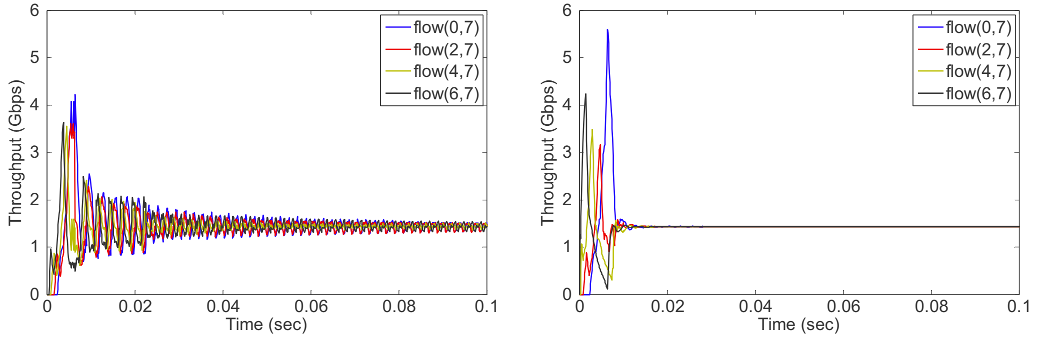
Figures 5(a)–5(d) present throughputs of flow(0, 7), flow(2, 7), flow(4, 7), and flow(6, 7) at station 7 by the AM, DBA, AFC, and FLAG, respectively, in a large parking lot scenario that contains 8 stations as in Fig. 4(a) but with various finite traffic demands. In this scenario, assume that each flow is generated by a truncated Pareto traffic model with a fixed Hurst parameter of 0.75, a fixed maximum value of 10.0 Gbps, and a minimum value [19,20]. Also, assume that flow(0, 7) and flow(1, 7) require a mean rate of 2.1 Gpbs with the minimum value of 1.05 Gbps; flow(4, 7) and flow(5, 7) require a mean rate of 1.5 Gpbs with the minimum value of 0.66 Gbps; and flow(2, 7), flow(3, 7), and flow(6, 7) require a mean rate of 1.0 Gbps with the minimum value of 0.42 Gbps. Station 6 will be the first to incur congestion, and the



(a) Large parking lot scenario with greedy traffic



(b) AM (c) DBA

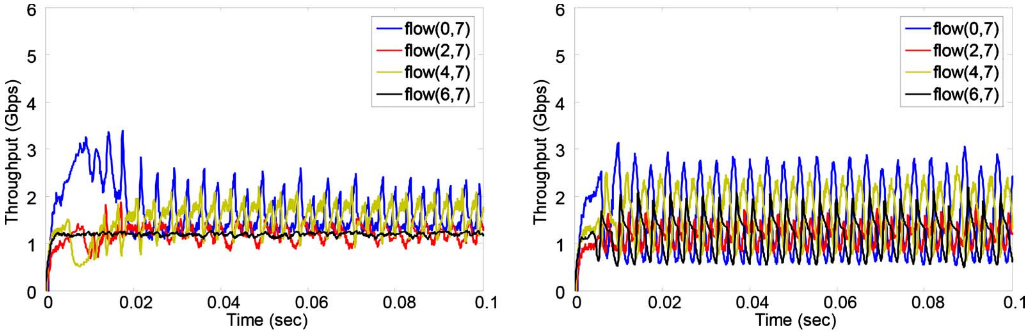


(d) AFC (e) FLAG

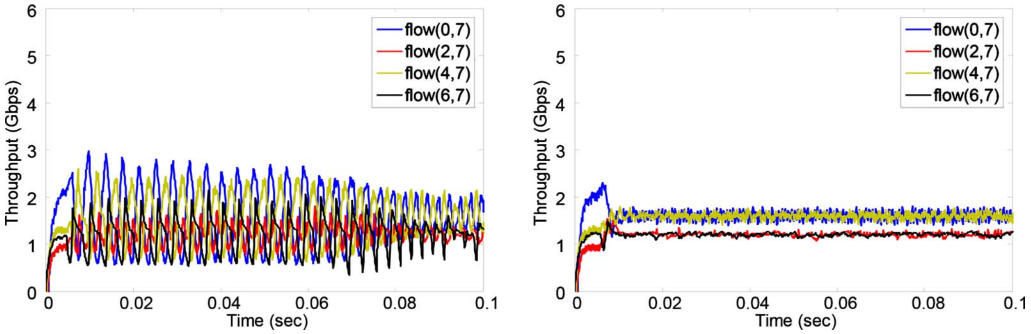
Fig. 4. (Color online) (a) Large parking lot scenario with greedy traffic, and the throughput of the (b) AM, (c) DBA, (d) AFC, and (e) FLAG.

