A New Fairness Model for Resilient Packet Rings

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Abstract- One of the main requirements in packet ring networks is to provide fairness in bandwidth allocation among the ring nodes. Each node must receive a fair share of the ring bandwidth and should not starve for an extended period of time. Due to the particular architecture of the packet rings, fairness models such as max-min fairness and proportional fairness are not suitable for these networks. Ring Ingress Aggregated with Spatial reuse (RIAS) is a proposed model for packet rings. However, it lacks generality and intuition. In this paper, a new fairness model for ring networks called Ring Ingress Aggregated Max-Min (RIAMM) fairness, is proposed. This model is invariant of the source behavior. We have analyzed conditions as well as feasibility criteria for this model. Considering Resilient Packet Ring (RPR) as a particular case, we have studied the effect of source behaviors and fairness algorithms. Three main source behaviors, namely, MF (Maximally Feasible), FEP (Feasible Equal Partitioning), and SC (Single Choke) are studied. We show that the FEP source behavior can result in a throughput loss of up to 17%, when traffic disparity exists. It is also shown that fairness algorithms with a slow convergence can result in permanent unfairness during a congestion period.

I. INTRODUCTION

One of the major requirements in the packet rings is to provide fairness in bandwidth allocation among the ring nodes. Each node (station) must receive a fair share of the ring bandwidth and should not starve for an extended period of time [1].

The fairness definition in packet networks has been the subject of many discussions [2]-[9]. In [3], the concept of Ring Ingress Aggregated with Spatial reuse (RIAS) fairness was defined. However, it ties the fairness in the ring to a particular source behavior, hence lacks generality. It is also not intuitive to characterize RIAS fair solutions without knowledge of the source rates and a detailed analysis.

Resilient Packet Ring (RPR) IEEE 802.17 technology, is a new MAC layer for metro-ring networks, devised to achieve objectives such as high throughput, fault tolerance, and bandwidth efficiency, which are not simultaneously achieved in current technologies [10],[11]. Similar to the other ring technologies, fairness among the nodes is the main challenge in RPR. In contrast to quota-based approaches, a distributed rate-based bandwidth management scheme is used in RPR [10]-[12]. A congested RPR node dynamically calculates a local fair rate at the end of every control interval of size T and advertises it to the upstream nodes. The RPR nodes continuously adapt their allowed rates, at which they can add traffic to the ring, based on the fair rates received from the downstream congested nodes. This eliminates the long delay and the waste of bandwidth that could be experienced in token-based and quota-based algorithms. However, the upstream nodes in RPR can take over the available bandwidth and starve the downstream nodes. When a node is starved it may not be able to access the ring for a long period of time. To prevent this problem, a fairness mechanism is required in RPR to regulate the access of all nodes to the ring with a minimal impact on the network throughput and delay.

In this paper, we first introduce a fairness definition for packet rings called Ring Ingress Aggregated Max-Min (RIAMM) fairness. This model distinguishes the ring level fairness from the source behavior. Therefore, it is invariant of any particular intra-station forwarding policy. We show that RIAS fairness is a particular case of RIAMM fairness. We also analyze the RIAMM fairness properties and specify the conditions under which RIAMM fairness is achieved. We then apply RIAMM fairness to RPR. The implementation and the performance of three general source behaviors are studied in this context. The three source behaviors are the ideal Maximally Feasible (MF) source, the approximate Feasible Equal Partitioning (FEP) source, and the Simple Single-Choke (SSC) source. We also introduce the performance criteria to evaluate fairness algorithms and source behaviors. Numerical studies are performed and results are presented in terms of the total ring throughput and throughput of the nodes with different distances from the congestion point.

The rest of this paper is organized as follows. In Section II, the existing fairness models and the service model in RPR are discussed. In Section III, a new mathematical model for fairness in the packet rings is provided and its properties are discussed. Then we analyze the conditions under which a bandwidth management algorithm results in fairness in RPR. Section IV is devoted to the implementation aspects of the MF source behavior and performance evaluation of various design options. Numerical and simulation results are presented. Also, various source behaviors and existing fairness algorithms are reviewed and their potential performance problems are illustrated. Finally, conclusions are drawn in Section V.

II. PRELIMINARIES

In this section, we review some of the existing fairness models and then explain the RPR service model.

