Unslotted Optical CSMA/CA MAC Protocol with Fairness Control in Metro WDM Ring Networks

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***Abstract*— Optical *Carrier Sense Multiple Access with Collision Avoidance* (CSMA/CA) is a *Media Access Control* (MAC) protocol proposed for future metro *Wavelength Division Multiplexing* (WDM) ring networks with a fixed receiver and a tunable transmitter at access nodes [1], [2]. In this paper, we focus on the unslotted version of the optical CSMA/CA MAC which is a fully-distributed and asynchronous protocol. We present the results of design and performance evaluation of fairness control schemes based on *Longest Queue First* (LQF) scheduling and two random routing algorithms – *Full Random Routing* (FRR) and *Partial Random Routing* (PRR). Through extensive network-level simulation of a WDM ring network with 10 nodes and 10 wavelengths on a 100 km ring at 10 Gbps line rate, we demonstrate a combination of the LQF scheduling and the PRR with a retransmission counter provides good fairness (fairness index [3] of 0.9995) with high bandwidth efficiency and small delay spread, under highly unbalanced traffic conditions.**

I. INTRODUCTION

Optical *Carrier Sense Multiple Access with Collision Avoidance* (CSMA/CA) has been proposed as a *Media Access Control* (MAC) protocol for HORNET (*Hybrid Optoelectronic Ring NETwork* [1], [2]), a promising packet over *Wavelength Division Multiplexing* (WDM) *Metropolitan Area Network* (MAN) architecture, where each node is equipped with a fixed receiver and a tunable laser. Among its many variations, the unslotted version has two unique benefits as an optical MAC protocol [4]: Firstly, it is a fully-distributed, asynchronous protocol not based on a centralized controller or a separate control wavelength to synchronize the operations of nodes on the ring. This is an advantage in implementation compared to the slotted optical MAC protocols, most of which maintain synchronous slot boundaries over many wavelengths through dispersion compensation. Secondly, it can naturally support variable length IP packets without segmentation and reassembly function if desired. These features make the unslotted optical CSMA/CA an attractive MAC protocol for future optical MANs and *Local Area Networks* (LANs).

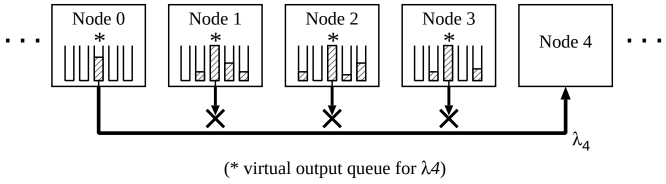

Fig. 1. An example network scenario showing severe unfairness due to positional priority and unbalanced traffic.

Because of unidirectional transmission of signal on the optical ring and collision avoidance action of the MAC protocol, incoming frames from upstream nodes take priority over outgoing frames at a node. Hence, there arises the so-called *positional priority* problem where for a given destination and the corresponding wavelength, access nodes farther from the destination node have higher priorities over those closer to the destination node [5]. Therefore guaranteeing fairness among different traffic streams at different nodes is critical for both the unslotted and slotted optical MAC protocols.

There have been proposed several slotted optical MAC protocols to address this fairness issue in WDM ring or dual bus networks [6], [7], [8], [9], where a dedicated control channel or separate control messages in the same data channels are used to exchange control information among access nodes. Unslotted optical MAC protocols, however, have been getting less focus in the literature in spite of the aforementioned benefits because of the complexity in their analyses by either simulations or mathematical techniques, and the seemingly lower bandwidth efficiency.

Recently we studied scheduling algorithms for unslotted optical CSMA/CA MAC protocol and demonstrated they can effectively guarantee fairness under uniform traffic conditions through network-level simulations [4], [10]. Scheduling alone, however, cannot guarantee fairness under highly unbalanced traffic conditions. For instance, as illustrated in Fig. 1, a single stream from node 0 to node 4 blocks traffic from all other nodes upstream to the same destination. Because there is only one traffic stream at node 0 in this configuration, any scheduling algorithm cannot but select the channel λ_4 all the time.