added FE traffic flow to the network at each station cannot always match its received fairRate due to the finite traffic demand at each station. Also, flow(0, 7) and flow(1, 7) will have the highest throughput when station 6 is in free congestion or the remaining bandwidth is large because of their largest required traffic demands. It can be seen then that the AM, DBA, and AFC always oscillate, while the FLAG can make all the flows almost converge and takes about 10 ms. This is because the FLAG indeed diminishes the effect of the propagation delay and generates the correct local fairRate at each agingInterval. Also, since each traffic flow has a different finite traffic demand, which is much less than that of the greedy case in Fig. 4(e), the damping amplitude of the FLAG in Fig. 5(d) is smaller than that in Fig. 4(e). Moreover, the FLAG realizes the RIAS fairness and has higher throughput than the AM, DBA, and AFC by about 1.8%, 2.7%, and 2.1%, respectively. On the other hand, the advertised fairRate by the AM is often set as the FullRate in this scenario because the bandwidth of the total demand traffic is 10.2 Gbps, which is slightly higher than the link capacity but much less than that of the greedy case in Fig. 4(b). In this situation, the aggregated traffic per agingInterval would be smaller, and the congestion, if any, could be solved by the AM most of time. Thus, the flows by the AM always oscillate and the flow(0,7) seriously oscillates due to its largest traffic demand. By the DBA, its generation accuracy of the local fairRate is susceptible to propagation delay, as seen in Fig. 4. Also, in this scenario, station 0 and station 1 are the farthest ones from station 6 and flow(0, 7) and flow(1, 7) have the largest traffic demand. Thus flow(0, 7) and flow(1, 7) cannot be regulated by station 6 quickly. This violent varying aggregation traffic per agingInterval and the effect of the propagation delay thus result in the DBA generating the local fairRate improperly. Notice that if flow(0, 7) requires less traffic demand, the oscillation amplitude of the flows will be smaller. The AFC has the same phenomenon, but its performance is better than the DBA by 1.0% due to using the moving average technique.

Figure 6(a) shows an available bandwidth reclaim-



(a) AM (b) DBA



(c) AFC (d) FLAG

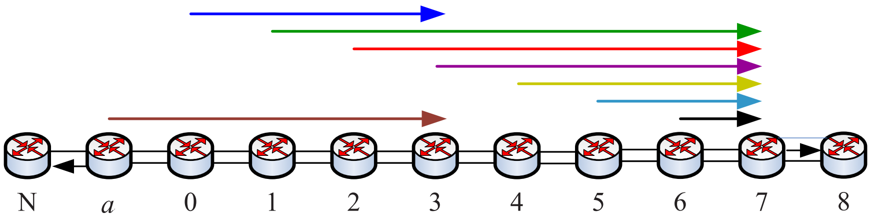
Fig. 5. (Color online) Throughput of the (a) AM, (b) DBA, (c) AFC, and (d) FLAG in a large parking lot scenario with various finite traffic flows.

ing scenario with reuse traffic flows, where there are nine stations with finite traffic demand and two spatial reuses of flow(a,3) and flow(0, 3). Figures 6(b)–6(f) present throughputs of flow(a,3) and flow(0, 3) at station 3 and throughputs of flow(1, 7), flow(4, 7), and flow(6, 7) at station 7 by the AM, DBA, AFC, FLAG, and M-FLAG, respectively, where M-FLAG denotes the modified FLAG with the DBA to replace the AFC. In this scenario, each flow is also generated by a truncated Pareto traffic model with a fixed Hurst parameter of 0.75, a fixed maximum value of 10.0 Gbps, and a minimum value [19,20], where flow(a,3) and flow(0, 3) require a mean rate of 3.0 Gbps with the minimum value of 1.70 Gbps; flow(1, 7), flow(2, 7), and flow(5,7) require a mean rate of 2.5 Gbps with the minimum value of 1.30 Gbps; and flow(3, 7), flow(4, 7), and flow(6, 7) require a mean rate of 1.0 Gbps with the minimum value of 0.42 Gbps. It can be seen that the AM, DBA, and AFC always oscillate with much larger oscillations than the FLAG and M-FLAG, and FLAG still performs the best. Also, all algorithms in this scenario behave worse than in the large parking lot scenario with various finite traffic flows given in Fig. 5. The reasons are as follows. Since flow(a,3) and flow(0, 3) are sunk at station 3, station 2 would have more transient FE traffic flows than station 3, where station 2 has an 11.0 Gbps traffic flow maximum, while station 3 has a 5.0 Gbps traffic flow maximum. This phenomenon is conversed in Fig. 5, where station 2 has a 5.2 Gbps traffic flow maximum, while station 3 has a 6.2 Gbps maximum. Therefore, station 2 in Fig. 6 will more frequently and heavily regulate its station 1, which has 6.0 Gbps transient traffic flow and 2.5 Gbps local traffic flow, than station 2 in Fig. 5 will regulate its station 1, which has 2.1 Gbps transient traffic flow and 2.1 Gbps local traffic flow. Thus it can be believed that all flows in Fig. 6 would oscillate worse than those in Fig. 5 for all algorithms. Also, that the M-FLAG has oscillations larger than the FLAG during the transitional periods shows that the AFC can indeed diminish the effect of the propagation delay once it occurs in the DBA. Moreover, according to our computation, the throughput at station 6 (3) by the FLAG is about 0.992 (0.9574), which is higher than the AM's 0.9479 (0.9263), DBA's 0.951 (0.9386), AFC's 0.960 (0.9431), and M-FLAG's 0.990 (0.9465).