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A. Fairness Models

In connection-oriented technologies, fairness is defined for individual flows such as VCs in ATM. The prevailing definition of fairness has been max-min fairness that can be achieved by the weighted fair queuing techniques such as packetized GPS as discussed in [4],[5]. With connection-less switching methods, fairness is usually maintained at the port level. Hence, a flow traveling a larger number of hops will receive proportionally lesser bandwidth than a flow traveling a shorter distance. This is formally called proportional fairness in which the allocated bandwidth of a flow is scaled according to the total amount of resources it consumes in the network [6],[7]. The proportional fairness model is also used in the context of the TCP flow control to increase the overall reward function of the network. The proportional fairness model contradicts the RPR per station fairness objective.

In [8], the concept of user fair queuing is addressed. It is argued that the inter-user fairness must be maintained regardless of the number of traffic flows of the users. The intra-user fairness among flows belonging to a user is managed and maintained by the users themselves. In RPR, the objective is to provide per-station fairness in a max-min sense. This is compatible with the user fairness model but it needs to be customized and formally defined in the context of packet rings. In [3], the concept of RIAS fairness is introduced. RIAS fairness model maintains max-min fairness among ingress-aggregated flows while maximizing spatial reuse in the ring. The problem with this model is that it ties the ring fairness to a particular source behavior and hence lacks generality. It is also not intuitive to characterize RIAS fair solutions without knowledge of the source rates and detailed analysis.

B. RPR Service Model

RPR depends on Buffer Insertion Ring (BIR) procedure, which adds or drops packets on the ring without full de-multiplexing of the incoming traffic (Fig. 1). Since upstream nodes can take over all of the bandwidth for an unpredictable period of time, the access delay to the ring may not be bounded. To support real-time applications, three classes of traffic are defined in RPR: high-priority low delay/jitter class A, medium priority bounded delay/jitter class B, and low-priority best effort class C. Class A has exhaustive priority over class B and class B has priority over class C. Each of class A and class B are further divided into two subclasses: A0, A1, B-CIR (Committed Information Rate), and B-EIR (Excess Information Rate). The bandwidth for class A is reserved throughout the ring. The remaining bandwidth called unreserved rate is available for the other traffic classes. The bandwidth is allocated for class A1 and B-CIR but can be reclaimed by class C if not used. The bandwidth reservations are applied through traffic shapers used for each of class A0, A1 and B-CIR. The conforming traffic receives exhaustive service priority over fairness eligible (FE) traffic consisting of class B-EIR and class C. The rate of FE traffic is regulated by a shaper enforcing the fair rate.

III. RING INGRESS AGGREGATED MAX-MIN (RIAMM) FAIRNESS

A. Frameworks

The main objective for the bandwidth management mechanisms in packet rings such as RPR is to provide per station fairness in utilizing the ring bandwidth. Given the same per-station weights (or priority) and the same bandwidth demands, the ring bandwidth should be equally divided among the competing stations. Let us denote a source-destination flow from node i to node j by f(i,j) and an Ingress Aggregated (IA) super-flow transiting node n and originated at node i by sf(i,n). The ring bandwidth management consists of two components:

1) Ring behavior: It deals with calculating a fair rate at each node in order to maintain inter-station fairness. From a fairness point of view, IA super-flows are visible and not the individual source-destination flows. The advertised fair rates regulate the rate of IA super-flows so that none of the stations suffers from starvation.

2) Source behavior: It deals with intra-station fairness and allocating bandwidth to the individual flows at each node based on the received fair rates from downstream nodes.

The main objective in intra-station fairness is to maximize spatial reuse and the total ring throughput. That is, if long-haul flows face congestion, other flows destined to the nodes before the congestion point must be able to claim the available bandwidth. However, due to the complexity considerations, stations may be designed and hence behave in many different proprietary ways. Fairness in the ring should not depend on any particular assumption on the source behavior. It should only govern the ring behavior. RIAS fairness model described in [3] does not make this distinction. RIAS fairness provides a useful benchmark for fairness in a packet ring but it is not applicable for any arbitrary source behavior. In the following, we formally define the fairness in a ring and discuss the impact of the source behavior.

B. Ring Behavior

Let C be the available bandwidth on a link (or unreserved rate), \( r^n_i \) be the rate of \( sf(i,n) \), and \( F_n \) be the local fair rate calculated at node n. Note that \( r^n_i \) is a non-increasing function of \( n \), that is, \( r^n_i \geq r^{n+1}_i \).