In this paper we propose and present the performance of fairness control schemes based on *Longest Queue First* (LQF) scheduling and random routing algorithms – *Full Random Routing* (FRR) and *Partial Random Routing* (PRR) – for unslotted optical CSMA/CA MAC protocol that can provide fairness among streams even under highly unbalanced traffic conditions as well as balanced traffic conditions. Unlike the existing fairness control schemes in the slotted optical MAC protocols, the proposed schemes do not need any dedicated control channels

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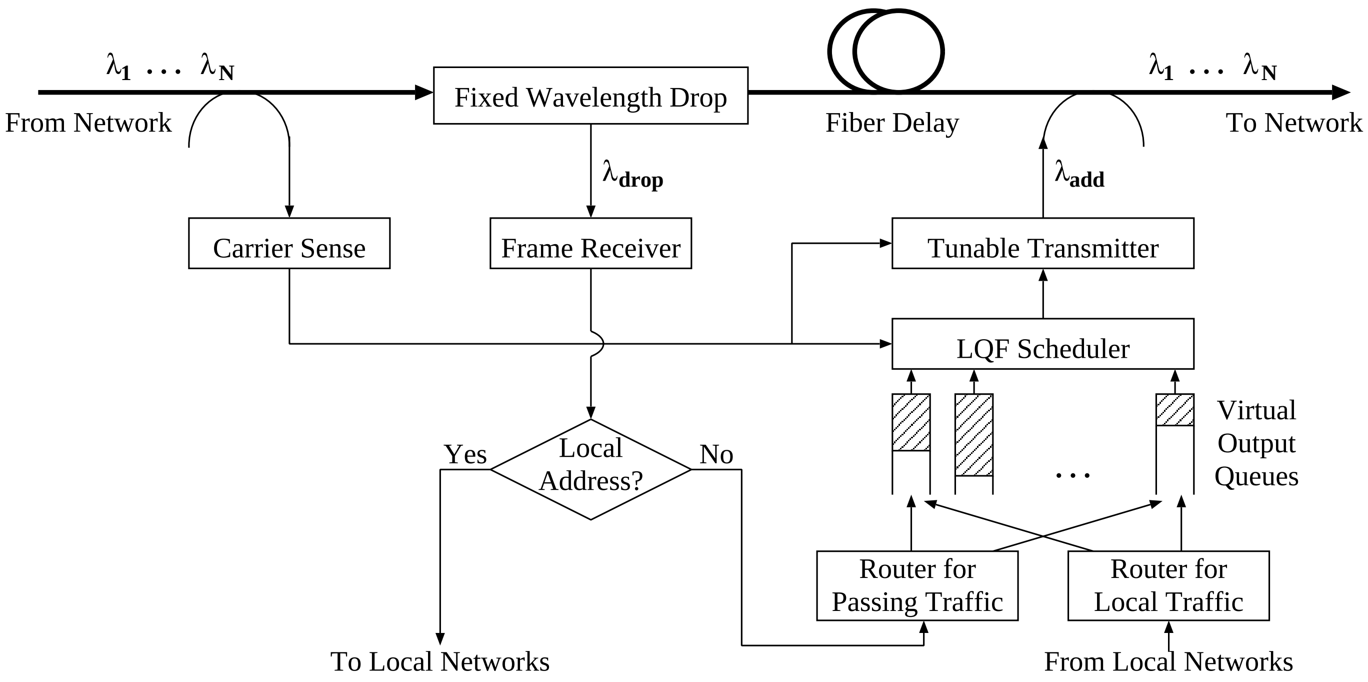

Fig. 2. Access node for unslotted optical CSMA/CA MAC with fairness control.

or messages.

The rest of the paper is organized as follows: In Section II we describe the proposed fairness control schemes with a possible implementation of access node structure. In Section III we present initial simulation results for the proposed fairness control schemes. In Section IV, based on the initial simulation results, we discuss the enhancement of the fairness control schemes with a retransmission counter, and show performance improvements of the enhanced scheme against the original one through simulations in Section V. Section VI summarizes our work and discusses future work.

II. UNSLOTTED OPTICAL CSMA/CA MAC WITH PROPOSED FAIRNESS CONTROL

Fig. 2 shows a block diagram of an access node for the unslotted optical CSMA/CA MAC protocol with the proposed fairness control scheme based on the LQF scheduling and random routing.

While the frame receiver receives the frames on a fixed wavelength, the carrier sense *listens* to all wavelength by monitoring either sub-carriers [1] or baseband optical signals [11], depending on the implementation. When there are frames ready for transmission in *Virtual Output Queues* (VOQs) and channels are available, the LQF scheduler chooses a channel for frame transmission based on channel availability and VOQ lengths.