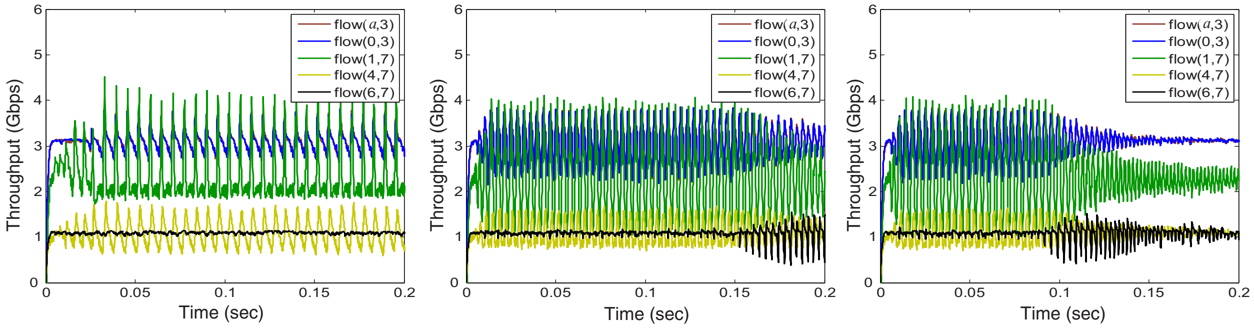
Finally, the FLAG has low computation and implementation complexity and is thus cost-effective since it is mainly designed by using fuzzy logic systems, which have small computational complexity and can be easily realized in a chip [15].

V. CONCLUSIONS

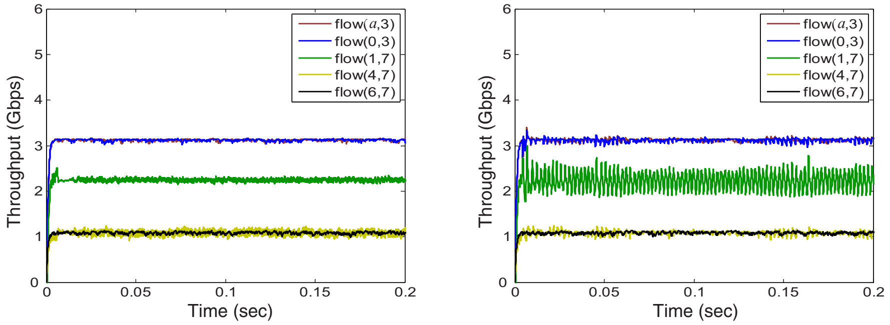
In this paper, an effective fuzzy local fairRate generator (FLAG) has been proposed for resilient packet ring (RPR). The FLAG is sophisticatedly composed of three function blocks: an adaptive fairRate calculator (AFC), a fuzzy congestion detector (FCD), and a fuzzy



(a) Available bandwidth reclaiming scenario with finite traffic demand and two reuse traffic flows



(b) AM (c) DBA (d) AFC



(e) FLAG (f) M-FLAG

Fig. 6. (Color online) (a) Available bandwidth reclaiming scenario with finite traffic demand and two reuse traffic flows, and the throughput of the (b) AM, (c) DBA, (d) AFC, (e) FLAG, and (f) M-FLAG.

fairRate generator (FFG). The AFC pregenerates a fairRate that meets RIAS fairness and can diminish the effect of the propagation delay. The FCD softly detects the congestion degree of the station, considering the STQ length and its change rate, which is the arriving transit FE traffic flows to the STQ. Subsequently, the FFG generates a suitable local fairRate by intelligently fine-tuning the pregenerated fairRate using fuzzy logic, based on the congestion degree of the station. The FLAG can make traffic flows satisfy RIAS fairness criterion and converge to an ideal fairRate in an efficient way. Simulation results show that each flow by the FLAG is indeed close to the designated rate with the smallest damping amplitude and the least convergence time in the parking lot scenarios and the available bandwidth reclaiming scenario, compared with conventional AM and DBA fairness algorithms. These prove that the configuration of the FLAG is indeed sophisticated, where the AFC pregenerates the local fairRate using the moving average technique; the FCD determines the congestion degree of the station using fuzzy logic, considering not only the STQ length but also the change rate of the STQ length; and finally the FFG adopts the fuzzy logic and the expert's domain knowledge to precisely generate the local fairRate by fine-tuning the pregenerated local fairRate by the AFC according to the congestion degree by the FCD. Also, the performance superiority of the AFC over the DBA proves that the moving average technique is indeed effective in diminishing the effect of the propagation delay on the stability of traffic flows.

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