Definition 1: The set of rates \( F = \{ F_n, \forall n \} \) and alternatively the matrix of super-flow rates \( R = \{ r^n_i, \forall i,n \} \) are defined to be RIAMM fair if they meet the following criteria simultaneously:

\[
\begin{align*}
& r^n_i \leq F_n, \forall i,n, \\
& F_n = \max_{\text{min}} \{ C, \{ r^n_i, \forall i \} \} \\
& = \max_{\text{min}} \{ C, \{ r^n_i, \forall i \} \} + \alpha[C- \sum r^n_i]_,
\end{align*}
\]
where $[x]^\dagger = \max\{x,0\}$ and $0 < \alpha \leq 1$. The distinction between $\max_{\min}$ and $\max_{\min}$ is essential. When the bandwidth is not utilized, $\max_{\min}$ results in a value that is larger than the rate of any of the current super-flows. This is controlled by parameter $\alpha$. For $\alpha > 0$, the unused bandwidth can be claimed by the backlogged flows. In the absence of an explicit signaling, this is a way that a backlogged node can inform its downstream nodes to re-evaluate and increase their local fair rates.

**Definition 2:** Node $m$ is a bottleneck for $s_f(i,n)$ if the following two conditions are satisfied:

$$
\begin{align*}
   r_i^m &= F_m, \\
   r_i^j &\leq F_k, \forall m < k < n.
\end{align*}
$$

(3)

It is easy to verify that with RIAMM fairness, any super-flow that is backlogged will have a bottleneck node. Otherwise, its rate can be feasibly increased.

**C. Source Behavior**

Each station adds its local traffic on a per-destination basis at a prescribed rate. In the context of RPR, per-destination queues at each node are called Virtual Destination Queues (VDQs), where traffic destined to node $j$ is buffered in VDQ. Let $r_{ij}$ be the add rate of flow $f(i,j)$, i.e., the service rate of VDQ at node $i$. We have $r_i^m = \sum_{j \approx m} r_{ij}$. 

**Definition 3:** The set of rates $\bar{R} = \{r_{ij}, \forall j\}$ is called feasible if the following conditions hold:

$$
\begin{align*}
   \sum_{j \approx m} r_{ij} &\leq F_m, \forall n, \quad (4) \\
   \sum_{j \approx m} r_{ij} &\leq C_i, \quad (5)
\end{align*}
$$

where $C_i$ is the predefined maximum rate of the FE traffic at node $i$. In RPR, $C_i$ is equal to $C$ or $F_i$ depending on the type of the fairness algorithm. Any source behavior that results in a feasible solution is called feasible.

**Proposition 1:** For any feasible source behavior, if $F = \{F_i, \forall k\}$ is a RIAMM fair solution, then at any node $m$, that is a bottleneck for at least one super-flow, we must have

$$
\sum_{j} r_i^m = C. \quad (6)
$$

**Proof:** Suppose that $\sum_{j} r_i^m < C$. Then from (2), we will have $F_m > r_i^m, \forall i$. Therefore, this node will not be a bottleneck, which contradicts the assumption. □

**Definition 4:** The set of rates $\bar{R} = \{r_{ij}, \forall j\}$ is called maximally feasible if it is feasible and that for every backlogged superflow there is a bottleneck node, that is, its rate cannot be feasibly increased. A source behavior that results in a maximally feasible solution is called maximally feasible (MF).

Due to the complexity of the MF source, other source behaviors have been considered as follows:

1) Feasible Equal Partitioning (FEP) source: In this case we have

$$
\begin{align*}
   r_{ij} &\leq \min_{\alpha \leq j} \{F_i/N_{\alpha}(i)\}, \forall j > i+1,
\end{align*}
$$

(7)

where $N_{\alpha}(i)$ is the number of flows transiting node $n$ and originated at station $i$. Note that the rate of single hop flows, $r_{i,i-1}$ is not constrained in (7). These flows are only constrained by the feasibility constraint in (5). Hence, they can take over the whole unused bandwidth, up to $C_i$, on the outgoing link since it does not have any impact on the other flows.