The LQF scheduler has been chosen because it shows the best performance in terms of throughput and fairness guarantee under balanced traffic condition with the minimum optical buffer size of 13 octets [4], [10]. The LQF scheduler selects a channel with the longest VOQ to counteract the effect of positional priority because VOQs with lower positional priorities are likely to be longer than those with higher positional priorities.

After waiting for a guard band time, if the scheduled channel is still available, the access node starts transmitting the frame. However, since the access node cannot know if the opening on the channel is long enough to accommodate the entire frame, it continues to monitor the channel. For this purpose a small 'fixed' optical delay line (*i.e.*, optical buffer) is placed between the carrier sense and the tunable transmitter. If the carrier sense detects a frame arriving on the same wavelength and the optical buffer size is not big enough for successful transmission of the remaining frame with a guard band, it immediately interrupts the frame transmission and sends a jamming signal. Otherwise, it can transmit the entire frame without interruption.

Note that the optical buffer size should be at least large enough to transmit the jamming signal and the guard band before the incoming frame. The jamming signal (like in the Ethernet) could be a unique bit pattern, either at baseband or on sub-carrier. The frame receiver at downstream access node recognizes the incomplete frame by the presence of the jamming signal and pulls it off the ring. The access node can reschedule the transmission of the frame for a later time.

To provide fairness even under unbalanced traffic conditions like the one shown in Fig. 1, we use random routing schemes. We propose two random routing schemes, FRR and PRR, for this purpose. In the FRR, frames from local networks (local frames) and from other nodes (multihopping frames) are randomly routed over VOQs, while in the PRR, only local frames are randomly routed but multihopping frames are correctly routed based on their destination addresses. Then the scheduler schedules transmission of frames in VOQs based on its scheduling algorithm as usual.

In random routing schemes, some frames are directly delivered to their destinations, but others through several intermediate nodes until finally reaching their destinations. By this random nature in distribution of traffic over channels, there can be some alleviation in channel overloading. Therefore we can avoid starvation of nodes closer to the destination, which leads to better fairness among traffic streams under highly unbalanced traffic conditions.

III. SIMULATION RESULTS I – FRR AND PRR

We have developed a simulation model for the performance evaluation of the proposed fairness control schemes based on *Objective Modular Network Testbed in C++* (OMNeT++) [12]. The OMNeT++ is a discrete-event-driven simulator based on C++ and supports models of hierarchically nested modules with multiple links between them, which is an essential feature for the simulation of WDM systems.

The simulation model is for a WDM ring network with HORNET architecture, consisting of 10 access nodes and 10 wavelengths on a 100 km ring network at 10 Gbps line rate, where each node on the ring receives frames through a fixed wavelength and send frames any wavelengths available through a tunable laser. IP packets are generated according to Poisson process with the packet size distribution matching that of a measurement trace from one of MCI's backbone OC-3 links [13].

In the simulation IP packets are encapsulated in Ethernet frames before being transmitted over the fiber. Since we set the line rate to 10 Gbps for our simulation, we adopt frame format from 10 Gigabit Ethernet specifications and assume a frame overhead of 26 octets. We also assume that a guard band is 12 octets (=9.6 ns), a jamming signal 1 octet, the optical buffer size 13 octets, which is the minimum required for the transmission of interrupted frame, and the VOQ size 10^5 octets.

For traffic condition, we consider a scenario where nodes 0 to 8 communicate only with a hot-spot node 9 at rates of 1.2 Gbps bidirectionally, which overloads the channel to node 9. Note that there is only one outgoing stream at nodes 0 to 8, while at node 9, there are streams to all other nodes.

Fig. 3 shows throughputs of both upstream and downstream connections. Note that we also include the performance of the non-random routing scheme (LQF scheduling alone), which we call *fixed routing*, for the purpose of comparison. It is clear that fixed routing suffers from unfairness in upstream direction, due to which nodes closer to the destination (in this case, nodes 5 to 8) actually starve. In downstream direction, however, the fixed routing can provide good throughput and fairness because the traffic condition at node 9 is balanced and there is no contention over channels.

On the other hand, the random routing schemes can provide better fairness preventing starvation of nodes closer to the destination. The FRR shows pretty good fairness in both directions, but there are significant penalties in throughput, which results from the increasing contention in the network due to significant amount of multihopping traffic. In the case of PRR, which limits the maximum number of hops to 2 and thereby reduces the amount of multihopping traffic, we can see significant improvements in throughput over FRR but at the expense of fairness.