2) Single Choke (SC) source: In this case, the rate of a flow is not controlled individually. Let us define $m$ as the most congested node so that $F_m = \min_{\alpha \leq j} \{F_i\}$. When the SC source behavior is used, we have $\sum_{j > m} r_{ij} \leq F_m$. It means that the aggregate rate of the flows passing through the most congested node is regulated by $F_m$. The rate of the other flows is regulated by the feasibility constraint in (5). With the SC source behavior and under overload conditions, permanent rate oscillations may occur. In this paper, a simpler but stable source behavior is considered as follows.

3) Simple Single Choke (SSC) source: With the SSC source behavior, the total add-rate of a station is regulated by the fair rate of the most congested node. That is, $\sum_{j \approx m} r_{ij} \leq F_m$. The FEP, SC, and SSC source behaviors do not always result in maximally feasible solutions.

**Example 1:** Let us consider the scenario in Fig. 2 and assume a RIAMM fair behavior at the ring level and that all of the flows have infinite demand. All rates are normalized to the link rate. Flow $f(1,30)$ is facing congestion at node 29 and cannot transmit more than 0.04. Let $F_1 = F_3 = 0.5$. With the MF source behavior, we have $r_{1,30} = 0.04, r_{1,4} = 0.46,$ and $r_{2,4} = 0.5$. This is a RIAMM fair solution satisfying (1) and (2). However, with the FEP source behavior, we have $r_{1,30} = 0.04, r_{1,4} = 0.25,$ and $r_{2,4} = 0.5$. This is not a RIAMM fair solution since (2) is not satisfied for $n = 2$ and $n = 3$ that requires $F_{1,30} = 0.5$ and $F_{1,4} = 0.5$. The solution that simultaneously satisfies (1), (2), and (7) is $F_1 = F_3 = 0.64, r_{1,30} = 0.04, r_{1,4} = 0.32,$ and $r_{2,4} = 0.64$. Therefore, this is also a RIAMM fair solution. RIAMM fairness is applicable regardless of the source behavior as it only governs the ring behavior. With the SSC source behavior, the rate of the most congested node will take effect and we have $r_{1,30} = 0.04, r_{1,4} = 0.02, r_{2,4} = 0.04$. Although this solution is fair, it results in a huge loss of the ring throughput. If we applied a per-flow max-min fairness, we would have $r_{1,30} = 0.04, r_{1,4} = 0.48,$ and $r_{2,4} = 0.48$. This is not a RIAMM fair solution. The reason is that at node 3, station 1 receives 0.52 of the available bandwidth but station 2 receives 0.48 of the available bandwidth, while it has infinite demand as node 1. Table 1 summarizes these cases.

**D. Comparison with RIAS fairness**

Ring Ingress Aggregated with Spatial Reuse (RIAS) fairness is defined in [3]. RIAS fairness model assumes the MF source behavior in all nodes. It does not make any distinction between the ring behavior and the source behavior. RIAS fairness corresponds to RIAMM fairness, when the MF source behavior is
assumed. Formally, a solution \( \hat{R} = \{r_{ij}, \forall i,j \} \) is called to be RIAS fair if it is feasible and if for each flow \( f(i,j) \) with bottleneck node \( n \), \( r_{ij} \) cannot be increased, while maintaining feasibility, without decreasing \( r_{i'j'} \) for some flow \( f(i',j') \) with bottleneck node \( n' \), for which

\[
\begin{align*}
    r_{i,j} \leq r_{i,j'} & \quad \text{when } i = i', \\
    r_{i,n} + r_{i,n'} \leq r_{i,n} + r_{i,n'} & \quad \text{when } r_{i,j} > 0 \text{ for } l = i,j, k = n,n' (n \neq n'), \\
    \sum_{i} r_{i,j} \leq \sum_{i} r_{i,j'} & \quad \text{otherwise}.
\end{align*}
\]

(8)

It is shown that \( \hat{R} \) is RIAS fair if and only if each flow \( f(i,j) \) has a bottleneck link with respect to \( \hat{R} \) [3].

**Proposition 2:** A RIAMM fair solution \( \hat{R} = \{r_{ij}, \forall i,j \} \) with a maximally feasible source behavior in all stations is a RIAS fair solution.

**Proof:** With the MF source behavior, every backlogged flow has a bottleneck node. Also, we have proved that with RIAMM fairness the outgoing link at node \( m \) is a bottleneck for at least one flow, is fully utilized, i.e., \( \sum_i r_i^n = C \). Therefore, it is a bottleneck link and hence it is a RIAS fair solution.

With the FEP source behavior, there is no fairness algorithm that can yield a RIAS fair solution in general. The counter-example in Example 1 demonstrates this point.

**E. Requirements of Rate Control Algorithms in RPR**

In RPR, we are dealing with a distributed rate control system (See Fig. 3). To achieve fairness, a global fair rate should be calculated so that if all of the rate controllers are set accordingly, congestion does not occur. The average rate of the arrival process to an arbitrary node \( n \) during control interval \( k \) is equal to

\[
r'(k)=\sum_{i} r_i^n(k) = \sum_{i=} r_i^n(k) + r_i^n(k).
\]

(9)

The first term in (9) is the average rate of the transit traffic at node \( n \) and the second term is the average arrival rate of the local traffic at node \( n \) to the virtual queue, in control interval \( k \). We have \( \sum_i r_i^n(k) \leq C \) and \( r_i^n(k) \leq F_{pk}(k) \). Note that \( r_i^n(k) \) is the amount of the local traffic conforming to the current fair rate, whether it is serviced or buffered. Therefore, \( r_i^n(k) \leq C + F_{pk}(k) \). When \( r_i^n(k) > C \), the local node does not receive its fair share. The eligible traffic in the excess of the available bandwidth is buffered at the local node. Therefore, each node can be modeled as a virtual queue with a service rate of \( C \) and the average arrival rate of \( r_i^n(k) \). A simplified model of this system is shown in Fig. 3.

![Fig. 3. A simplified model of RPR rate control system](image-url)

**Proposition 3:** Any ring bandwidth management algorithm that maintains \( \sum_{i} r_i^n(k) \leq C, \forall n \), results in a fair solution.

**Proof:** Assume an arbitrary node \( n \) and let \( r_{max} = \max_i \{r_i^n(k)\} \). If \( \sum_i r_i^n(k) < C \), we have \( F_{pk}(k) > r_{max} \). If \( \sum_i r_i^n(k) \geq C \), then we have \( F_{pk}(k) = r_{max} \). This case, we can write \( r_{max} = (C - \sum_{i} r_i^n(k)) / \|\{i: r_i^n(k) = r_{max}\}| = \max_{i} \min_{C, \{r_i^n \notin \forall i\}} \), which is a fair solution based on Definition 1.

This proposition indicates that to achieve RIAMM fairness, an explicit \( \max_{i} \min_{C, \{r_i^n \notin \forall i\}} \) operation is not necessary. The rate control mechanism must only be able to match the total incoming traffic rate at each node \( n \) to the ring bandwidth, that is, \( r_i^n(k) \leq C \). The ring bandwidth management function should be designed so that after any change in per-station traffic rates, it can speedily converge to maintain this condition. In the next section, first we will explain the implementation of the MF source behavior. Then we study the performance of two fairness schemes proposed in RPR draft standard through simulation results.

**IV. IMPLEMENTATION AND PERFORMANCE EVALUATION**

**A. Implementing MF source**

We discuss two possible implementations for the MF source behavior. The first approach is to use a separate shaper for each VDQ that operates independently (Fig. 4-a). The rate of each shaper can be calculated using the following iterative algorithm. Let \( k \) be the last node that node \( i \) has a non-zero flow destined to it and let \( L_k \) be the maximum per-flow rate of node \( i \) at node \( n \). The algorithm works as follows:

1. **Step 1:** set \( L_n = F_{in}, \forall n \)
2. **Step 2:** set \( r_{ik} \leq \min_{j \neq k} \{L_{ij} \} \)
3. **Step 3:** for \( j = k - 1, k - 2, ..., 0 \)
   - set \( L_j = \max_{i \neq j} \{F_i, \{r_{ij} \forall l \geq j \} \}
   - set \( r_{ij} = \min_{i \neq j} \{L_{ij} \} \)
4. **Step 4:** if \( r_{ik} \leq \min_{j \neq k} \{L_{ij} \} \), set \( r_{ik} \leq \min_{j \neq k} \{L_{ij} \} \) and go to **Step 3**; else terminate.