Fig. 4 shows end-to-end packet delay distributions of sampled upstream connections (from nodes 0, 4, and 8 to node 9, respectively). Because the FRR doesn't limit the number of hops packets can take, the delay distribution is more widely spread compared to the PRR. We can expect the difference in delay distributions to be bigger when we increase the total number of nodes in the network because the average number of hops for the FRR is the total number of nodes minus 1, while the maximum number of hops is limited to 2 in the case of PRR. Note that with the random routing schemes frames can be delivered out of order. So we need a resequencing buffer at the link/MAC layer. Due to its smaller delay spread, the PRR requires smaller resequencing buffer compared to the FRR.

IV. ENHANCEMENT OF PRR SCHEME WITH RETRANSMISSION COUNTER

Although PRR as described in Section III has better throughput and packet delay distribution than FRR, still there is a room for improvement in fairness guarantees.

When a node fails to transmit a frame on a channel due to incoming frames from upstream nodes, it keeps the frame in the VOQ and tries to retransmit it later when the channel is available. Careful examination of the simulation results in Section III, however, shows that when the channel is overloaded, it has little chance to transmit the holding frame therefore blocking transmission of all other frames in the VOQ, which eventually causes packet losses due to buffer overflow. This problem is severe especially when the positional priority of the node is very low or the frame in transmission process is very long.

To solve this long transmission blocking problem, we introduce a *Retransmission Counter* (RC) that limits the maximum number of retransmissions. The transmission procedure using the RC is as follows: The RC increases whenever frame transmission fails due to incoming frames. If the value of the RC reaches a certain limit, the transmitter discards the frame, schedules another one from the VOQs, and tries to transmit it as usual.

If TCP flow control is used for a connection in the upper layer, packets lost with this scheme will get retransmitted. Note that, in such a case, the PRR provides alternative paths (channels) to retransmitted packets, which would increase the chance of successful transmissions.

We call this new scheme *PRR with RC*.

V. SIMULATION RESULTS II – PRR WITH RETRANSMISSION COUNTER

Simulation settings are the same as in Section III. We set the maximum limit of the RC to 10.[1]

Fig. 5 shows the throughput of both upstream and downstream connections for the original PRR and PRR with RC. Our results verify that PRR with RC greatly improves the fairness for both upstream and downstream connections. The fairness index [3] is 0.9995 for both upstream and downstream in the case of the PRR with RC, while in the original PRR, they were 0.9150 and 0.9992 for upstream and downstream, respectively. Additionally, the bandwidth efficiency has been improved with the introduction of the RC: The total throughput of the whole