The second approach is to use cascade shapers as shown in Fig. 4-b. This approach does not require a per-flow rate calculation and it dynamically allocates the available bandwidth to the VDQs in a work conserving manner. However, a packet destined to node \( j \) from node \( i \) goes through \((j-i)\) shapers. The shapers are updated if the packet is served. Otherwise, if a
We have the performance of the FEP and the SSC source behaviors under-allocation of the head node. In the following, we study node in the unit of time expressed in bps and measures the does in general result in a maximally feasible solution if and only if some of the flows are not backlogged, i.e., \( r_{ij} < \rho_{n+1}(i) \). Let us assume that \( \rho_{n}(i) \) is a decreasing function of \( n \) such that \( \rho_{n}(i) < \rho_{n+1}(i) \) and \( \rho_{i}(j) > \rho_{i}(n), \forall n' < n \). Suppose that flow \( f(i,n+1) \) is backlogged. Since \( r_{i,n+2} < \rho_{n}(i) \), we have \( r_{i,n+2} < \rho_{n}(i) \). Therefore, \( r_{i,n+2} < F_{n} \) and backlogged flow \( f(i,n+1) \) does not have a bottleneck and hence this solution is not maximally feasible.

In Example 1, we have \( \rho_{i}(1) \geq 0.25 \) and \( \rho_{i}(1) > \rho_{n}(1) \). Therefore, the above condition (a) does not hold and we demonstrated that the FEP source behavior does not yield an MF solution.

**Example 2:** Let us consider the scenario in Fig. 5 that satisfies Proposition 4. We have \( \rho_{i}(1) = 0.5C/3, \rho_{i}(1) = 0.5C/2, \rho_{i}(1) = C/3. \) From (7), we have \( r_{1,3} = r_{1,4} = r_{1,5} \). Let \( r_{1,5} = x \) and \( r_{1,5} = y \). Also, from (6) at node 2 we have \( 3x + y = C \) and at node 4 we have \( y = (C-x)/2 \). Therefore, \( x = 0.2C \) and \( y = 0.4C \). The rest of the bandwidth will be taken by single hop flows, i.e., \( r_{1,2} = 0.4C \) and \( r_{4,5} = 0.4C \). This is a RIAMM fair solution with the MF source behavior.

In order to characterize the impact of using the FEP instead of the MF source behavior, we studied a number of traffic scenarios. In all cases, overload conditions are used since they pose greater challenges. We use the total ring throughput as the performance metric indicating the degree of spatial reuse. The scenarios are as follows:

1. **Mixed Hub-1:** In this scenario, there are \( N \) nodes all sending traffic to the hub (node \( N+1 \)). All of the nodes have infinite demand. The tail node also sends traffic to a node \( H \) hops away. The study is done for different values of \( N \) and \( H \). Fig. 6 shows this scenario for \( N=4 \) and \( H=2 \), where node 5 is the hub.

2. **Mixed Hub-2:** Each node has a long-haul and a short-haul flow. The long-haul flow goes to the hub and the short-haul flow goes to a node two hops away. All of the nodes have infinite demand. Fig. 7 shows this scenario for \( N=4 \) and \( H=2 \).
Fig. 8 illustrates the relative loss of the ring throughput of the SSC and the FEP source behaviors (compared to MF) for different $H$ in Mixed Hub-1 scenario. We assume that $N=9$ in all cases. With the SSC source behavior, the throughput loss of up to 43% is observed. In case of the FEP source behavior, the throughput loss is noticeable when there is a large disparity in the ring both in terms of the length of the flows and traffic load of the links. For $H=8$, traffic load of all links are equal and there is no disparity. In this case, the FEP source behavior is similar to the MF source behavior. Hence, the throughput loss of FEP is zero for $H=8$. Also for $H=1$, no loss occurs as the constraint (7) does not apply to the single-hop flows. However, for $H=2$, the throughput loss is close to 20%. The throughput loss decreases with $H$, as the traffic disparity in the ring and the RIAMM fair rate of the short-haul flow decreases.

In Fig. 9 the relative loss of the ring throughput of the FEP source behavior (compared to MF) for different $N$ in Mixed Hub-2 is shown. We assume that $H=2$ in all cases. The results for Mix Hub-1 with $H=2$ is also presented. One can see that the throughput loss increases with $N$ in both scenarios. The reason is that as $N$ increases the number of flows goes up, in Mix Hub-1 scenario, which increases the disparity. Also, traffic load of the links has more disparity in Mix Hub-2 as $N$ increases. Hence, the relative loss increases with $N$ in both scenarios. Note that for $N=3$, both scenarios result in an MF solution and the throughput loss is zero.