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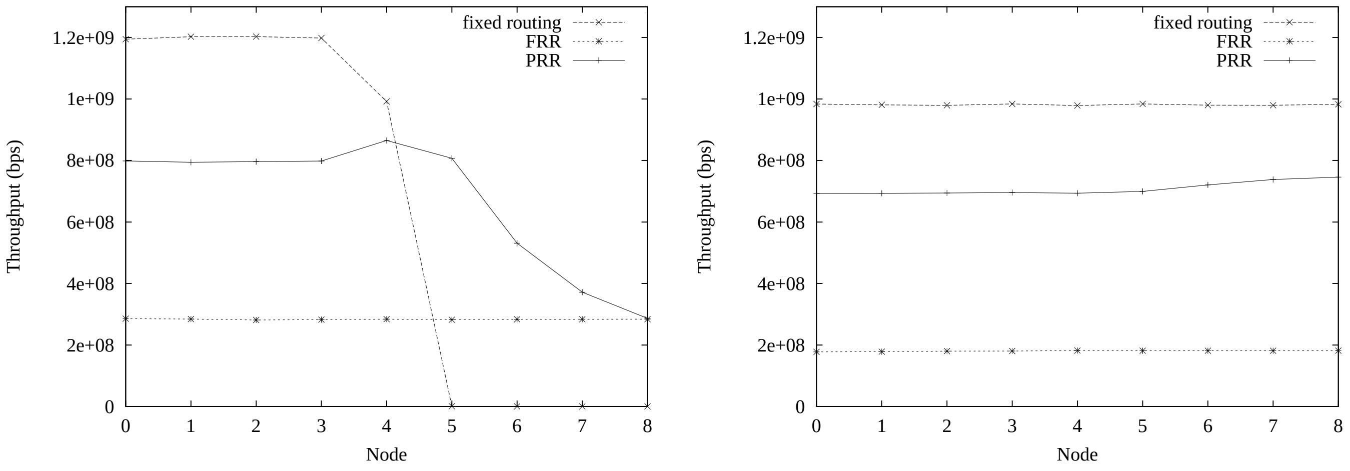
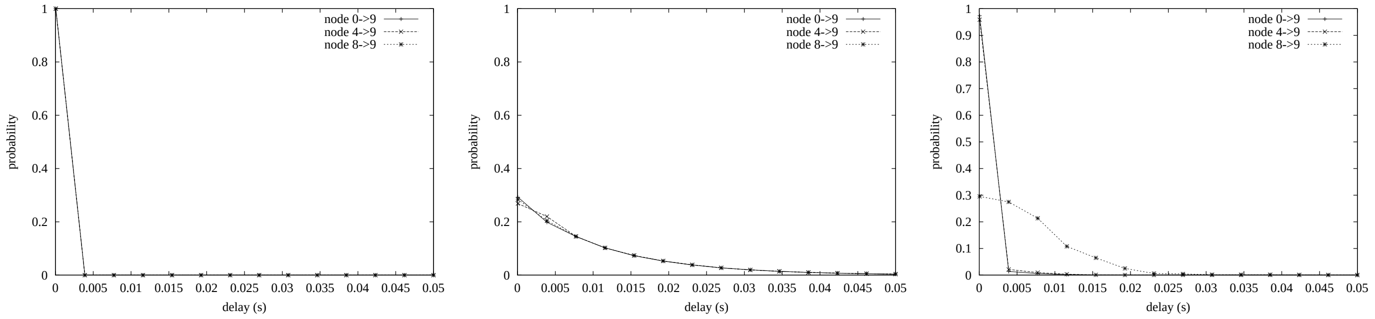
[1] We have verified that the maximum limit of the RC of 10 is optimal given the simulation settings through separate analysis which is not reported in this paper due to space limitation.



(a)

(b)

Fig. 3. Throughputs of connections for the proposed routing algorithms: (a) upstream and (b) downstream.



(a)

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Fig. 4. End-to-end packet delay distributions of sample connections for the proposed routing algorithms: (a) fixed routing, (b) FRR, and (c) PRR.

network has increased from 6.048 Gbps to 6.111 Gbps in upstream and from 6.372 Gbps to 6.975 Gbps in downstream, respectively.

Fig. 6 shows end-to-end packet delay distributions of sampled upstream connections. It is evident that with the RC, there is virtually no difference among delay distributions for different streams and the result looks like that of the fixed routing. Therefore we infer that the major cause of the delay spread for the stream from node 8 to node 9 in the original PRR (shown in Fig. 4) is the blocking problem discussed in Section IV.

From the results, we have verified that the introduction of the RC to the original PRR scheme greatly improves the performance of the unslotted optical CSMA/CA MAC protocol in all the measures we considered – throughput, fairness, and end-to-end packet delay.

VI. SUMMARY AND FUTURE WORK

In this paper we have proposed fairness control schemes based on the LQF scheduling and two random routing algorithms – the FRR and the PRR – for the unslotted optical CSMA/CA MAC protocol. Initial simulation results show the PRR, compared to the FRR, provides better throughput and delay performance, but at the expense of fairness. To enhance the fairness performance of the original PRR, we have introduced the RC to solve the problem of long transmission blocking by limiting the maximum number of retransmissions. Through simulations we have verified that the introduction of RC greatly improves the performance of the original PRR scheme in all the measures considered – throughput, fairness, and end-to-end packet delay. Considering that the PRR with RC does not use any reservation mechanism with separate control channels or messages, it is encouraging that the proposed scheme can guarantee good fairness, with fairness index close to 1, even under highly unbalanced traffic conditions.

The actual end-to-end performance of the optical unslotted CSMA/CA MAC protocol with fairness control can be estimated only with realistic network environment with upper layers including TCP/IP protocols. We are currently implementing new simulation models with full TCP/IP protocol stack, which will enable us to better understand the actual behavior of the MAC protocol and its interaction with TCP flow control. Also we are working on the *Adaptive Random Routing* scheme taking advantage of both high transmission efficiency of the fixed routing under balanced traffic conditions and good fairness of the PRR under unbalanced traffic conditions.

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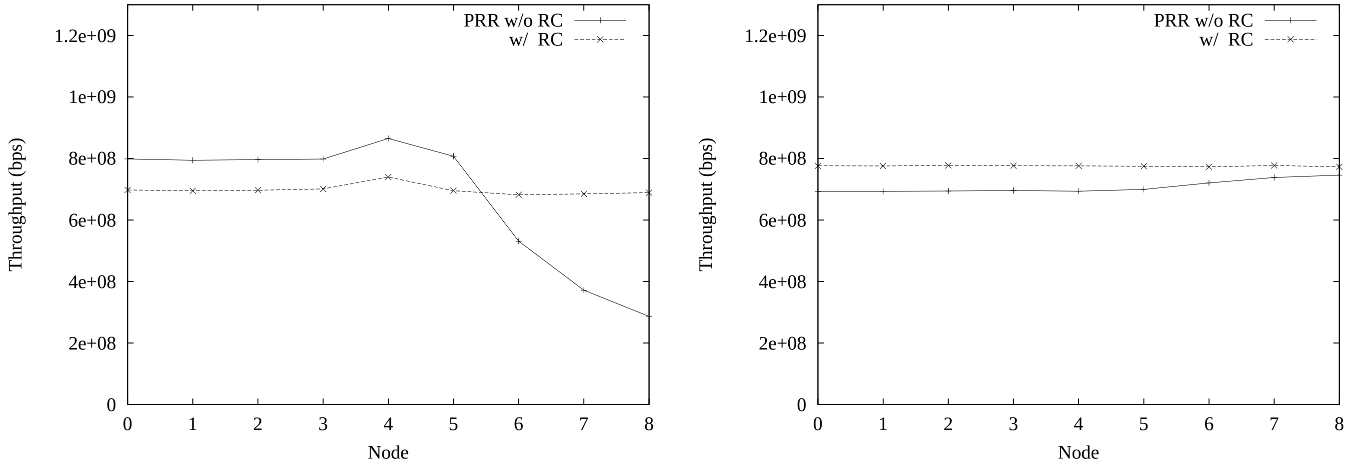

(a)

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Fig. 5. Throughputs of connections for the PRR and the PRR with RC: (a) upstream and (b)downstream.

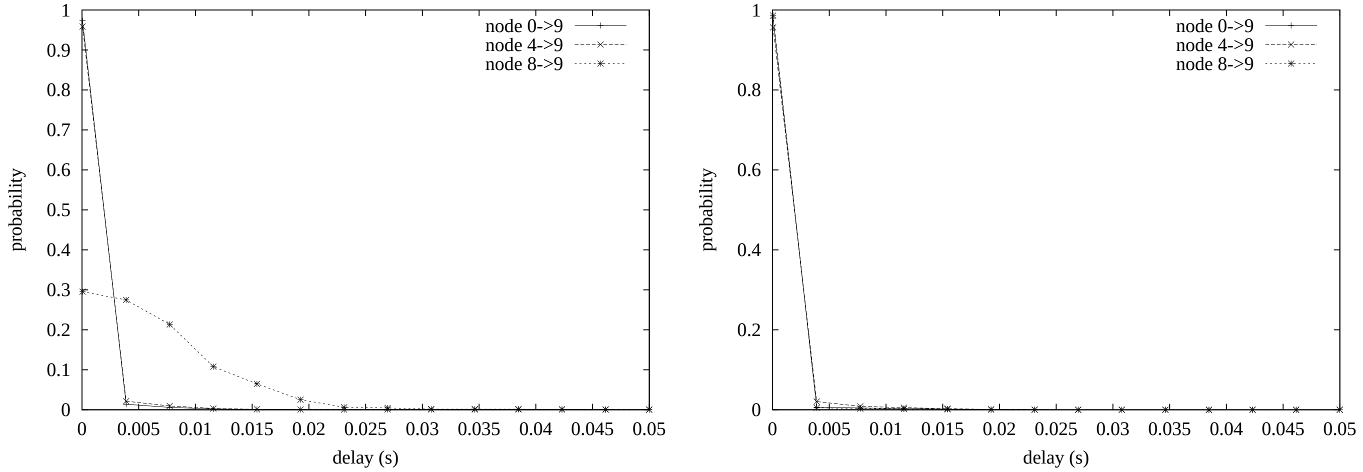

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Fig. 6. End-to-end packet delay distributions of sample connections for (a) PRR and (b) PRR with RC.

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