D. Evaluating the Ring Behavior in the RPR Fairness Algorithms

In the previous section, thesteady-state behavior of the various source types was studied. Here, we compare the performance and fairness properties of the two rate control algorithms proposed in RPR draft standard. A full description of these algorithms can be found in [3], [10].

The RPR standard fairness algorithm operates in two modes: Aggressive Mode (RPR-AM), and Conservative Mode (RPR-CM). In RPR-AM, the local fair rate is calculated as the low-pass filtered version of the add rate of the FE traffic of the local node. In case of congestion, the head node in the congestion span is not able to send at the previously advertised fair rate. Hence, the local fair rate decreases releasing the congestion. The nodes in the congestion span, directly apply the received fair rates to their rate shapers during the congestion. For the feasibility constraint in (5), $C_i$ is set equal to $C$ in RPR-AM. Therefore, the local fair rate is not applied to the local node itself.

RPR-CM algorithm is based on a rate ramp-up and ramp-down principle. In Conservative Mode, when the congestion is detected for the first time, the local fair rate is set to an initial value of $C$ divided by the number of active stations. If the congested node remains congested and the total service rate of the local and the transit traffic (except the service rate of class A0) is greater than $\text{high\_threshold}$ (e.g. 0.95-$C$), the fair rate is ramped up. If the total service rate is less than $\text{low\_threshold}$ (e.g. 0.80-$C$), the fair rate is ramped down. In RPR-CM the parameter $C_i$ in (5) is set to $F_i$. That is, the local fair rate is applied to the node itself. In RPR-CM, the total link utilization is maintained below the maximum available rate compared to RPR-AM. The throughput loss can be equal to $C-\text{low\_threshold}$. On the other hand RPR-AM algorithm is known to have an oscillatory behavior for some unbalanced traffic scenarios [3]. Therefore, RIAMM fairness may not be guaranteed. We have conducted simulations to study the fairness properties of RPR-AM and RPR-CM algorithms. The simulations are performed in OPNET. We considered 100Mbps links with 50μsec propagation delay (i.e., a distance of 10km between each pair of nodes) and control interval of 1msec. Our study is concentrated on fairness properties of these algorithms in overload conditions, as these conditions more pressing in order to demonstrate and compare the behavior of the algorithms. The simulations are performed with a small packet size of 512 bits and only FE traffic was considered. The simulation parameters are as follows: $lp\text{Coef} = 16$, $ramp\text{UpCoef}=ramp\text{DnCoef}=32$, $\text{low\_threshold}=0.8C$, and $\text{high\_threshold}=0.95C$.

A parking lot scenario (Fig. 10) with 4 nodes was used where all nodes send traffic to the hub (node 5). This scenario is widely considered in the literature [3]. In this experiment, all the nodes start sending traffic at the same time after an idle period. An unbalanced traffic scenario is assumed where nodes 1 and 3 can send at full link rate while nodes 2 and 4 can only send at the rate of 0.1C. The RIAMM fair rate is $F_5=0.4C$ and RIAMM fair solution for the super-flows is $r_{4,5}=r_{2,5}=0.1C$, $r_{1,5}=r_{3,5}=0.4C$. Fig. 11 shows the evolution of the fair rate and $\text{ATT}$ for RPR-AM and RPR-CM algorithms in time. $\text{ATT}$ grows during transient period in both algorithms. RPR-CM
converges after 50 control intervals and $ATT$ stays flat indicating that a fair solution is achieved. However, the fair rate in RPR-AM oscillates resulting in violation of condition (1). In Fig. 11-c, we observe a permanent growth in $ATT$ with RPR-AM, which shows a deviation from RIAMM fair rates. In this case the head node (node 4) receives on average 7% less than its fair share.

V. CONCLUSION

In this paper, we introduced a new intuitive fairness model for packet rings called RIAMM fairness. This model is invariant of the source behavior. It was shown that RIAS fairness model is a particular case of RIAMM fairness. We analyzed the properties of the proposed model and compared it to the existing ones. In particular, the impact of source behavior on the total ring throughput was studied. We showed that the FEP source behavior can result in up to 17% loss in ring throughput. Also, requirements for a RIAMM-fair rate-control algorithm in RPR were analyzed. We compared RPR-AM and RPR-CM algorithms using simulations. To maintain RIAMM fairness, a fairness algorithm with a fast convergence property is needed.

REFERENCES